Snow Removal and Ice Control Research

SPECIAL REPORT 185

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NATIONAL ACADEMY OF SCIENCES

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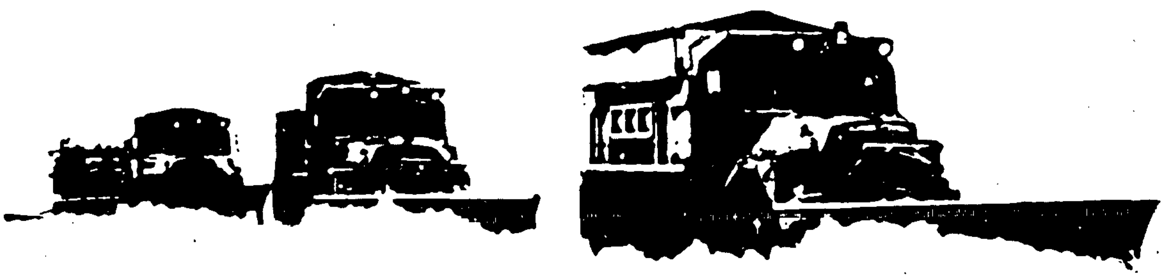

Proceedings of the Second International Symposium, held May 15-19, 1978, at Hanover, New Hampshire, and sponsored by the Transportation Research Board, the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, and the U.S. Department of Transportation

Transportation Research Board
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NATIONAL ACADEMY OF SCIENCES
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The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in this report are those of the authors and do not necessarily reflect the view of the committee, the Transportation Research Board, the National Academy of Sciences, or the sponsors of the project.

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Sponsorship of the Papers in This Special Report

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The organizational units and officers and members are as of December 31, 1978.

The special contributions of the following individuals are gratefully acknowledged.

L. David Minsk, U.S. Army Cold Regions Research and Engineering Laboratory, served as chairman of the steering group directly responsible for the symposium program and arrangements. He was assisted in his efforts by Philip Brinkman, Federal Highway Administration, and Robert R. Blackburn, Midwest Research Institute. Edward J. Kehl, chairman of the sponsoring committee, also served as a member of the steering group.

Walter V. Levitsky, Transport Canada, a member of the steering group, made arrangements for participation by Canadian representatives on the program.

Harold B. Coleman, U.S. Department of Transportation, served as liaison member from the U.S. Department of Transportation to the steering committee.

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Introduction and Overview

L. David Minsk, U.S. Army Cold Regions
Research and Engineering Laboratory

Since the first Symposium on Snow Removal and Ice Control Research was held in 1970, much has happened. Skirting the political areas, where during the interim the United States survived a traumatic experience only superficially related to the water-substance that sometimes causes a different, but sometimes equally traumatic effect in our ranks, I'll dwell on more substantive and relevant changes. The most important is the broader scope of this, the 2nd International Symposium on Snow Removal and Ice Control Research. The first was confined to highway-related snow and ice control, corresponding to the then constituted Highway Research Board, which co-sponsored the meeting with CRREL. In 1974, the Highway Research Board became the Transportation Research Board, encompassing all aspects of transportation — in addition to roads, rail, air and water which are now incorporated in TRB's purview. Since this enlarged scope corresponds more closely to CRREL's interests in all aspects of snow and ice, the current symposium reflects this and includes papers on the control of snow and ice on communications facilities, ships, guideway systems, railroads, airports and aircraft. The broader scope is not capricious: no transportation system can operate effectively nor indeed survive without a communications network tying the system together, whether it is a signboard on a highway, an antenna providing a radio link, or an aerial cable joining nodes overland. One goal in bringing together a diverse group is to stimulate cross fertilization. You might say we here are an analog to a Department of Transportation and Communications, and that in fact is the title of a ministry of the Province of Ontario, Canada.

A measure of the interest and activity in snow removal and ice control research is the number of papers to be presented this week. During our early planning we envisioned a 3 1/2 day meeting of no more than eight sessions. As more and more offers were received we were first forced to lengthen the symposium to four days, from noon Monday to noon Friday, knowing full well that in so doing we might possibly decrease accessibility to many who could not afford to spend all that time with us. With the receipt of more offers we were obliged to decrease accessibility even more by instituting dual sessions on both Tuesday and Wednesday.

Perhaps the great interest in snow removal is the result of the extreme winters recently. However, heavy incapacitating snowfalls are not new events suddenly bursting on an unsuspecting North America. The experiences of Buffalo and Watertown, New York, during the winter of 1976/77, culminating in the first-ever declaration of a civil emergency by the federal government because of paralysis caused by accumulated snow, commanded the headlines in February of last year. Buffalo's seasonal snowfall of 199.4 inches (506.5 cm) that year set a new record, as did the 53 consecutive days of observed snowfall. The residents of Oswego, New York, on the southeastern shore of Lake Ontario, can be excused their slightly disparaging view of Buffalo's plight when they recall the lake-effect storm that lasted five days in January 1966 and left 102 in. (259 cm) of snow on the ground. Two years later, in February 1968, continuous lake-effect snow squalls over a 12-day period dumped 113 in. (287 cm) on Oswego. The 68 in. (178 cm) of snow that fell on Adams, New York, on the eastern shore of Lake Ontario, appears to be the record 24-hr. lake-effect snowfall in the eastern Great Lakes region. Boston's 31-in. (79-cm) snowfall last February compares with the 28 in. (71 cm) that fell in a little more than a day on Washington, DC, in January 1922, killing 100 people when the roof of the Knickerbocker Theater collapsed.

What distinguishes recent winters is the greater extent to which the Midwestern and Atlantic states have received heavy, disabling snows, such as in Kentucky, Indiana, and Ohio just 3 months ago. No one can predict with any certainty what next winter will bring, but as George Santayana has warned "those who fail to learn the lesson of history are doomed to repeat it."

Welcoming Addresses

Dr. Andrew Assur, Chief Scientist, U.S. Army Cold Regions Research and Engineering Laboratory

On behalf of the Cold Regions Research and Engineering Laboratory and on behalf of its Director, Colonel Robert L. Crosby, I would like to welcome you to Hanover, New Hampshire.

One of the best ways to advance the state of the art is doing exactly what you are doing today: bringing interested people together, exchanging points of view especially in private discussions, listening to presented papers, and examining their contents. Great credit is due the Organizing Committee for the Symposium in making all of this possible.

A quick look at the list of speakers reveals the wide range of interest in the topic: 35% came from abroad. The eminence of Japan is especially gratifying but so too is the participation of Canadian researchers (13% each). Other countries include India, Italy, Great Britain and the Netherlands. Especially interesting are the snow and ice problems of India in the Himalayas.

In the United States the biggest participation came from federal laboratories and experiment stations (18% of all speakers), universities (15%), and not much less from state agencies (13%), private R&D firms (11%) and federal departments (8%).

There is a distinct need for solutions and we are here to lay stepping stones on the road to finding them. Topics of discussion range from basic research in snow mechanics and ice adhesion to broad questions of economy and environmental protection, various means of snow and ice removal, visibility and detection, as well as advanced systems of snow and ice control. Of particular interest, and a first as far as I have been able to determine, is the discussion of snow and ice accumulation and control problems on the transportation technology of the future, the automated guideway systems.

It is a difficult field but challenges exist to be overcome. Most of the advanced industrialized nations have to cope with the impact of snow and ice on their activities; by joining forces and sharing our experience and knowledge we will all benefit. That is also a challenge. So let us continue with our endeavors to succeed!

W.N. Carey, Jr., Executive Director, Transportation Research Board

It is a pleasure for me, on behalf of the Transportation Research Board, to welcome you to the Second International Symposium on Snow Removal and Ice Control Research. Our co-sponsor, the Cold Regions Research and Engineering Laboratory, is undoubtedly the finest facility of its kind in the United States.

My first inclination was to express pleasure for the opportunity this Symposium provides to share U.S. snow and ice control research findings with representatives of other countries but it turns out that the Canadian contribution to this Symposium is so significant that it is more appropriate to express pleasure that we in North America have this opportunity to exchange research findings with you. I also want to acknowledge other individuals and organizations that have made a major contribution to preparing and arranging this meeting. These include the U.S. Department of Transportation and Harold Coleman; Ed Kehl, Chairman of the Board's Committee on Winter Maintenance that is sponsoring the meeting; the special program committee chaired by David Minsk, the person who has probably made the greatest single contribution; members of his program committee including Robert Blackburn, Midwest Research Institute, Charles Brinkman, Federal Highway Administration, Walter Levitsky, Transport Canada, and Adrian Clary, representing the Transportation Research Board.

Obviously, those of us who are here recognize that snow and ice control is a timely subject. The United States has just suffered two very severe winters. This past winter was apparently the coldest that we have ever had--at least in the east. Gulf coast states that do not normally budget for snow and ice removal faced serious icing, and northern states, accustomed to using major portions of their budgets on snow and ice control, were unable to keep ahead of the weather in many cases. If this is indicative of the future, this Symposium assumes greater than ordinary importance.

The 1970 Symposium had great significance in the areas of classification of snow and ice, ice and snow detection and warning systems, ice adhesion, salt damage to bridge decks, the use of earth heat, management of ice and snow control programs, controlling snow drifting and equipment development. This work was published in TRB Special Report 115.

It seems appropriate to review with you some of the changes that have occurred between the first symposium in 1970 and today.

- Our Transportation Research Board was concerned almost entirely with highway problems in 1970. Since then we have taken on the whole world of transportation to the wistful regret of some of us oldtimers.

- Our courts and legislatures have eroded the concept of sovereign immunity that carried over from English law. Our transportation agencies and individual administrators have become painfully aware that their actions may, at any time, become subject to lawsuits.

- The environmental protection movement has "flowered." The environmental impact of chemicals used for snow and ice removal has been a popular target. Attempts have been made to measure the benefit/cost relationships related to chemical use - free winter movement versus chemical damages. We have learned that we were not blameless and we have responded by constructing enclosed storage facilities for chemicals, by adding ground sensor controls to salt spreaders and by training crews in procedures to insure accurate rates of chemical application. "Sensible salting" has become the gospel.

- The 1973-74 oil embargo moved energy concerns to the forefront of United States National Concerns and the cost of snow buildup was translated into energy consumption as another input to management.

We are still concerned with problems evidenced at the first Symposium. Corrosion of bridge deck steel and widespread deck distress has resulted in the development of epoxy coated reinforcing steel, protective membranes, better construction controls, different deck design criteria, less permeable surface course, polymer impregnation and other similar treatments.

Management emphasis is continuing and perhaps intensifying. Serious questions are being raised about the quality levels that maintenance budgets will support. Have higher expectations been engendered by superior performance in the past that now cannot be accommodated? On the other hand, can our interdependent economy accept less than a major effort?

So much for background. Where do we go from here? What should this Symposium produce?

- Can sophisticated guideway systems be designed to operate trouble-free in snowbelt cities?

- Short term weather forecasting, aided by satellite photography, is far better than it was in 1970--how much help will it provide in the next decade in view of the massive infusion of research money that is being spent to improve the system?

- Attempts to develop accurate ice dectors and warning systems have not been completely successful. Is it possible to develop devices that will be successful? Pioneering work by Japan on development and installation of an ice detection, prediction and warning system on highways, described at the 1970 Symposium, has not spurred similar installations in the U.S. Why not?

- How far, how fast, and what applications may we expect to see as we build on the sensing techniques described in the 1970 Symposium and on current work in the Netherlands?

- Ice removal costs ten to fifteen times as much as snow removal--what can we do to beat that game?

- What alternate maintenance strategies should we employ to optimize the effectiveness of winter maintenance programs?

During the coming week we ask that you consider the stated objectives of the Symposium:

> "To define the likely level of expenditures and the objectives that should be set for transportation-related snow and ice research during the next decade."

We have charged our presiding officers with a portion of the responsibility for accomplishing this objective. We, in turn, ask you to make your thoughts and opinions known to the presiding officers verbally or in writing during the week and if further thoughts occur to you during the next month or two after the Symposium, we request that you send them to Adrian G. Clary at TRB, David Minsk at CRREL or to Edward Kehl at the Illinois DOT.

May you find the rest of the week interesting to you and beneficial to the organization you represent.

Dr. James Costantino, Director, Transportation Systems Center, U.S. Department of Transportation

I'm pinch-hitting for Jack Fearnsides, the Deputy Under Secretary, who at this moment is probably sleeping off his jet lag in a motel near Red Square in the Soviet Union...he is heading an American delegation looking into rail and transit issues.

I would like to add my welcome to that of the previous speakers. Having moved to Boston last year from the more temperate climate of the Nation's Capitol, and with the past Boston winter still fresh in my memory--need I say it's a pleasure to be here in New Hampshire on this day in May...even if it is raining.

Within the Department of Transportation, the subject of snow removal and ice control is receiving considerable attention from our Urban Mass Transportation Administration (UMTA), Federal Highway Administration (FHWA), Federal Aviation Administration (FAA), and the U.S. Coast Guard. I will say just a few words about some of the things going on in these organizations.

The methods to achieve successful winter operation of conventional rail and bus transit have become relatively routine. We are more concerned now, however, with Automated Guidway Transit (AGT) systems where the traction and power pickup requirements are more stringent than those of nonautomated transit. Therefore, our development efforts are primarily directed towards problems of maintaining signal transmission, power and traction.

At the Transportation Systems Center, we are also helping UMTA plan a winterization demonstration program to ensure that the Automated Guideway Transit systems to be installed in major cities under the Downtown People Movers program will have adequate winter capabilities. UMTA will share the cost of each demonstration conducted by the system suppliers. Testing is scheduled to begin during the 1978-1979 winter season.

The federally coordinated program of highway R&D has included considerable research related to safety and maintenance problems associated with bad weather. Much of this work was reported on at the last Symposium and has already been mentioned this afternoon by Mr. Carey.

While progress continues to be made in the more innovative development such as tapping earth heat and use of solar and wind energy for pavement deicing, plowing and salting continue to be the backbone of the winter maintenance operation. Having recognized the damage caused by road salt, FHWA is examining physical and chemical alternatives to its use. One of those studies is being conducted here at CRREL.

Highway departments have long sought an ice detector reliable enough to operate motorist warning signs, particularly for icy bridges. FHWA has examined the problem of ice detection using predictive devices, point detectors, area detectors, and even detection based on traffic behavior. We are not yet confident in recommending any detector for operating warning signs, but there is promise in some of these methods, and detectors are currently available which may aid maintenance men by alerting them to a possible problem.

In addition to all this applied research, the Department of Transportation supports fundamental research aimed at solving transportation related problems through its University Research Program. Two such studies, one by the South Dakota School of Mines and Technology and one by the University of Maine, are investigating the mechanisms of ice adhesion to roadway surfaces. These studies, both of which will be reported on at this meeting, may provide insight into ways of breaking or reducing the ice bond for removal purposes.

The Federal Aviation Administration's concerns range from aircraft icing to airport snow removal and runway icing problems. Looking to the future, an ice detector system is being studied which would measure surface temperature and free air temperature to provide more precise guidance to airport operators as to type of chemicals necessary for use, substantially altering the need for a standby labor force. Further research efforts may be directed to in-pavement heating utilizing earth heat sources, and possibly electrically heated areas using solar amorphous/semi-conductor technology. The development of fuel-efficient large volume snow melters to eliminate stockpiled snow in high snowfall areas is also being considered.

Turning to the marine mode of transportation within the Department, although the St. Lawrence Seaway Development Corporation and the U.S. Coast Guard are plagued with ice-coated surfaces at locks and on ships, no specific research effort is being presently made to overcome this problem. There is, however, a possible spin-off from a project directed towards finding a special coating for ships' hulls to reduce ice friction. Over the past several years, the Coast Guard has sponsored laboratory and field tests of some 150 candidate coatings capable of providing both low ice friction and high wear and hull adhesiveness properties. Six of these materials show some promise; as a result, certain solventless formulations, e.g., polyurethane and epoxy, are under test on the tug RARITAN and the icebreaker POLAR STAR. There is hope that such coatings might not only have low ice friction, but also low ice adhesion after the ice is struck a sharp blow.

With the U.S. Congress' continued interest in extending the navigation season in the Mid-West and with the severity of the last two winters, the formal Coast Guard research, development, test and evaluation effort has been directed towards breaking ice in channels and the subsequent clearing of the broken ice.

I appreciate this opportunity to give you a quick summary of some of our activities, and hope you will find this conference a rewarding and pleasurable experience.

New European Views on Snow and Ice Control Development

Peter M.W. Elsenaar, Chairman of the PIARC Technical Committee on Operational and Winter Maintenance.

In Europe developments in the winter maintenance field seen to be similar to those in U.S.A. and economic aspects still ask attention. Decreasing spreading rates, use of slush ploughs, and anti-skid bituminous surfaces that prevent or retard black ice formation are mentioned. Large field trials in spreading $CaCl_2$ solution instead of solid NaCl or $CaCl_2$ are reported as is some progress in black ice prediction.

Introduction

The information presented in this paper became available from cooperation in the PIARC Technical Committee on Operational and Winter Maintenance.

In order to obtain a good understanding, PIARC (Permanent International Association of Road Congresses)* has its main task in organizing a World Road Congress every four years and it enables a number of Technical Committees to operate. PIARC has about 60 member countries. The Technical Committee on Operational and Winter Maintenance was founded in 1965 in order to exchange information on winter maintenance. One of the main tasks of the Committee is to present a state-of-the-art report every four years to the World Road Congress. The Committee supports International Winter Maintenance Congresses in Europe at two-year intervals. This is one of the modes to fulfill the task of exchange of information. For this reason the Committee appreciates the liaison with the TRB Committee on Winter Maintenance and taking part in this symposium.

Most of the recent information on Committee activities and findings is to be found in reports to the Prague (1) and the Mexico City (2) World Road Congresses. The Proceedings of the International Winter Maintenance Congresses in Vienna (3) and Dobiacco (4) contain valuable information on European experiences. Since 1976 the scope of the Committee has been widened to the whole field of maintenance, as the name indicates, but still winter maintenance takes an important place in discussions between about 18 nations represented in the Committee.

*Secretary General: 43 Avenue du President Wilson, Paris 16

General Tendencies

In comparing developments in winter maintenance research and field experience in both the U.S.A. and Europe, my conclusion is that no large differences exist. The same topics of environmental aspects, energy conservation, mechanization of equipment, and social and economic aspects are to be found. However, the U.S.A. has had recent winters with heavy snow storms, whereas in Europe a number of recent winters have been relatively mild. This influences public opinion, motivation and training of personnel, and cost figures. Under the following headings some more detailed information on a number of items is given.

Environmental Aspects

From studies (2) in a number of European countries, it appears that under normal conditions damage to the environment by de-icing salt gives no cause for alarm. Simple measures can be taken to prevent damage at places where there could be danger. It is important to know that in many cases the interest of the ecologist and the economic interest of the road authority are parallel.

It is recommended that the use of de-icing chemicals be limited as far as possible. For this purpose the following twelve proposals are considered:

Winter Maintenance Without Salt

Winter maintenance without salt has been investigated as an alternative in Finland and Switzerland. In Finland it was concluded that no salt resulted in a lower standard of road condition, increased slipperiness and lower vehicle speeds. The use of salt did not seem to have any effect on the overall number of road accidents, but there were less severe accidents on roads where no salt was used.

In Switzerland in the winter 1972/73, slipperiness was fought on two road sections with only abrasive materials that increase skidding resistance.

The conclusions in comparison with previous years were:

1) On the road sections no serious accidents took place.
2) The number of accidents did not increase.
3) No appreciable changes of plants or animals in the surroundings have been reported.

The cost of winter maintenance without de-icing agents within the test period appeared to be more than three times as high as the cost of winter maintenance with salt spreading.
From the experiments and the observations of many road authorities it was concluded that melting agents have to be used for winter maintenance for reasons of road safety and economy.

Spreading Amounts

Owing to the climatic differences between the various countries a uniform recommendation for all cannot be made. As a minimum, 10 g/m^2 is recommended
Scandinavian countries sometimes use 6 g/m^2. In nearly all countries a normal use of 10 to 20 g/m^2, with a maximum of 40 g/m^2 for heavy snowfall, is advised.

Personnel

Personnel should be made more aware of the environmental effects of salt in order to avoid superfluous spreading. It is therefore necessary that they be well instructed and informed. The choice of equipment for winter maintenance and the determination of the right moment for action have a great influence upon salt consumption.

Spreading Equipment

Effective limitation of consumption requires that equipment be constructed in such a way that a prefixed amount of spreading material per square metre cannot be exceeded, independently of road speed and spreading width.
In Italy and France tests with special spreading equipment have been carried out with a solution of calcium chloride. From these tests it appears that the consumption of de-icing agents can be limited to 5 g/m^2. Spreading of this solution appears to be suitable for the prevention of black-ice slipperiness.
In the German Democratic Republic, winter maintenance is carried out by the spreading of a solution of magnesium chloride, as this is a mining waste product.

Snow Clearing

Large quantities of de-icing material can be saved by clearing snow with ploughs instead of melting by means of salt only.
Snow melting requires considerable amounts of salt. For slush clearing, special ploughs have been constructed with which the road can be swept practically dry.
In the interest of the environment and in order to prevent plants from being mechanically damaged, snowblowers on rural roads should not throw too far into the bordering ground.

Storage Yards

In the late 1950's and early 1960's when salt began to be used in increasing quantities for winter maintenance purposes there were a number of instances of fatal salt damage to both trees and plants in the vicinity of open stock piles. Having the modern covered salt stores and impermeable foundations with drainage away from vegetation, complaints have been reduced to a few isolated instances and cannot be considered a problem at the present time.

Figure 1. Covered salt store (the Netherlands).

Highway Design and Maintenance

Salt spreading should be taken into account when designing a road. If there is a risk of contaminating wells or ground water, adequate provision must be made for ditches or drains to remove water from the road to surface waters that are least susceptible to pollution. When designing highways, it should be borne in mind that maintenance centres constitute an integral part of the road and that they must include covered salt stores.
For roadside vegetation, species must be chosen that are salt resistant. In the report by three countries, 19 species are recommended and 17 are not recommended.

Ice-warning Systems

Ideally ice-warning systems may make it possible not only to give an early alert to personnel of the incidence of black-ice, but also to determine the right moment for action, preventative if possible, and the right doses.
The existing ice-warning systems are still in an experimental stage and are therefore not yet fit for the purpose. Investigations into ice-warning systems continue.

Organization

Good management of the winter maintenance service in which everyone's task is well-defined also assists in reducing salt consumption. One item in this connection is the careful pre-planning of spreading routes to be followed by the spreading lorries. This is of great importance for motorways with complicated multilevel junctions.

Road heating

This method of winter maintenance is least detrimental to the surroundings of the road, but looked at more broadly, it adds to the environmental problems associated with the generation of electricity, such as cooling water problems. For economic reasons, however, road heating is not generally applicable since it is much too expensive and we will have to economize in energy consumption. For this reason road heating is not expected to play a significant part in winter maintenance. Application will be restricted to the beginning and the end of tunnels, bridges and other road sections, where no other means of winter maintenance can be used.

Drivers' attitudes and information

Drivers have come to expect winter traffic conditions to be identical to those in summer. This increases the responsibility of the winter maintenance service and very often gives rise to difficult situations, since changing winter conditions do not always allow complete removal of snow and black-ice in good time.

In many cases economic aspects are the determining factors. However, a first requirement must always be for the winter maintenance service to give the latest information to road users about the actual conditions on the road. Not only traffic safety but also economic interests require the unharmed traffic progress permitted by a high standard of winter maintenance. This is emphasized by the increasing tendency to prohibit the use of studded tyres, as in the Federal Republic of Germany and the Netherlands, or to restrict their use, as in many other European countries.

As a result an even greater responsibility rests with those in charge of winter maintenance. This means that close co-operation between the different highway authorities ranging from motorways to rural roads is necessary.

General

Improving the techniques and organization of winter maintenance is a continuing process parallel to that of traffic development and will continue to be so. More investigations on the influences of winter maintenance on the environment need to be carried out in order to give better founded recommendations.

Winter Maintenance Equipment

Winter maintenance equipment is no longer subject to large modifications or new findings. Automatic salt spreaders, with a constant rate of spread independent of the vehicle speed, are used more frequently. Rates of spread lower than 10 g/m^2 ask for careful calibration and periodical testing of equipment. The positive experience in using low spreading rates resulted in field experiments in Italy (5), France and Belgium with spreading $CaCl_2$ in solution.

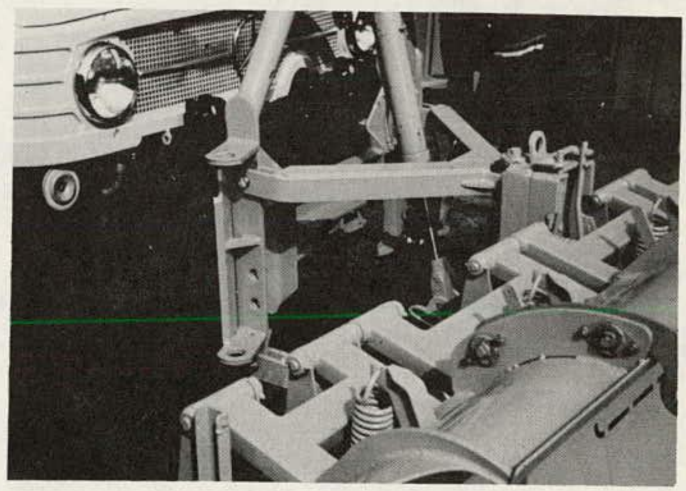
When using liquids, more accurate spreading rates are possible; other advantages, like easy loading, should be evaluated in relation to the financial aspect of the use of liquids. The trials at a number of maintenance stations in France and Italy that are fully equipped with special trucks and tanks for spreading solutions are encouraging.

Construction development of snow cutters and rotary blowers has led to a reliable series of machines that show modification for safety reasons and also for universal use in summer maintenance (see Fig. 2).

Figure 2. Summer use of winter maintenance trucks.

Snow blades have been made more efficient over the last years, and automatic mounting is more common (see Fig. 3).

Figure 3. Standardized plow hitch to decrease preparation time of equipment and stimulate multi-purpose use.



Attention should be paid to the slush plough. The special rubber blade (Fig. 4) enables it to remove slush with speeds up to 60 km/h. Continuous ploughing during snowfall might result in black pavements, if the snow storm is moderate. Removing slush is important in order to increase skid resistance, as slush is very slippery.

Figure 4a. Special plow for slush removal.

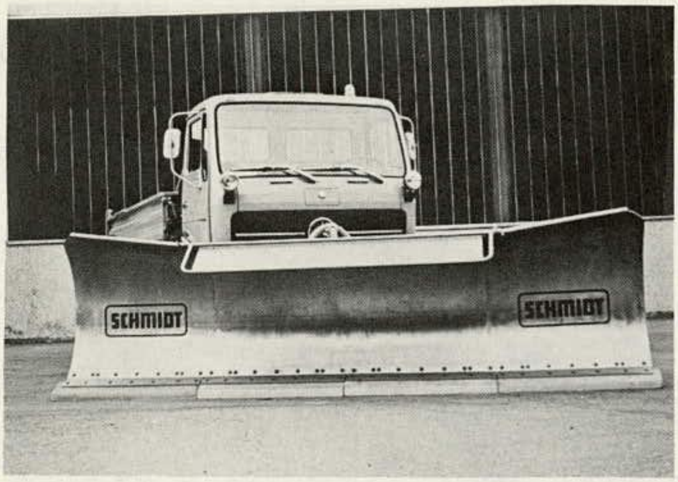


Figure 4b.

Anti-skid Bituminous Surfaces

Since 1974 experiments have been made with bituminous mixes containing 4-6% of a special agent, for instance, "Verglimit." Due to wear of tyres the special agent, primarily consisting of $CaCl_2$, is present on the road surface and will prevent or retard black ice formation. Field trials both on normal road stretches and bridges are carried out in Switzerland, Austria, Germany and France. Significant differences in performance have been found, compared with normal pavements. It took longer for black ice to form and the adhesion of snow to the road surface was lessened; accident figures are not yet available, however. In one field trial the cost per m^2 for a bituminous layer was 11 DM/m^2 for normal asphalt. This leads to the conclusion that the economic prospect for Verglimit, which also depends on its yet unknown durability, is not such that general application would be possible. However, if field trials remain positive, the anti-skid surfaces would compensate for preferential icing of bridges and other dangerous spots during black-ice formation. Special attention should be paid to skid resistance properties in the summer especially when formation of calcium chloride-hydrate is possible.

Economic Considerations

This will not be the last discussion on economic evaluation of winter maintenance. Due to differences in cost recording in the member countries it is hardly possible to compare and evaluate cost figures. Ahlbrecht (4) proves from results on 332 km of motorways in Germany that accident costs would have been 4 to 6 times as high as actual winter maintenance costs if no winter maintenance had been carried out. Monot and Bachelard calculated for the French national road network that salt, personnel and capital investments in buildings, equipment and radio systems are the most important cost elements. Figures of fixed and variable costs are, in this respect, meaningless because the severity of the winter might change the whole figure. Hammond showed a decision-making model to examine the economic justification of winter maintenance. Further experience with this model should be gained. It seems that economic justification of winter maintenance on motorways is not difficult. More difficult, however, is to establish the level of service in winter of other road categories with less traffic and comparable maintenance costs.

Prediction of Black-ice Formation

More experiences have been gained with ice-alert systems. Austria now has a leading position in this respect with 80 ice warning installations and 140 snow warning apparatuses in use, most of them of the "Boschung" type. Rosema and Welleman (6) investigated factors influencing black-ice formation. A model to predict road surface temperatures has been built. Field trials, such as spot measurements and infrared line scanning from an aeroplane, indicated that this model was suitable.

Photos showing the thermal image of road sections and adjacent areas stress the influence of sunshine at daytime and the heat flow in the road. In case of the absence of this heat flow, as on bridges, considerable differences may be found.

Differences on normal pavements from 267 K to 271.6 K were found. This type of investigation would lead to more insight into dangerous spots and places to locate ice warning equipment. Generally a model is necessary to predict black-ice formation.

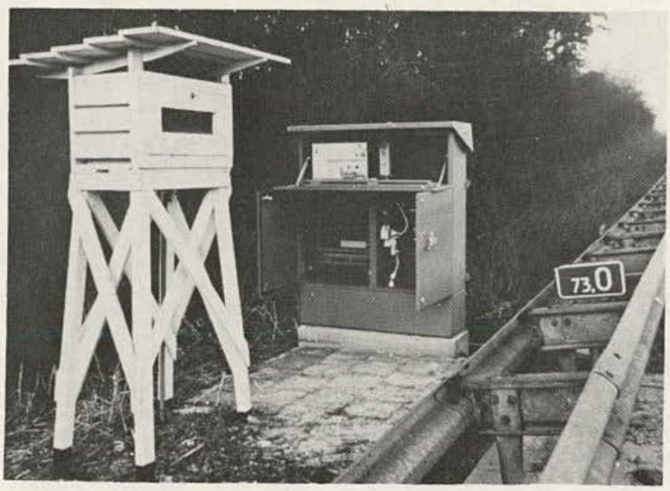
Ten Cate (4) reported that current results of the 't Harde ice warning project indicated that saltings may be reduced by 10 or 20% and salting actions could prevent black-ice formation. The system used consisted of 10 measuring spots (Fig. 5) in which road temperature, road conductivity, air temperature and air humidity could be measured and processed by a central minicomputer.

In these systems man-machine interactions are of significant meaning for the success of this type of equipment. Cost estimates are difficult to judge as social and environment aspects are hard to evaluate.

Conclusion

In winter maintenance, laboratory investigations and field experience both contribute to progress. Economic and environmental aspects receive more attention than pure technical developments. Exchange of research is a fruitful approach in this very special area.

Figure 5. Sensors and transmitting equipment at 't Harde ice warning project.



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Studies Related to Removal of Snow and Ice from Transportation Facilities

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The various research and development programs that have been conducted at the National Research Council of Canada in the general field of snow and ice removal are described briefly. The research work ranges from aircraft icing dating back to the 1940s to current research on unconventional methods of snow and ice removal by techniques such as high pressure water jets and air lubrication.

A liberal interpretation of the title of this paper has been taken partially as a result of reading the preliminary program and realizing that there would be those in attendance with rather wide interests in snow and ice. The secondary reason for the broader view was to allow for some of our own earlier work to be reported.

The Division of Mechanical Engineering of the National Research Council of Canada has been involved in one aspect of ice removal research for the past forty years. This work has been in the anti-icing and de-icing of aircraft flight and propulsion components. The physical facilities provided for research, to a large extent, have guided or limited the activities that could be pursued. Until the late 1940s laboratory facilities did not exist at NRC in which work could be conducted with ice and snow. The aircraft icing research work that was conducted prior to 1950 was carried out in flight under natural icing conditions at some personal risk to the investigators. In 1950 an icing wind tunnel capable of speeds up to 290 km/h (180 mph) was made available as one of the physical facilities of the Low Temperature Laboratory (1). This name was intended to denote that the laboratory was concerned with climatic low temperatures and as it was a section of the Mechanical Engineering Division its concern was with various engineering equipment. A number of cold chambers were included as part of the physical plant. During the first year of operation of the cold chambers requests were received for snow in off-season periods for test purposes and thus snow making has been one of the activities for the past thirty years.

Aircraft Icing Research

During the early 1950s research work was conducted in the laboratory and in flight using a North Star aircraft while investigating electro-thermal methods of de-icing flight surfaces. Previously the electro-thermal conducting rubber propeller de-icing system had been developed. This was subsequently fitted to most propeller driven transport aircraft of that era. The electro-thermal wing de-icing system was fitted to two of the first all-weather aircraft flown in North America. In addition to investigating de-icing methods considerable effort was involved in icing instrumentation development to measure in flight the conditions experienced. In the de-icing of aircraft flight and propulsion surfaces, one of the physical problems involved is that of ice adhesion. Over the past thirty years a number of facilities have been developed and used to evaluate the adhesion of ice to various surfaces. A whirling arm fixture was first developed to evaluate possible helicopter rotor blade de-icing pads. Ultimately this fixture was modified to conduct self-shedding adhesion tests of droplet formed ice (2).

In the de-icing of aircraft surfaces it is essential that an automatic control system be employed that senses the ambient icing conditions. Since 1950 work has been conducted on ice detectors for both fixed wing and rotary wing aircraft. The helicopter has posed a unique problem since it can hover at zero forward speed and yet collect ice on the rotor blades at almost the same rate as in forward flight. In the last decade considerable work has been conducted on a dynamic principle ice detector for helicopters with a high response rate that in addition to detecting ice is capable of measuring the liquid water content of the ambient clouds.

Non-Aeronautical Icing

The knowledge of cloud physics and the thermodynamics of icing that had developed during the aircraft icing research and development work eventually led into non-aeronautical icing research. One of the icing problems encountered is that of ship icing. In this case the cause of the more severe icing is not that due to either cloud icing or spindrift but is the result of high winds, high waves and heavy spray resulting from ship motion. For smaller vessels, such as fishing trawlers, the growth of superstructure ice can cause loss of stability with the subsequent capsize of the vessel. We have examined various methods of removing ice from the ship superstructure (3). For flat surfaces and cylindrical surfaces an inflatable boot, similar in principle to the early pneumatic de-icers for aircraft, is a low energy means of removing ice from surfaces. For masts, whether single or multileg design, one of the interesting means of antiicing is by application of a two-phase thermal siphon. This converts the mast into a massive heat pipe where engine waste heat could be employed to advantage.

A novel solution to the icing problem of marine buoys was developed by personnel from the Gas Dynamics Laboratory of NRC. The problem with buoys in winter icing conditions has been loss of stability and capsize but not sinking.

By application of a thermal siphon to the buoy, the small amount of heat available in the sea water above the freezing point has been employed to anti-ice or de-ice the superstructure.

For almost a decade we have been collecting information on the icing of ships at sea off the east coast of Canada during the winter season (4). From the information gained to date we have concluded that the International Standards for the icing of ships are not sufficiently stringent for ships operating off the east coast of Canada.

The icing of various structures including electrical power transmission lines and their supporting towers, communication towers and some high rise buildings has caused millions of dollars damage. Each winter there are reports of power line failures from icing in some area and to date the main solution has been to raise the standards for new construction to allow for heavier accumulations.

The icing of runways at airports where corrosive salts cannot be employed poses a special problem to the operators. While urea may be an effective, even though expensive, solution to this problem under moderate conditions, it is not satisfactory at colder temperatures or with heavy ice deposits.

Recently we have been examining the removal of ice from a concrete surface by means of high pressure water jets (5). This method has the potential advantage of using a non-mechanical contacting method, thus irregularities in the surface or the ice thickness are of minor significance. Concrete can be cut with a high pressure water jet, thus one of the initial questions in considering this method was whether the ice could be removed without damaging the concrete. Initial tests showed that concrete test slabs developed signs of surface erosion when passed under a water jet with a pressure of 35,000 KPa (5000 psi). While ice can be penetrated by a water jet of 35,000 KPa (5000 psi) tests showed that to employ a reasonable nozzle stand-off distance with small diameter orifice, higher pressures were necessary. A series of ice removal tests were conducted using ice film thicknesses of 3 mm (1/8 in.) and 6 mm (1/4 in.) at different traverse speeds, with various nozzle sizes and water pressures. Tests were also carried out with different nozzle orientations with respect to the ice surface and the direction of traverse. It was established that high pressure water jets could be employed to remove ice without damage to the concrete substrate at much higher pressures than originally considered by orienting the nozzle for a low attack angle. It was fortuitous that this orientation also proved to be the most efficient for ice removal. The high pressure water jet is employed much like a plane or wood chisel in ice removal. At a low angle pressures of over 140,000 KPa (20,000 psi) have been employed without damage to the concrete substrate. We believe this method of ice removal shows sufficient promise for runways to warrant further study and development.

Snow Making and Snow Removal

During the first twenty years of research and test work in the cold chambers of the Low Temperature Laboratory only a limited amount of the work involved snow. On occasions various programs required the production of snow in the cold chamber, for example to test small snow throwers, or to examine the performance of electrical insulators with snow covers. Snow is manufactured using raw water atomized by compressed air in an external mixing nozzle. Various arrays of nozzles have been fabricated depending on the coverage required. Two nozzle arrays are mounted on wind chill fans in order to produce snow at high velocity when necessary to simulate blizzard conditions.

In the large cold chamber, 15 x 4.5 meters (50 x 15 ft) in floor area, snow has been made at rates equivalent to a snowfall of 12.5 cm/h (5 in. per hr). More commonly, snowfall rates of 2.5 cm per hr (1 in. per hr) are simulated. While working with the railways on the problem of railway track switches failing to transfer due to the presence of snow, a standard test condition of a snowfall at 2.5 cm/h (1 in. per hr) with a 32 km/hr (20 mph) wind at an ambient temperature of -18 Celsius (zero degrees Fahrenheit) was established. A full-sized railway switch complete with ties and ballast was installed in the cold chamber and various protection systems have been tested and evaluated in the laboratory prior to field tests. The design criteria established for the test program has proven to be adequate in field applications except for a few limited areas where the ambient conditions were known to exceed the values chosen.

While snow making in the laboratory was extremely useful in evaluating and developing railway switch protection systems, for other snow related problems it is inadequate.

Some years ago when this subject of alternate high speed urban and interurban transportation systems based on air cushion technology was first considered, various schemes were proposed for use in Canada. In view of the difficulties that were experienced by existing transportation systems as a result of snow, it was considered urgent to ensure that any new system contemplated would not involve more serious problems with snow.

Various proponents of high speed transportation systems had proposed different vehicle and track designs. In discussions with the designers of the various tracks it became evident that they had not given serious consideration to the snow problem.

After considering the possibility of examining the performance of model track sections under simulated conditions in a laboratory, the decision was made to conduct field tests with full scale track sections depending on nature to supply the snow, wind and low temperature. With Ottawa as a test site there was never any doubt about the reliability of nature to provide the test conditions on a regular basis. One of the conclusions resulting from this test was rather obvious in retrospect, namely that a snow fence, or a track section similar to a fence, is a good device for accumulating snow and it matters little whether the snow fence is made of wood or concrete (6).

While waiting for snow accumulations to gather on the high speed transportation track sections, it seemed desirable to give some thought as to how snow might be removed more rapidly from these or other surfaces. It appeared that 100 km/h (60 mph) was considered high speed snow removal from either highways or airport runways. Since this speed was approximately equivalent to the legal vehicle speed on the highway it seemed doubtful that there would be any need for higher speed snow removal from highways. When compared with the proposed speeds for the new systems, however, it was evident that snow clearing at 100 km/h (60 mph) would not be compatible with high speed vehicle operation.

At least one of the vehicle developers considered the problem of snow removal as insignificant. They believed air cushion vehicles would maintain a track clear of snow if operated at sufficiently frequent intervals. While this supposition is probably true for some types of snow and some snowstorms, there are other snow conditions that seemed to be less amenable to this solution.

In order to evaluate some unconventional methods of removing snow, including the air cushion, a short test track was constructed on a test site in Ottawa adjacent to the site with the high speed track sections. This test track was a concrete slab 36 meters (120 ft) long between steel rails on standard gage. The dual steel track is 90 meters (300 ft) long to allow for accelerating a vehicle prior to the test section and braking afterwards. This test track was intended only for the initial, low speed tests of unconventional snow removal. The test section is elevated approximately 1.3 meters (4 ft) above the surrounding terrain to allow for some accumulated snowfall without interference. A propulsion vehicle and a test vehicle for mounting experimental equipment have been provided. Both of these are modified railway maintenance equipment vehicles.

One of the first methods examined was a system based on the claim of the air cushion vehicle developer. An engine driven fan capable of developing pressures to 45 cm (18 in.) water column or flows to 324 cu. meters/h. (12,000 cfm) was installed on the experimental vehicle. The fan outlet was connected to a full track wide plenum with a lower adjustable outlet. This outlet simulated the gap between the air cushion vehicle skirt and the normal substrate. At low speed and with dry non-adherent snow the snow removal was excellent. With a wet adherent snow the plenum acted as a mechanical snow plow and some snow cover remained. With a wet snow that had been allowed to sinter and freeze to the substrate the removal was completely inadequate.

Various nozzle systems were evaluated with this fan system and on another vehicle at higher speeds and with higher nozzle pressures. All of these nozzles showed similar results, i.e., with dry, non-adherent snow the removal is excellent; with wet adhesive snow, removal is adequate at higher nozzle pressures, while with snow compacted onto the substrate or frozen to the substrate, removal is unsatisfactory.

While conducting the test work with nozzles on unconventional snow removal simulating an air cushion vehicle the discussion of the low friction characteristic of this vehicle led to the consideration of the inversion concept. If a vehicle supported on an air cushion passes over snow with low friction, then might not snow pass over a vehicle surface, a snow plow blade for example, with low friction if supported on a film of air? This technique might allow for higher speed snow removal. Work on this concept has been progressing and is discussed in another paper (7).

Snow has been a somewhat unexpected source of trouble with another transportation system, in this case a helicopter. Flight of one type of helicopter in snow had resulted in engine flame-out. Since this was a single engine helicopter, this type of failure was not only undesirable, it was disconcerting to the pilots. It was shown that the cause of the difficulty was accumulation of snow in the engine inlet plenum which on entering the engine in an accumulation caused the engine to flame out. As a follow-on to this investigation work has been carried out on the measurement of airborne snow and the correlation of these measurements with visibility (8). This work is being reported in another paper.

Some of the work conducted in the Low Temperature Laboratory that falls in the classification of snow and ice removal has been described. In other papers that are due to be presented at this Symposium the work is described in greater detail.

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Snow Mechanics: Machine-Snow Interaction

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Response performance of snow is conditioned by the system within which it is stressed, boundary conditions, and initial conditions - not only with respect to the stress situation but also with respect to material properties, formation, and thermodynamic history. The shear resistance of snow is examined since this is considered to be a basic strength property of the material which participates fully in the development of snow shear resistance to applied stresses - such as those encountered in machine-snow interaction.

The changes in the state and character of snow from an unstressed region can readily be observed in the study of snow performance under load. Types of shear failure in snow however, are difficult to characterize or evaluate - both from a qualitative point of view and also from a quantitative viewpoint. The reasons are found in the fact that snow is an extremely varied material whose properties and characteristics are very sensitive to climatic, physiographic, temperature, thermodynamic history, and pressure dependent situation. Thus for example, variations in differences in snow properties and characteristics are found between tree-line snow and prairie snows, coastal as opposed to Alpine, Arctic as opposed to sub-Arctic snows, etc.

It has been noted from previous experiences in many other related fields of study that the mechanical response characteristics of any assembled material are dependent on the intergranular interaction, e.g. Yong and Warkentin, (1975). In that regard, the response characteristics of snow are also seen to be dependent on the type of intergranular force. In this sense, at least four main types of snow, consisting of various intergranular interactions can be identified - insofar as gross mechanical response characteristics are concerned. These are:

1. Fresh snow (with original crystal shape).
2. Granular snow.
3. Semi-bonded snow (with water film).
4. Sintered snow.

These types of snow change from one state to another with time and temperature. Thus, for example, fresh snow becomes sintered snow with time, and granular snow becomes a semi-bonded snow with temperature and is transformed to sintered snow with time. Note that this transformation of snow type is often accompanied by changes in density and grain characteristics as a function of time, temperature and pressure.

Taking into account the influence of climatic and physiographic factors, and other conditions such as time and local pressures which will contribute to the metamorphic processes of snow, it becomes obvious that for a proper appreciation of snow properties it is necessary to recognize:

a. The problem of appropriate and varied characterization of snow.

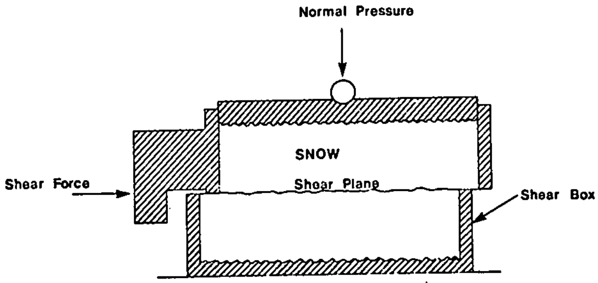
b. The fact that the response performance of snow is conditioned by the type of snow, and also by the nature and manner of physical testing for assessment of snow properties.

In the case of machine-snow interaction - e.g. snow removal from machine ploughing or vehicle mobility on snow covered terrain, compressibility and shear resistance constitute the prime response mechanisms of the snow layer or snow pack. The performance of snow in confined compression has been reported previously by Yong and Fukue, (1977). The methods for determining the kinds of snow used, together with characteristics of the material in shear under confined status have been examined. In the study, the direct shear performance of snow is examined. These characteristics are seen to be fundamental to the development of machine-snow interaction phenomena.

Apparent Failure Modes in Direct Shear Performance

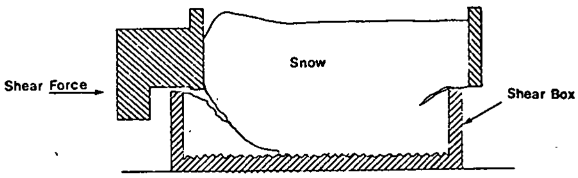
For granular snow, the failure mode exhibited in direct shear performance under sufficient normal stress is the "cutting shear" as shown in Figure 1. This is seen to correspond well with other types of granular materials. However, if snow is well sintered (bonded), the failure mode, without normal pressure or with relatively lower normal pressure, differs from the

Figure 1. General shear failure of snow in a direct shear test.



ordinary shear failure mode, as shown in Figure 2.

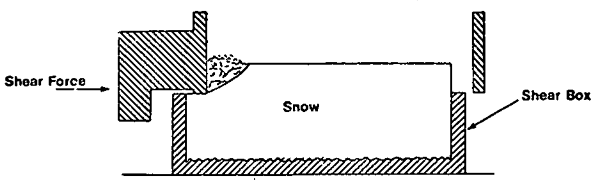
Figure 2. Typical tensile failure mode for snow without normal pressure or with relatively lower normal pressure in a direct shear test.



This failure mode may be identified as "tension failure" of well sintered snow in direct shear tests similar to the observations of Butkovich (1956) for double shear ring test on snow.

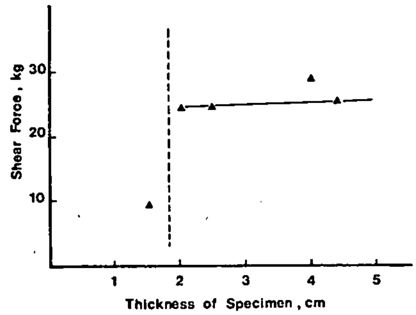
Note that in the evaluation of snow performance in direct shear, proper attention to boundary conditions and constraints is necessary. Figure 3 shows an irregular type of failure mode when the thickness of the shear layer of the snow specimen is very shallow.

Figure 3. Irregular failure mode of snow in a direct shear test when the thickness of specimen is insufficient. Note that the failure mechanism is not unlike that of snow cutting.



The occurrence of this irregular failure leads the very low shear resistance in comparison with the ordinary shear failure performance. This phenomenon is not unlike that developed in soil or metal cutting. If one wishes to examine the effect of thickness of snow specimen in direct shear performance, the thickness of the top shear layer can be expanded. This leads to the results shown in Figure 4. As can be observed, there is a limiting thickness of the shear layer, such that for a thickness of more than 2.0 cm, the shear force seems to remain almost constant as shown in the Figure. To maintain uniformity in testing, the shear tests conducted in this study required the thickness of snow specimens to be at least 3 cm thick in the upper layer above the shearing plane.

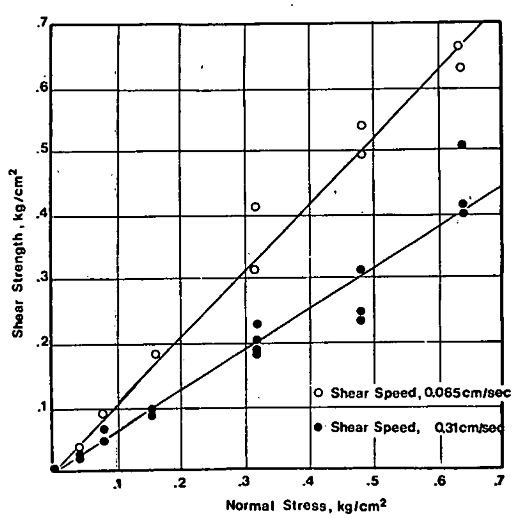
Figure 4. Shear force developed as a function of thickness of snow specimen in direct shear test.



Effects of Shear Velocity

Figure 5 shows the relationship between shear strength and normal pressure for the granular snow [used previously by Yong and Fukue, (1977)] at two ranges of shear velocities, e.g. 0.065 and 0.31 cm/sec.

Figure 5. Relationships between shear strength and normal pressure for granular snow in direct shear, tested at shear velocities of 0.065 and 0.31 cm/sec.



The open circles indicate the shear strength obtained at a shear velocity of 0.065 cm/sec, whilst the black circles indicate the shear strength for the same snow at a shear velocity of 0.31 cm/sec.

The results show that the relationship between shear strength τ and normal pressure σ_n is almost linear at both shear velocities of 0.065 and 0.31 cm/sec. This trend is not uncommon for granular materials.

The relationship between shear strength and normal pressure may be evaluated in a manner similar to that given by the Coulomb-Navier theory:

$$\tau = \sigma_n \tan \phi' \tag{1}$$

where

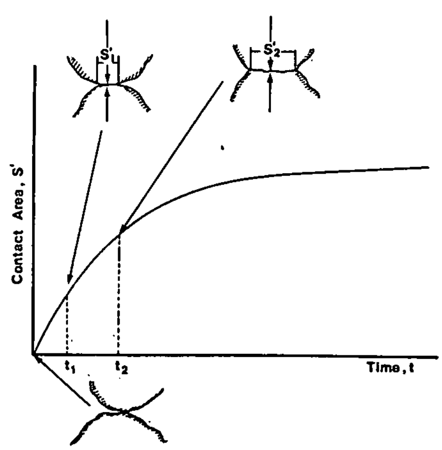
τ = shear strength
σ_n = normal pressure acting on the shear plane
ϕ' = apparent correlative angle

Note that the designation of ϕ' as the apparent correlative angle is deliberate. The temptation to identify ϕ' with the physical characteristic of block or particle friction should be discouraged. In the present context, ϕ' is taken as a mathematical correlative angle - and does in no way represent the friction angle of the material. Proponents of the Mohr-Coulomb theory will recognize the inherent dangers of application of the theory to a high volume change material. As shown in Figure 5, the apparent correlative angle ϕ' is strongly dependent upon the shear velocity. In this set of experimental results for example, we note that the apparent correlative angle ϕ' is 46° for a direct shear performance at a shear velocity of 0.065 cm/sec. This value reduces to 33° for tests at a shear velocity of 0.31 cm/sec. This suggests that the shear strength of snow decreases with the increasing shear velocity. This trend is not common with other materials.

Shearing Mechanism of Snow

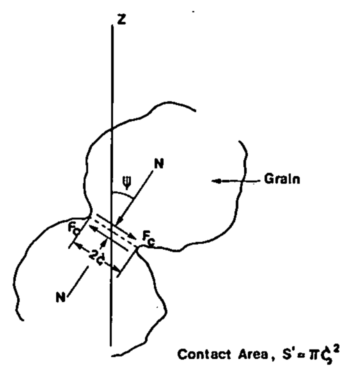
To obtain an appreciation of the implications of the apparent correlative angle ϕ' it is necessary to examine snow inter-granular activity under stress. It is known that the contact area between snow grains must increase with irrecoverable deformation in the absence of inter-granular slippage. To develop a simplistic picture, we consider firstly a point contact between two grains as shown in Figure 6. This Figure illustrates the relationship between grain contact area for a developed normal stress between grains as a function of the time taken to reach inter-granular slip [i.e. incipient shear failure]. If at time t equals zero, the corresponding load is zero, then the contact area for a granular snow condition can be considered to be very small or negligible.

Figure 6. Development of grain-to-grain contact area prior to shear failure as a function of speed of shear test. Note that times t_1 and t_2 represent time taken to reach incipient shear failure for two different shear loading velocities.



If loading occurs immediately after t = 0, one can envisage that under dynamic loading conditions, if the time taken to reach failure occurs at $t = t_1$, the contact area between grains increases to S_1'. Similarly, if the time taken to reach failure occurs at $t = t_2$, for a slower rate of loading, the contact area becomes S_2' as shown in the Figure. Under direct shear, the relationships formed by S_1, S_2 ..... S_n and t_1, t_2..... t_n with regard to different shear velocities are seen to be dependent on the time required to initiate or promote relative slippage of grains i.e. when slip between grains occurs the relationship between contact area development and time becomes affected. It is noted that at a lower shear velocity for example, a longer time period is required for the slippage or shear failure to occur. As shown in the Figure, if we assume that for slip to occur under conditions of a high shear velocity is for example t_1, and the time required to initiate slip at a particular lower shear velocity is t_2, the tangential forces required to initiate slippage between two adjacent snow grains in contact may be given by, [see Figure 7]:

Figure 7. General stress conditions at snow grain contact.



for $t = t_1$,

$$F_{c1} = A_c S_1' + N \tan \phi_i \tag{2}$$

for $t = t_2$

$$F_{c2} = A_c S_2' + N \tan \phi_i \tag{3}$$

where

F_{c1} and F_{c2} = the tangential forces to initiate slip for $t = t_1$ and $t = t_2$ respectively.
A_c = the adhesion per unit area on the contact, S_1' and S_2' are contact areas in relation to t_1 and t_2 respectively.
N = the normal pressure acting on the contact area
ϕ_i = the apparent correlative angle for the granular snow.

From the preceding statements, the condition can be written as :

$$F_{c1} < F_{c2} \tag{4}$$

indicating thereby the situation where the higher the shear velocity, the smaller is the tangential force required to initiate slip between grains. This idea can be extended to account for similar phenomena in unconfined compression performances.

Writing equations 2 and 3 in a general form:

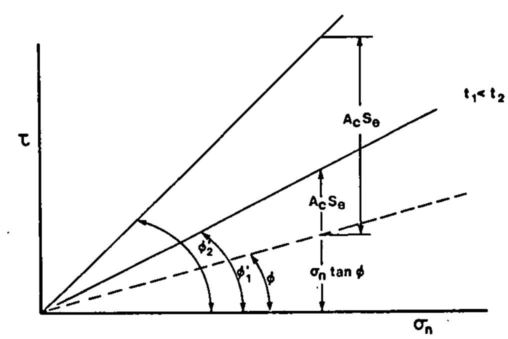
$$\tau = A_c S_e + \sigma_n \tan \phi \qquad (5)$$

where

τ = shear strength
A_c = adhesion per unit area
S_e = "effective contact area" of the specimen
σ_n = normal force acting on the shear plane
ϕ = apparent correlative angle for a granular snow condition [from the macroscopic point of view].

If one assumes that the apparent correlative angle ϕ is constant, then the experimental results obtained are explainable as shown in Figure 8. The Figure demonstrates that the shear strength of snow consists of a pseudo frictional characteristic dependent on the normal stress and an adhesive resistance component proportional to the effective contact area. The adhesive resistance component is seen to increase as the failure time increases because the longer time provides for a greater contact area. As noted earlier, a higher shear velocity provides for a shorter time for failure to occur in the snow. Therefore, one could deduce that the minimum shear strength of the snow can be obtained at a very high shear velocity since inter-granular slip can occur without sufficient development of grain contact area.

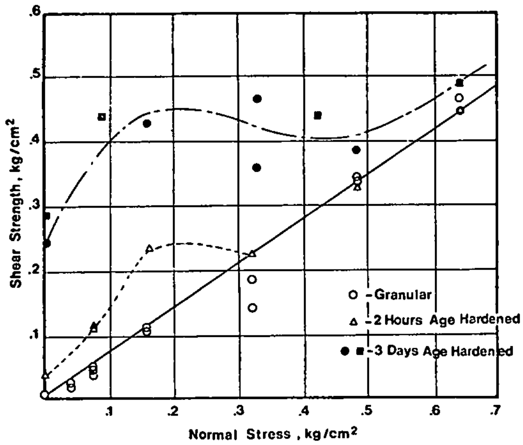
Figure 8. Illustration of shear strength showing adhesion component.



Effect of Initial Bonding of Snow in Direct Shear Test

To examine the influence of initial conditions [i.e. initial snow structure] on development of strength, direct shear tests on snow of various "ages" were tested. Figure 9 shows relationships between shear strength and normal stress obtained from differently age hardened snow. In these test series, various snows, i.e., granular snow obtained from laboratory preparation techniques reported previously by Yong and Fukue (1977), 2-hour age hardened granular snow and 3-day age hardened snow were examined. As noted, the basic snow used was a laboratory prepared granular snow whose grain size distribution was similar to that of a 5-day old fresh fallen snow - as reported by Yong and Fukue (1977). Granular snow is identified as an assemblage with discrete grains while age hardened snow is identified as sintered snow. The

Figure 9. Relationships between shear strength and normal pressure for various age hardened snow in direct shear test.



use of a laboratory prepared snow as a basic snow is necessary if one desires to control initial material properties. This provides one with a repeatable controlled uniform material for testing. As noted previously, the apparent relationship between shear strength τ and normal stress σ_n for granular snow is almost linear and the apparent correlative friction ϕ' is approximately 33° for a shear velocity of 0.31 cm/sec.

The $\tau - \sigma_n$ curve of the 2-hour aged snow [indicated by the triangles in Figure 6] is not totally linear as shown. The results show that the non-linear part of curve for the aged snow appears under normal pressures of less than 0.3 kg/cm^2. Under greater normal pressures the relationship between τ and σ_n is seen to be almost linear as shown in the Figure. For the 3-day age hardened snow, the relationship shows that non-linearity in shear exists under normal pressures of less than 0.55 kg/cm^2. Since the age leads to bond development, the non-linearity between shear and normal stress is seen to be dependent upon establishment of bonds.

Concluding Remarks

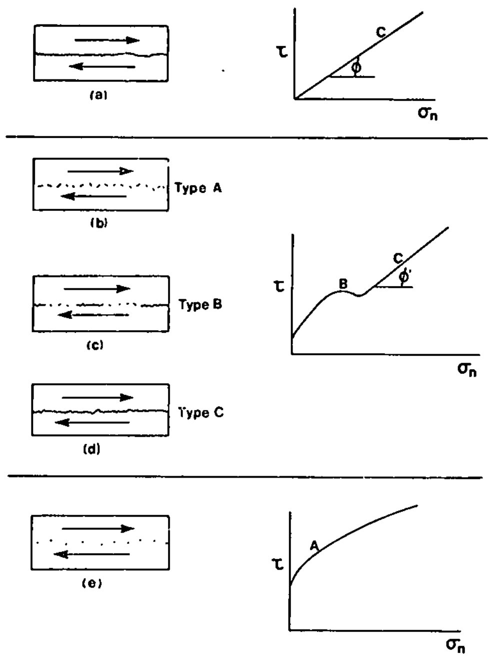
The shear response behaviour of snow for the same test temperature condition is seen to be dependent on the following factors:

1. Snow type.
2. Normal pressure acting on the shear plane.
3. Shear velocity.

A simplistic structure model to explain the shear behaviour with respect to both snow type and normal pressure effects can be developed as shown in Figure 10. In Figure 10a the simple model shows the shearing characteristics of granular snow. The shear plane of the granular snow is initially indicated as a discontinuity - which means a no bonding condition between grains. From the engineering point of view, at relatively low temperatures, the water film effect between snow grains is not too pronounced.

Figures 10b - 10d illustrate the effects of normal pressure for sintered snow on the shearing characteristics of the snow. Figure 10b shows the behaviour

Figure 10. Typical shearing responses of snow in direct shear test in relation to snow type.



of the structural model without benefit of normal pressure or with relatively lower normal pressure - when no breakage of inter-granular bonds occurs. As noted earlier, tension failure occurs during shear application under relatively lower normal pressure. At this level of low normal pressures, the $\tau - \sigma_n$ curve shows a high gradient, indicated as Type A [Figure 10b]. If a higher normal pressure is applied during the shear process, micro-failure [i.e. the breaking of bonds] may occur. The phenomenon induced at this level of normal pressure is identified as Type B shown in the Figure. The apparent feature of Type B for the $\tau - \sigma_n$ curve is recognized as a very low or negative gradient performance of the curve as shown in the Figure. Note that a negative gradient of the $\tau - \sigma_n$ curve indicates a relaxation phenomenon brought about by the selective bond breakage sequence in the snow test specimen.

If a very high normal pressure is applied prior to and during shear, one might assume that almost complete breakage of the inter-granular bonds occurs. The final snow condition will reach a totally granular snow status. The density of the final granular snow condition is seen to be higher than the initial density because of the occurrence of microfractures due to inter-granular slip.

For a highly bonded snow or ice, the $\tau - \sigma_n$ curve obtained may be seen to be similar to those obtained from soft rock testing as shown in Figure 10e. This type of curve is similar to Type A and is similar to the $\tau - \sigma_n$ curve for high density snows tested by Butkovich (1956).

The shearing characteristics of snow in relation to snow types can be divided into three main types, i.e. sand-type granular snow, moderately bonded snow, and a rock-type strongly bonded snow. These distinctions must be taken into account in the evaluation of shear strength of snow - particularly with respect to machine-snow interaction considerations. A knowledge of the $\tau - \sigma_n$ variation with respect to both speed of shear application and normal pressures can lead to a proper selection of the kinds of tools and techniques for handling the snow material.

Acknowledgments

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The Compaction of Wet Snow on Highways

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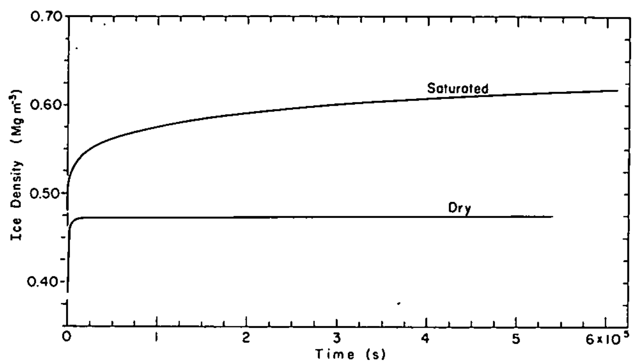
The compressibility of wet snow decreases with decreasing liquid water content but increases with decreasing salinity. Also, the tendency for snow splashing on highways increases with increasing liquid water content and increases with decreasing salinity. These opposite effects are complicated by the fact that liquid water content and salinity are not necessarily independent. The amount of liquid present can be controlled somewhat by the road grade and salinity is generally determined by how much salt is applied to the road surface. For different situations it may be desirable to regulate salt applications in order to achieve a maximum amount of splashing with a minimum of compaction of wet snow into ice. Here we provide a qualitative review of wet snow and suggest how an understanding of wet snow's behavior on a road surface might increase our ability to deal with snow removal problems.

Snow fall on highways has some very expensive consequences for our society. The most obvious costs include the direct costs of snow removal, snow related accidents, and chemically caused deterioration of vehicles, roads and bridges. The indirect costs of reduced mobility and chemical contamination of water supplies and roadside vegetation are also large. The advantages of de-icing chemicals (usually salt) are well known by virtually everyone using the highways in the temperate zones but the problems caused by salt are equally well known. The alternatives to the use of salt (reduced mobility and increased risk) are unacceptable, hence much research is being done in order to find ways to optimize the use of salt. The effects which liquid water and salt have on the mechanical properties of snow must be well understood in order to realize the best possible methods for removing snow from highways.

Hydrologists are quite familiar with the rapid changes which occur in snow upon the first introduction of liquid water (1). There are also marked variations in the properties of wet snow (ie, snow containing some liquid water) depending on the liquid water content (percent liquid by volume), salt content, grain size, density, and the history of these parameters. These parameters must be carefully specified to predict the exact behavior of the snow. Although it is well known that wet snow is more easily compacted than dry snow (see Figure 1) very little quantitative information about the properties of wet snow has been developed. Our purpose here is to provide a qualitative description of wet snow, review what is known about its mechanical behavior (especially the compaction of wet snow under an applied load), and suggest how this might increase our understanding of wet snow's behavior on a road surface.

Figure 1. Measured density (ice only) versus time for wet and dry snows (-2°C) compacted by a stress of 4790 Pa (0.69 psi).



General Description of Wet Snow

Snow is a complicated material because of the variety of forms it can take and because it is a thermodynamically unstable material which undergoes rapid changes when stressed, subjected to a temperature gradient, or wetted. The application of stress or formation of water are particularly important here because snow on highways is compressed by traffic and wetted by rain, melting and/or salting. The importance of melting is enhanced on highways because the snow cover is kept relatively thin thus allowing solar radiation absorption on a dark road surface which may cause melting even at subfreezing air temperatures. Also, salting is an important consideration here because cold, dry snow can be wetted by the application of salt; thus salting alone can change the character of the snow from dry to wet. As shown on Figure 1, the compressibility of wet snow is very much greater than that of dry snow, hence wetting by the application of salt can have the drawback of greatly increasing the rate at which the snow can be compacted into ice.

With the first introduction of liquid, snow undergoes rapid changes, especially grain rounding, grain growth, and densification. The distribution of grain sizes in wet snow has been measured (2) and thermodynamic relationships which describe the equilibrium conditions among the three phases of water have been derived (3). In the case of liquid soaked snow as is often found in the snow just over a road surface, the pore space is mostly filled with liquid and the ice particles tend to round off very quickly. In this state there is very little bonding between the ice particles hence very little resistance to discrete particle motion. If any adhesion does exist at the grain boundaries between particles, it tends to disappear when the grain boundaries are stressed or exposed to solar radiation. Thus the ice particles tend to behave individually without forming strong structural bonds with their neighbors. The destruction of the inter-particle adhesion partly accounts for the densification which occurs when snow is wetted for the first time.

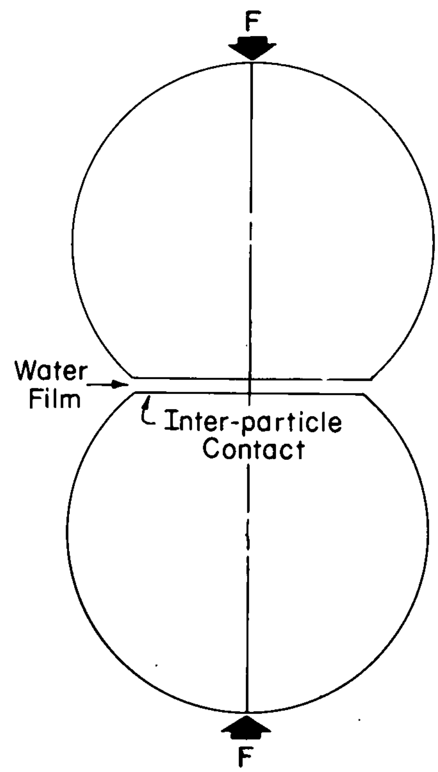
Freely draining snow normally contains a very small amount of liquid water which is almost entirely confined in liquid menisci between the ice grains. When these liquid menisci are present the spherical particles are thermodynamically unstable hence grain growth and grain rounding do not occur so intensely at low liquid contents. The presence of the liquid meniscus assures some adhesion between the ice particles because the liquid pressure is less than that of either the air or ice particles (i.e., the liquid exhibits a "tension"). Accordingly, wet snow has a higher inter-particle strength at low liquid contents thus unsaturated snow is relatively strong as compared with well soaked snow.

Meltwater moves freely downward in wet snow until a relatively impermeable boundary (such as a road surface) is encountered (1). At that boundary a soaked layer is formed whose thickness is determined by the rate of melting and/or rain, slope of the road surface, and permeability of the soaked snow. The thickness of the layer of snow which is soaked by water is important because the soaked snow behaves quite differently than the unsaturated snow. We quantify these differences later but here we note that the thickness of the soaked layer is less for less intense melting and/or rain, for steeper or well drained surfaces, and for lower density snow. Note that we can increase melting by salting and affect the surface drainage by small adjustments in the surface slope but the density of the soaked snow is determined by the complicated interaction of its history of liquid content, salinity, and the loads applied by the passing traffic. In order to understand the compaction of wet snow on highways, the theory and observation of the compression of wet snow is reviewed.

Snow Compression Model

When confined and stressed, wet snow compacts very quickly up to a density about 0.5 Mg/m^3 where the particles are packed in a fairly efficient manner. Further densification requires the particles to change shape in order to accommodate the same number of particles in a smaller volume. Wet snow is nearly unique in that pressure melting is the dominant mechanism responsible for the deformation of particles at their stressed contacts (4). Pressure melting occurs at the stressed particle contacts (see Figure 2) because the ice-liquid temperature is depressed by 0.0074°C per 10^5Pa (14.5 psi) stress between the particles. The depressed temperature at the contact causes heat flow from the stress-free surfaces where refreezing occurs. The meltwater being discharged from between the particles causes a separation of about 2×10^{-5} mm (4) thus ensuring that little inter-particle adhesion will develop at least as long as a load is applied. Each particle tends to conserve its mass by refreezing an equal mass of water on its stress-free surfaces as it melts on its stressed surfaces.

Figure 2. Two particles pushed together melt at their mutual contact thus allowing the particles to change shape to accommodate a closer packing.

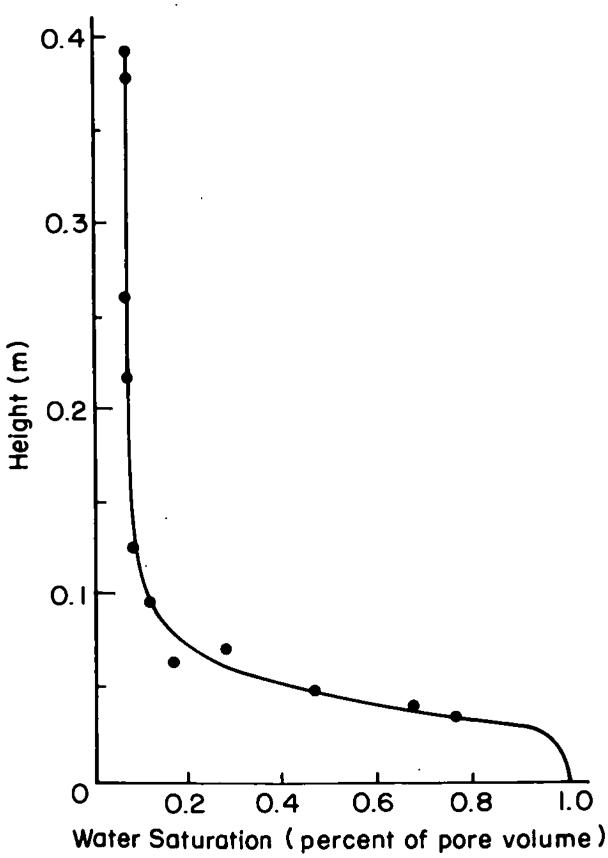


The rate of pressure melting and rate of densification have very complicated dependence on the density, particle size, applied load, salt content, and liquid water content. The density increase with time can be computed when the necessary parameters are specified (4) but these computations involve a complicated number of feedback loops involving heat flow, fluid flow, salt and dissolved air flow, and changes in geometry. Without describing the details of the model, we turn to the discussion of the significance of the results of the model runs, associated laboratory tests, and other concepts about the physical properties of wet snow.

Application to Snow on Roads

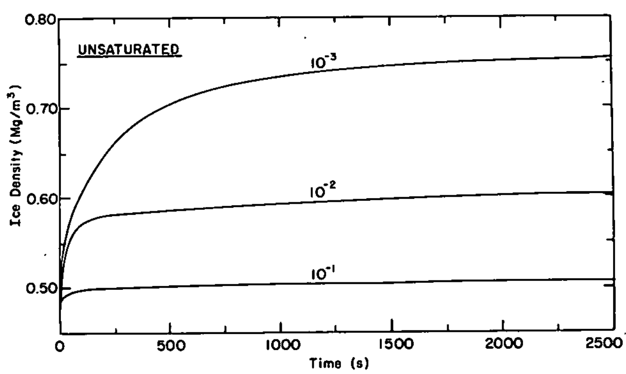
During rainstorms or periods of melting, some water must be "ponded" on the road surface thus soaking at least some of the snow. The fraction of the snow which is soaked depends on the ability of the water to drain away (rain and melt rates, surface slope and snow density) and, of course, on the depth of snow on the road. In cases where the depth of the snow is greater than the depth of the soaked layer, a typical water retention curve would look like that shown in Figure 3. The sharp transition from saturated to unsaturated snow is typical of porous materials with large grains. A measure of the large pores of snow is provided by the "bubbling pressure" test. In this test, the height to which water in a sample of snow can be raised above a water surface without draining is measured. Typical values for a small sample of snow are 3 to 4 cm of rise above the water surface (5). Of course the height of water ponded on a road surface may be different depending on the drainage of the surface.

Figure 3. Typical water retention curve for a snow sample whose bottom touches a water surface (taken from 3).



The significance of the profile of liquid water content contained in the snow overlying a road surface becomes obvious when we consider the different responses that soaked and unsaturated snows have to vehicle traffic. As stated earlier, there is very little bonding strength between the particles in soaked snow hence well soaked snow tends to splash rather than compress when loaded suddenly by a vehicle tire. Splashing is common and very desirable compared to the compression of snow into ice under the weight of the vehicle tires. Since splashing has a minimal effect on traction as opposed to the compression of wet snow which greatly decreases traction, we should understand this phenomenon as well as possible. When a road surface is drained and a large fraction of the snow is unsaturated, the inter-particle strength due to the liquid meniscus and ice-to-ice adhesion is sufficient to prevent or at least minimize splashing. In this case the snow is compressed under the vehicle loads and our model (4) of the compaction of wet snow can be used to compute the compaction for various loads, salinities, and liquid contents. For a stress of 2×10^5 Pa (29 psi) on a highly unsaturated snow, the compaction is shown as a function of time for various sodium chloride contents on Figure 4. At very low salinities the snow compacts rapidly to densities approaching that of pore close-off where snow becomes, by definition, ice. The compaction is most rapid when the stress is first applied and proceeds at an ever decreasing rate. After being stressed for 500 seconds, the snow reaches an ice density (neglecting the liquid mass) of more than 0.70 Mg/m^3 and thus would have the same coefficient of friction with rubber as wet ice.

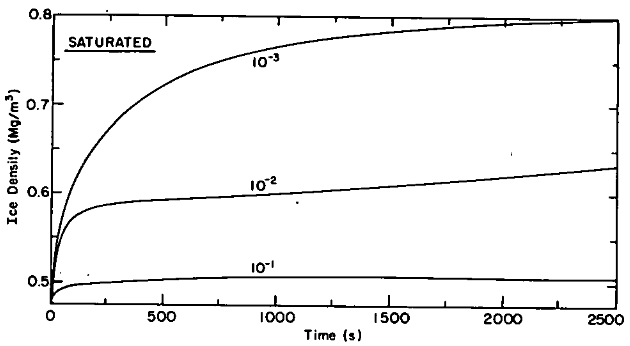
Figure 4. Computed density (ice only) as a function of time for various salinities (g-mol NaCl per kg of solution times ions per molecule). The snow is highly unsaturated and compressed in confinement under a constant stress of 2×10^5 Pa (29 psi).



At lower salinities the compaction is little different from that shown for the 10^{-3} concentration because of the action of electrostatic forces between the ice particles (4). However, Figure 4 shows that the rate of compaction decreases rapidly with increasing salinity. As observed by Yarkin et al (6), snow is much harder and more resistant to compaction when more ionic impurities are present. The salinity of the wet snow on highways is highly variable but considering typical application rates of salt and typical tire pressures, the results shown on Figure 4 should be representative of the compaction of unsaturated snow on highways. The wide range of compaction rates shown on Figure 4 suggests another benefit of salt, a large reduction in the rate of compaction of wet snow into ice due to the passage of vehicles. This action greatly increases the time available for snow removal before vehicles compact the snow into ice. However, it should also be noted that the presence of the salt increases the inter-particle adhesion thereby decreasing the chances that splashing will occur.

In soaked snow the inter-particle strength tends to be very low hence splashing is more likely than compression to ice. However, in some situations, well soaked snow can be compressed under vehicle tires. These situations might include a snow cover which is soaked at the road surface but highly unsaturated just above the road surface. In this case the overlying snow may have sufficient strength to confine the soaked snow and prevent splashing. In another situation, the snow may have just become soaked in which case the particles could not have had time to lose their bonding strength and splashing may be prevented or reduced. In Figure 5 we show how saturated snow compresses under a stress of 2×10^5 Pa (29 psi); salinity is shown as a parameter.

Figure 5. Computed density (ice only) as a function of time for various salinities. The snow is soaked and compressed in confinement by a constant stress of 2×10^5 Pa (29 psi).



The rate of compaction is somewhat greater when the snow is saturated as shown by the experiments of Tusima (7) and explained by the physical model used here (4). Figures 4 and 5 show the difference between the unsaturated and saturated snow. These results also show that the salinity effect may be more important than the liquid water content. At low salinities ($\leq 10^{-3}$ g-moles NaCl per liter times ions per molecule which is equivalent to 4.81 lb salt per lane mile on 0.5 in. water in the snow), compaction occurs quickly for both saturated and unsaturated wet snow. At a salinity of 0.01 which would be typical if all of the salt applied on a road surface were dissolved uniformly throughout the liquid, the rate of compaction is greatly reduced for both saturation regimes. In fact, at salinities of 10^{-2} or greater, it seems unlikely that really high density snow could ever be achieved by vehicle compaction.

Summary

Much attention is being given to improved methods of snow removal from highways. The properties of wet snow are discussed here to help provide an understanding of the material being removed. Snow is either dry (no liquid present), unsaturated (low liquid content) or well soaked (nearly 100 percent of the pore volume filled with liquid). Dry snow compresses very slowly but wet snow can be compressed to ice quite quickly. The rate of compression depends on the liquid content, load and salinity. Well drained road surfaces retain less liquid hence the snow does not compress so easily (an advantage) but at the same time the snow will not splash so easily (a big disadvantage). The introduction of salt further complicates this situation because salt reduces the rate of compaction of snow into ice but salt also increases the inter-particle strength and thus decreases the tendency for splashing to occur. Of course a dry snow can be wetted by the application of salt hence these two parameters, liquid water content and salinity, are not necessarily independent.

The advantage of salt cited most frequently is its ability to keep snow from bonding to the road surface but its use introduces complicated physiochemical responses which should be investigated in more detail and included in our thinking about the best ways to remove snow from highways.

Acknowledgments

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Studies on Tensile Strength of Wet Snow

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With a view to snow accretion on electric wires, railway trains, parabolic antennas and other structures, experimental studies were conducted on the tensile adhesive strength of wet snow onto various kinds of both hydrophilic and hydrophobic materials as a function of free water content of a snow sample ranging from 4 to 30% and compressive stress ranging from 1.5 to 18KN/m^2 when the snow sample was initially brought to contact with a material. For a small initial stress the adhesive strength of snow was small, though varying with different material used, and remained constant for each of them regardless of the free water content of snow. Meanwhile, for a larger initial stress, it was large and increase in free water content; namely, for the initial stress more than 15KN/m^2, it had the maximum when the free water content was 12-16%, whereas it was unexpectedly large for hydrophobic materials, being of the same order of magnitude as the one for hydrophilic materials. For a heavily wet snow, a linear relationship was obtained between adhesive strength and initial stress. The adhesive strength of snow onto rubber materials was always small regardless of initial stress and free water content. Direct microscopic observations were made of behaviours of water in contact with a glass plate as it was found in a capillary state, enveloping or inundating wet snow particles.

Introduction

Snow is very adhesive material. In particular, wet snow containing free water is adherent to any other materials. Falling snow flakes, for instance, easily accrete on electric wires, telephone lines, parabolic antennas, trains, automobiles and other structures, which causes much trouble and impediment in power transmission, communication, transportation, and so on. Cables are torn off and transmission towers crashed down at times by a heavy snow accretion almost every year when a strong cyclone is passing by the northern Japan (1).

It may be assumed for wet snow that a negative pressure is induced in water existing at an interface between a snow sample and a contacting material and that it makes the snow adhere it. The pressure, p, is given by the formula $p=-(\sigma/r)$, where σ is the surface tension of water and r is the radius of curvature of a concave water surface at the interface. The value of r may depend on factors which include free water content, grain size and density of snow, contact angle between water and a material. The adhesive force between wet snow and various kinds of materials is, therefore, very important in the study of practical problems.

Although extensive studies have dealt with ice adhesion (2, 3), only a limited number of studies have been conducted on adhesion of snow (4, 5). This paper presents the results of an experimental study on the tensile adhesive strength of wet snow onto various kinds of hydrophilic and hydrophobic materials including aluminum, glass, cellulose acetate, vinyl, teflon, polyethylen, silicone-rubber, ethylene-propylene rubber and butyl-rubber, which were brought into contact with snow samples with different free water contents and at different initially given compressive stress.

Experimental apparatus

The tensile adhesive strength, S, is defined as a value of F/A, where F is the tensile adhesive force and A is the apparent contact area between two contacting materials. In case of wet snow in contact with another material, it is not very easy to measure accurately the value of A. If an adhesive force is measured between a flat surface of wet snow and the other material, the apparent contact area is apt to be over-estimated resulting in the underestimation of the adhesive strength. A semi-spherically shaped snow sample 50mm in diameter was used in the present experiment, because it was confirmed after careful calibrations that the apparent contact area could be obtained very accurately.

A thin plate 3mm in thickness was sliced from each material prepared. A semi-spherically shaped snow sample was slowly compressed from on the top of it by the plate by moving it downward at a constant speed of 1mm/min by a motor through reduction gears, under which a strain-gauge type force measuring device was placed as shown in Fig.1. The compressive force increased with time as illustrated in Fig.2, and the motor was stopped at the moment when the force reached, for instance, 1.6N. It was followed by relaxation of stress. When the force reduced to a quarter of the initially given compressive force, the pulling up of the plate was started by the motor at the same speed as in case of initial compression.

The sign of the force soon changed from compressive to tensile, and the tensile force linearly increased with time until the plate and the wet snow sample were separated from each other as shown in Fig.2.

Figure 1. Experimental apparatus for measuring tensile adhesive strength of wet snow. U: strain-gauge type force-measuring device. P: a plate in contact with a semi-spherical snow sample.

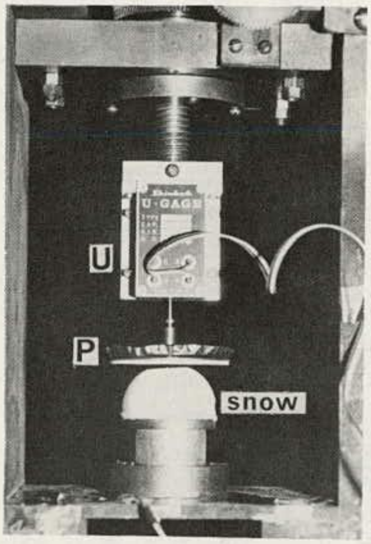
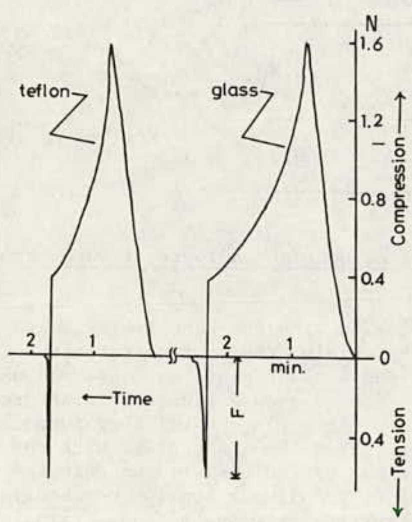


Figure 2. Examples of adhesive force-time curves.



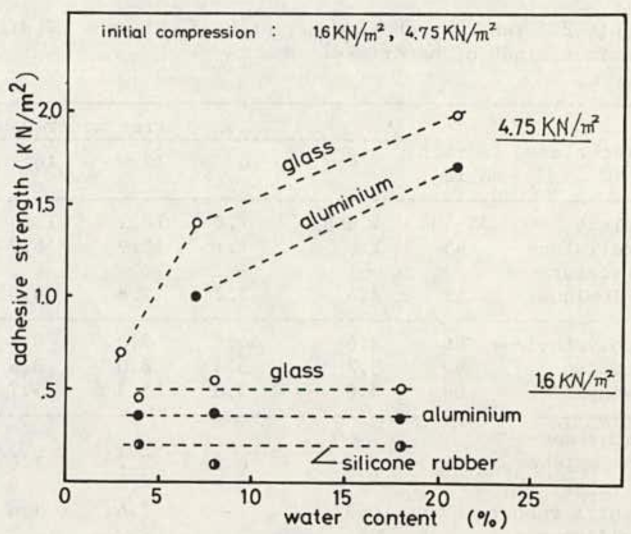
The apparent contact area was obtained both by measuring directly the diameter of the circular shaped contact plane on top of the snow sample and by using the time duration of initial compression, the compression speed and the geometry of the semi-spherical snow sample. The values obtained by these two methods agreed very well.

Experimental results

The adhesive strength was obtained by dividing the adhesive force by the apparent contact area. The adhesive strength of wet snow onto various materials thus obtained were tabulated in Tables 1 and 2 for different free water contents that ranged from 4 to 30% and for different initial compressive stress as given at the contacting surface. The contact angle between water and a plate made of each material was measured as listed in the second column of Table 2.

For a small initial contact stress such as $1.6KN/m^2$, the adhesive strength was found smaller than $0.5KN/m^2$, and it remained constant for each material regardless of free water content of snow as seen in both Fig.3 and Table 1. For a larger initial stress such as $4.75KN/m^2$, the larger adhesive strength was observed, which increased with an increase in free water content of snow as shown in Fig.3.

Figure 3. Adhesive strength vs. free water content of snow for different initial compressive stresses.



When the initial contact stress of about $15KN/m^2$ was applied to a snow sample, the adhesive strength became larger for each material with an increase in free water content of snow, whereupon it was found maximum when the free water content was 12-16%, as seen in Table 2 and Fig.4.

Figure 4. Adhesive strength vs. free water content of snow for a large initial compressive stress of $15KN/m^2$.

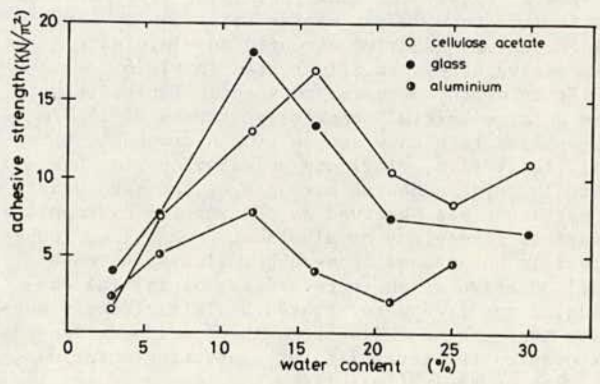


Table 1. Tensile adhesive strength of wet snow onto various kinds of materials for different free water contents and for two initial compressive stresses.

Initially applied compressive stress	$1.6KN/m^2$			$4.75KN/m^2$	
Free water content of snow (%)	4	8	20	7	20
glass	$0.4-0.5KN/m^2$	0.5	0.4-0.5	1.5	0.20
cellulose acetate	0.4	0.5	0.5	1.0	0.9
aluminum	0.3-0.4	0.3-0.4	0.3-0.4	1.0	0.17
polyethylene	0.2	0.2	0.2	0.7	0.7
teflon	0.2	0.2	0.3	---	---
vinyl	0.1-0.2	0.1-0.2	0.2	---	---
butyl rubber	0.2	0.1	0.2	0.2-0.3	0.2-0.3
silicone rubber	0	0.1-0.2	0.1-0.2	0.2	0.2-0.3

Table 2. Tensile adhesive strength of wet snow of different free water contents to various kinds of materials.

Material	Contact angle	Free water content (%) 4	6	12	16	21	25	30
glass	35-40°	$4.0KN/m^2$	7.8	18.2	13.4	7.4	---	6.5
cellulose acetate	65	1.6	7.7	12.9	16.9	10.4	8.4	11.4
aluminum	59	2.4	5.2	7.8	4.0	2.2	4.7	---
polyethylene	86	3.6	4.4	8.0	8.3	---	6.9	5.5
teflon	90	5.2	3.4	8.0	8.6	---	---	10.
vinyl	89	2.0	3.0	13.3	5.7	---	4.8	---
ethylene-propylene rubber	78	0	0.9	2.2	1.6	1.0	---	0.3
butyl rubber	85	0.5	---	1.4	1.4	---	---	---
silicone rubber	90	0.5	0.4	---	0.5	---	0.2	0.3

Such large values as $15-18KN/m^2$ observed at the free water content of 12-16% may be due to a smaller contact area of snow, because the adhesive force itself remained constant for each material when the free water content of snow was larger than 7-8% as illustrated in Fig.5. In fact, a smaller contact area was observed for the snow containing free water of 12-16% than that observed for the snow which contained free water of less or more than these percentages.

For a heavily wet snow containing free water of 20% or more than 20%, a linear relationship was obtained between adhesive strength and initially given compressive stress as illustrated in Fig.6.

It is worthy of note, as seen in Table 2, that when a large initial compressive stress of $15KN/m^2$ was applied to a snow sample by a hydrophobic material like teflon, vinyl and polyethylene, an unexpectedly large adhesive strength of the same order of magnitude was observed as the one for hydrophilic materials like glass or aluminum. Meanwhile, rubber materials such as silicon-rubber always showed a small adhesive strength regardless of initial compression and free water content. This strongly suggests that the adhesive strength of wet snow depends not only on the wettabilty of contacting materials, but also on their flexibility.

Direct observation of behaviours of water at the Interface

In connection with the adhesive strength of snow onto other materials, the contact surface between snow grains and a glass plate was observed under a microscope. Sieved snow grains were scattered to be adhered onto a glass plate until they formed two or three layers. Then the glass plate with the snow grains on it was placed upside down onto the stage of a microscope to allow a continuous observation of the contact surface between the snow grains and the glass plate at the room temperature kept between 0° and +1°C. Snow grains began to melt, resulting in an increase in the amount of meltwater with time. At the beginning stage, each snow grain was enveloped by a small amount of water at its bottom as seen in Fig.7(a). The side view of such snow grains is schematically shown in Fig.9(a). With an increase of the amount of meltwater, an increasing number of snow grains were immersed in an assemblage of water as shown in Fig.7(b). and Fig.9(b). Finally, the whole snow grains formed a continuous water mass on the glass plate as shown in Fig.9(c).

To examine the behaviour of water existing at the interface at the time of its separation from one another, a method was designed using two combinations, i.e., a glass plate and a brass plate, and a teflon

Figure 5. Adhesive force vs. free water content of snow

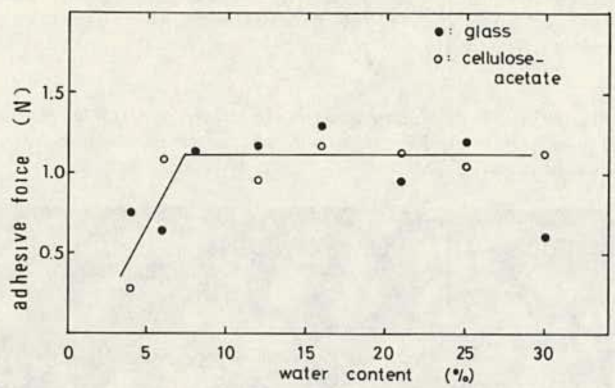


Figure 6. Relationship between adhesive strength and initial compressive stress for wet snow containing 20% of free water.

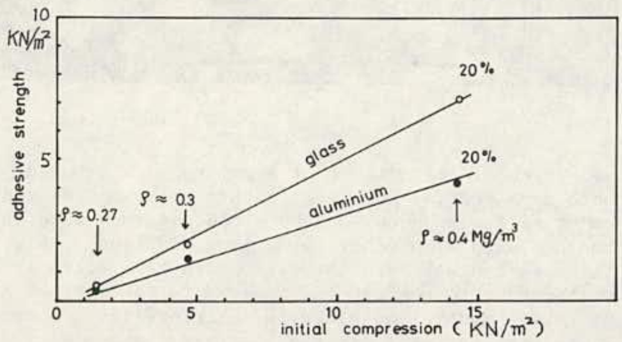
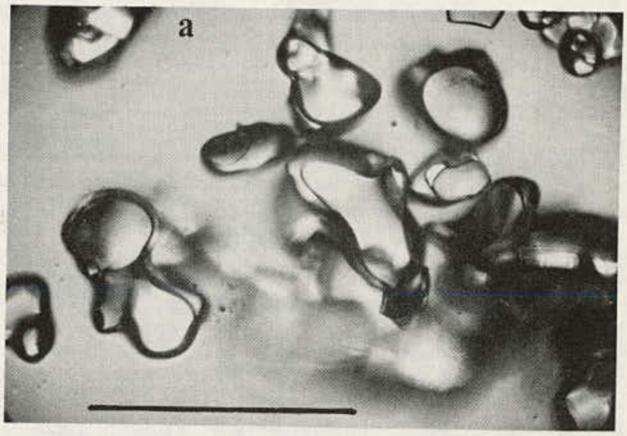


Figure 7. Wet snow grains in contact with a glass plate. a: small amount of free water; b: larger amount of free water. Scale: 1mm.



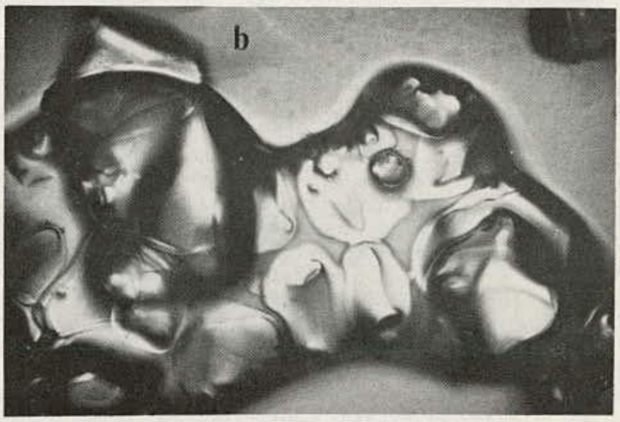


Figure 8. Simulated side view of water at the interface immediately before a complete separation. (A: a glass plate and a brass plate; B: a teflon plate and a brass plate)

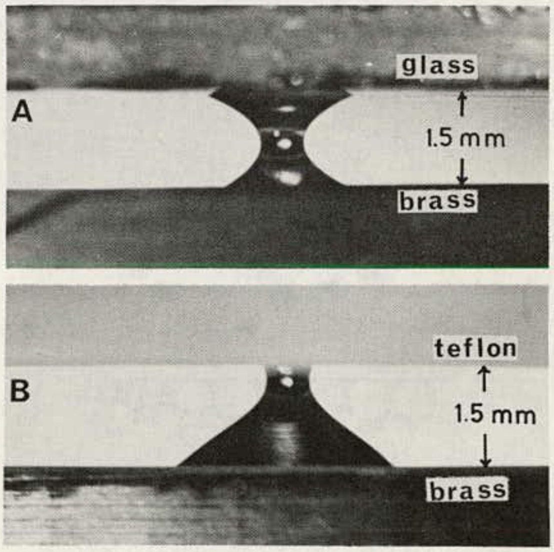


plate-a brass plate. Two photographs in Fig.8 show the shape of water at the interface immediately before a complete separation.

The distance between the surface of snow and the contacting plate at the moment of separation was estimated by using the time duration of tensile adhesion and the tension speed (1mm/min), and it was found that the separation distance was 30-35μm and 50-70μm for hydrophobic and hydrophilic materials, respectively. The difference in the separation distances is reflection of the difference in the contact angles between hydrophilic and hydrophobic materials as seen in Fig.8.

Discussion

It was observed under a microscope that a contact surface was wetted by water for each of snow samples containing different amounts of free water. This suggests that only the water existing at the interface plays the dominant role in adhesion of wet snow. If there is no water at the interface, i.e., in case of dry snow, only a very small adhesive force is to be expected. In fact, such a force was observed for dry snow when it was measured one minute after it was brought to contact with a glass plate at a temperature of -5°C.

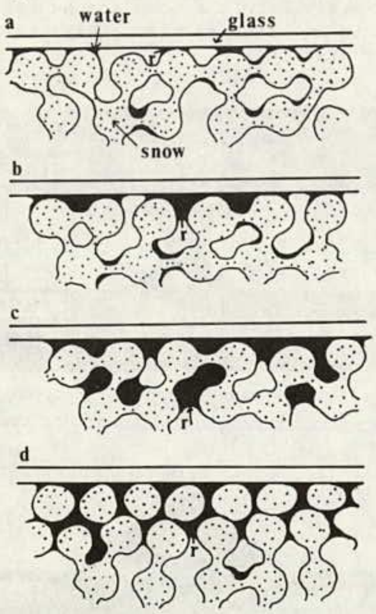
Experimental results show that when a small initial stress such as $1.6KN/m^2$ was applied to a snow sample, the very small adhesive strength S was observed for each material regardless of the free water content, w, of snow. This may be due to a "poor" contact between a snow sample and a test plate under such a small initial contact stress as $1.6KN/m^2$.

When the initial compressive stress such as more than $3\text{-}4KN/m^2$ was applied to a snow sample, the adhesive strength S became dependent on the free water content w, and the maximum value of S was found when w was 12-16% as shown in Fig.4 and Table 2. These results can be explained as follows: As described before, the adhesive force F of wet snow may be dependent on the negative pressure $p=(-\sigma/r)$ induced in water existing at an interface between a wet snow sample and a contacting plate, and also the sum of the area B of water in contact with the plate; hence $F=B\cdot(\sigma/r)$ and the adhesive strength $S=(B/A)\cdot(\sigma/r)$, in which B and r vary with the interfacial snow density, free water content, grain size of snow, contact angle between a water droplet and the plate, and time duration after the contact. The grain size of snow, the contact angle and the time duration are the same for each experiment, and the interfacial snow density may depend on the initial compressive stress.

When a snow sample contains only a small amount of water less than 10% in free water content, the area B is so small that F, hence S, is small (Fig.9a). As the free water content w increases, B becomes larger until the whole interface is wetted by water when (B/A) reaches the maximum value of 1. In addition to this, it is probable that snow grains near the interface is locally compressed by the initial compression as schematically shown in Fig.9d. When the snow is locally densified, the radius of curvature r of the concave water surface at or near the interface becomes smaller because the distances between neighbouring snow grains become small as illustrated in Fig.9d. This state may be realized when a snow sample contains free water of 12-16% for which the maximum value of adhesive strength S was observed.

When a snow sample contains a larger amount of water such as 20-30%, most of air-voids among snow

Figure 9. Schematic diagrams of water existing at or near the interface between snow and a glass plate. For different free water contents of snow (a, b and c). d; for the snow densified at the interface by an initial compression.



grains are saturated with water and r becomes larger as shown in Fig.9c, while the adhesive strength slightly decreases when the free water content becomes too large (Fig.4).

The shear adhesive strength of wet snow is of minor importance in a snow accretion problem compared to its tensile adhesive strength, because the former is generally much smaller than the latter; for example, the value of the latter onto electric wires was $0.19 KN/m^2$ when the free water content was greater than 20%, while the value of the former was only $0.02 KN/m^2$ (1).

Figure 10. Dry snow grains in contact with a glass plate. Mirror-like contact plane surfaces are seen. Scale: 1mm.

It should be noted that even dry snow adhered onto any material at a temperature below the melting point of ice such as -5° and -10°C, if they were in contact with each other for a long duration of time. The real contact area increased with time after it was brought to contact and adhered to the surface of glass, metals and plastics. Mirror-like contact plane surfaces were clearly observed under a microscope as illustrated in Fig.10.

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Adhesion of Ice to Concrete Surfaces — Preliminary Results

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We are involved in a project whose objective is to determine the relative importance of the two components of binding between ice and concrete, namely: the actual microscopic forces between water and substrate molecules; and mechanical interlocking of ice with a porous surface. Tensile interfacial-strength tests of ice-concrete are being performed, as well as a fundamental examination of adsorption isotherms and immersional heats of wetting. Bulk strength tests of ice are also being conducted in order to characterize the samples. Results obtained to date are: (1) Bulk ice compressive strengths (typically 36 Kg/cm^2), tensile ring strengths (13 Kg/cm^2) and flexural strengths (11 Kg/cm^2), show good agreement with previous work of others on lake ice. (2) The interfacial tensile strength, S, for pure ice-concrete shows no dependence upon percentage air entrapment in the concrete in the range 2 to 8% air, suggesting that the total binding force is nearly independent of pore structure. Below $-7^{\circ}C$, S is nearly independent of temperature, typically 8.3 Kg/cm^2. Above $-7^{\circ}C$, preliminary results indicate that S is significantly lower, 6.1 Kg/cm^2. A model is proposed by which, with a more complete data base, one should be able to determine the relative importance of the ice-concrete adhesion mechanisms.

1) Problem Studied

To date there have been a large number of reports on techniques for ice and snow removal; a list of a good many reports up to and including 1972 are given in CRREL Special Report 115[1] and EPA-R2-72-125[2]. Studies carried out to date have a strong practical bias and the conclusions are empirical[3,4,5,6]. Our project takes a more basic approach. While the overall practical objective of prevention or removal of ice from a highway surface is kept in mind, we are primarily concerned with developing a more fundamental understanding of the problem of ice adhesion to concrete and asphalt. We are looking at it from the point of view of the forces between atoms and molecules and the energies of monomolecular layers.

Immediately one sees that the problem is complex. Surface micro-and macro-structure, temperature, contaminants, freezing mode and bulk properties of ice all interact in ways that are mostly unknown. In order to help identify the interactions, and hence provide an aid to clearer planning of our attack on the problem, the interaction flowchart shown in Figure 1 was developed. The basic premise of this device is that the total binding force between ice and a porous surface has two components: the actual microscopic forces of cohesion between the water molecules and the substrate molecules, and the macroscopic forces derived from the mechanical interlocking of the ice with the porous surface. When the components and interactions are broken down in this manner, the basic variables of the problem become clear: macro- and micro-surface structure of the substrate, surface composition, surface contamination, water purity, freezing mode, and temperature. In terms of interfacial testing, factors such as testing mode (shear or tensile), uniformity of stress distribution, and rate of loading also become factors.

The first objective of our investigation was to discern the relative role of cohesive forces and mechanical interlocking forces. Adhesion is intrinsically derived from normal, tensile forces. Therefore tensile interfacial strength tests, in combination with interfacial simulation, were selected as the primary investigative tool. Additional, tangential components of force, derived from interactions between ice and surface asperities during a shear test, are thereby avoided.

Fundamental examination of the cohesive forces is being performed using adsorption isotherms (gravimetric) and immersional heats of wetting. The latter measurement provides a measurement of the total surface energy of interaction between water and the various components of concrete and asphalt, whereas the isotherms provide more information about the first adsorbed monolayer. Table 1 summarizes the overall experimental program which is underway.

Full scale interpretation of the results will not be attempted until a greater data base has been completed. Several alternative models and considerations are however, developing from the results obtained to date and from the literature survey performed. Primary sources are the work of

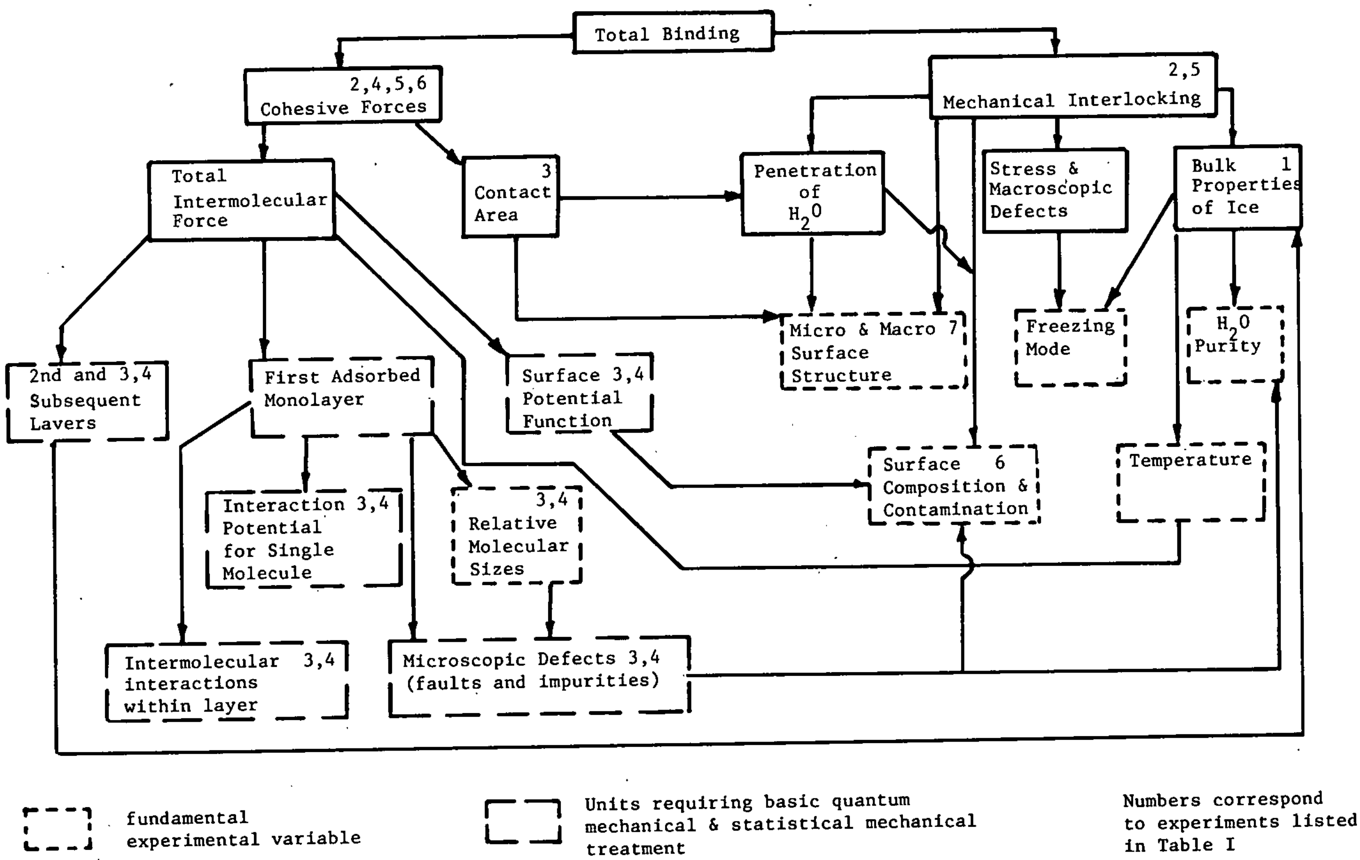

Figure 1. Dependency and Interaction Flowchart

Table 1. Summary of Program Tasks

Task No.		Test Methods	Purpose	Parameters
1	Bulk strength of ice	a) Compressional b) Flexural c) Ring test	a) Classify samples b) Corroberate existing data c) Obtain data for parameters of specific interest	a) Method of growing b) Freezing rate c) Impurity type and concentration
2	Tensile Test of concrete/ice Interface	a) Embedded rope b) Concrete holder	a) Discern role of mechanisms b) Determine dependence on parameters c) Provide discriminatory information for various models	a) Surface composition b) Surface preparation (including contaminants) c) Temperature d) Water/Solution type e) Freezing rate
3	Mass adsorption Isotherms	a) Differential microbalance	a) Determine adsorption characteristics b) Determine heats of adsorption (binding agency)	a) Components of substrates
4	Heats of wetting (immersional)	a) Differential calorimeter	a) Determine heats of wetting	a) Components of substrates b) Water/Solution type
5	Surface simulation	a) Numerical	a) Simulate behaviors found in task 2, particularly discern the role of mechanisms	
6	Contact angle	a) Sessile drop	a) Correlate contact angle with interfacial strength	a) Surface composition b) Surface preparation c) Water/Solution type
7	Surface classification	a) Optical micrograph b) Scanning electron microscope	a) Record and classify surface structures	a) Surface composition b) Surface preparation

Jellinek[7,8,9] and Raraty and Tabor[10]. Their investigations of ice adhesion to stainless steel and plastics are, of course, not directly applicable to ice/concrete adhesion. Nevertheless they do provide very useful information, as will be indicated below. Of particular interest are their descriptions of the differences between shear and tensile strengths. Interfacial region models such as the disordered, or liquid-like, layer model[8,11,12] and the grain boundary diffusional models,[10,13] can be applied to a concrete-ice interface since they provide a theoretical reference against which to compare our data.

2) Tasks Accomplished

Most of the research effort has been directed towards tasks 1 and 2 (Table 1) during this first half of our program. Mass adsorption isotherm, heats of wetting and contact angle measurements are in progress, but will not be reported here.

Studies on the bulk and adhesion properties of ice have been made for pure ice. This has involved construction of the test and sample preparation facilities. Methods of producing good samples for the bulk samples and for distribution of the stress in tensile test samples have been developed as discussed in the next section. The dependence of interfacial strength on surface composition, surface preparation, freezing rate and temperature have been investigated for pure water ice on concrete.

3) Experimental Procedures

a) Preparation of Samples for Bulk Property Tests.

All samples have been prepared from distilled, deionized water which has been de-aerated by boiling for about one hour. They were solidified in Plexiglas molds with aluminum bases. The cross-section of the mold was circular, square or annular depending upon the test involved. Compressional test samples were nominally 7.5cm diameter by 15cm high; flexural test samples were nominally 5x5x15cm long; ring test samples had outer and inner diameters of 7.5cm and 2.5cm respectively and were 6.5cm thick.

Molds were filled carefully with water (so that the least possible amount of air is introduced) and then placed in a domestic-type freezer. Heat is primarily conducted away from the water through the aluminum base. Foam insulation was placed around the sides of the mold and a low intensity radiative source placed above it. This arrangement prevented freezing at the top of the mold and allowed the sample to be formed at a single planar growing surface. Unfortunately, regardless of the precautions taken to de-aerate the water, the ice contained streaks of air bubbles.

Several modifications to the freezing technique have been tried. A modification of the technique developed by Bilgram[14] for growing heavily doped ice samples was successful. This is illustrated in Figure 2. It involves the production of a gentle convective current in the melt. Heat is dissipated in the upper layers of the water. The lower, colder layers become buoyant. Gentle convective stirring results, and sweeps away gas molecules which would otherwise accumulate at the growing surface. As the surface advances, the power dissipation in the water is gradually reduced. Samples are produced which are completely free from bubbles. The rate of heating can also be used to regulate the overall rate of growth of the samples.

b) Bulk Property Test of Ice.

These tests were performed primarily to classify the particular quality of ice produced for the interfacial tests. Since few specific test procedures for ice have not been laid down, the methods used were adaptations of accepted procedures. All tests were carried out on a Tinius Olson 400,000 lb. testing machine equipped with a simple environmental chamber as shown in Figure 3. The chamber was cooled by a Neslab RTE-4 circulating temperature bath with methanol used as the cooling fluid. Temperatures down to $-23^{\circ}C$ could easily be maintained to within $\pm 1/2^{\circ}C$ - a calibrated thermistor monitored the actual temperature of the enclosure and the sample.

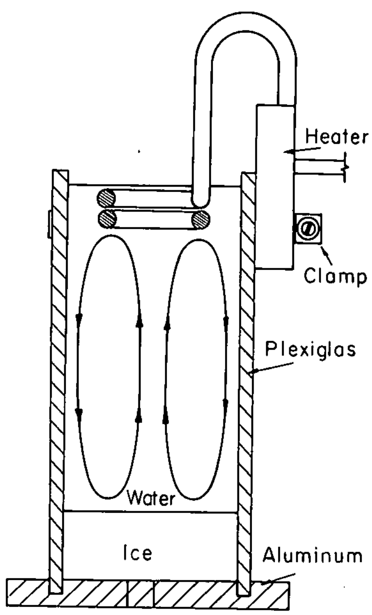

Figure 2. Apparatus for Growing Bulk Ice Samples.

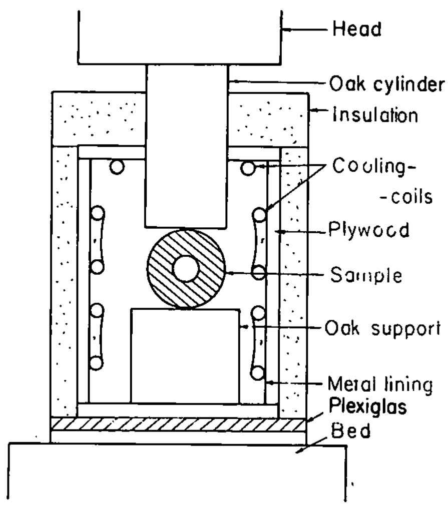

Figure 3. Test Facility for Compressional, Flexural and Tensile Ring Measurements on Ice.

The three modes of testing were patterned as follows:
Compression Test - based on compression test for concrete ASTM C39.
Flexural Test - based on flexural test for concrete ASTM C78.
Tensile Ring Test - based on a ring tensile strength test for ice described by Burkovick[15], and by Graystone and Langleban[16].

c) Tensile Interfacial Tests.

To accommodate these tests, some device for clamping the concrete or asphalt bases was needed, together with a means of transmitting tension to the ice. Because of space limitations it was not possible to do this within the environmental chamber on the compressional test facility. There was also the consideration of temperature control. Sufficient space was provided by mounting a Cal-Tester Model TH-5 5000 lb. tester outside a freezer and having the loading members pass through its side as shown in Figure 4. This arrangement was convenient from the sample handling standpoint, and kept the test machine itself at room temperature. Temperature control inside the refrigerator was achieved by combination of the freezer thermostat and a variable heat source inside the freezer. Air circulation was maintained by a fan to promote uniformity of temperature. Temperatures in the range -25°C to 0°C were available.

The test procedure has been based on the ASTM Standard Test Method for Tensile Properties for Adhesive Bonds D 897.

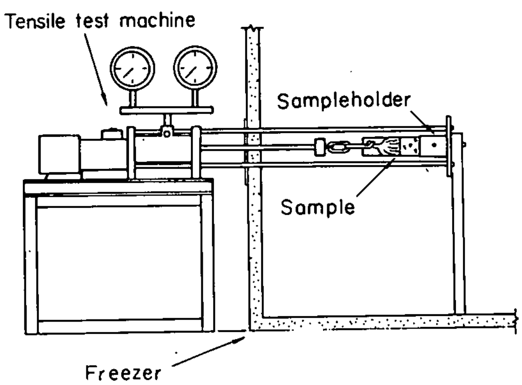

Figure 4. Tensile Testing Facility.

Previous tensile tests on relatively small single crystal ice samples utilized a cup-like arrangement for attachment[17]. This scheme works well for relatively small samples. The present test program was designed around 7.5cm diameter concrete specimens. This particular size was chosen because of its preferred use for concrete testing. Also, with the variability of aggregate size, density and distribution, tensile tests on small diameter samples would be open to gross statistical fluctuations. Preliminary tests indicated that fracture of the bulk ice due to non-uniform stress occurs readily in samples of larger sizes. Some means had to be found to distribute the stress.

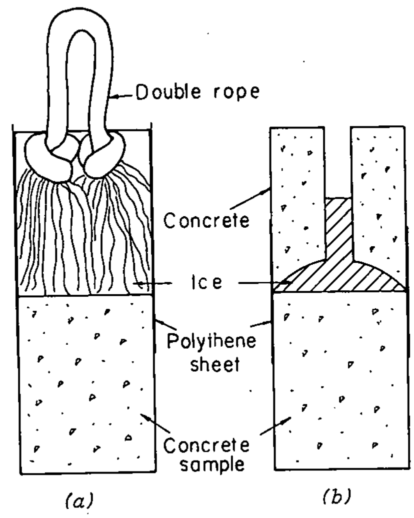

Figure 5. Sample Configurations Designed to Apply and Distribute Tensile Stress.

a) using nylon rope
b) using shaped concrete cylinder

The first successful scheme utilized a nylon climbing rope which had been frayed. Figure 5a shows the best configuration which has the rope doubled, knotted, and then frayed. Although cracking occurs in the ice block, breaks are being achieved which involve ice contacting the surface. Schemes involving conical blocks of ice, which are considerably more difficult to fabricate, have not produced better results.

Since the bonding of ice to concrete is so strong, the use of two concrete surfaces was tried. A configuration much like that used by Ravaty and Tabor[10] for ice to stainless steel adhesion was employed. The main drawback to this scheme is the modification of the ice by the concrete. As liquid water is applied and soaks into the concrete, some gases are apparently dissolved into the water. As a result, as the ice is formed, bubbles collect under the upper surface and produce a weak joint. To overcome this problem the specially shaped upper block can be used (Figure 5b). If water is simply poured into the interspace, bubbles still collect and weaken the upper joint. But if ice is formed on the lowest sample face first, and then the warm upper block allowed to melt down the ice, a good joint can be formed. The melted ice flowing over the concrete surface apparently carries air bubbles away.

Interfacial tensile strengths, S, given in Table 3 below, were obtained by the rope method. Data given in Table 4 for the investigation of surface smoothness were obtained with a concrete block. Strengths obtained by this latter method include higher values than those obtained with ropes, but they also include much more variation. The concrete support method gives results which are highly dependent upon operator technique in fabricating the upper joint.

Sample temperature is an important parameter, and should be known fairly accurately. This is especially true for the interfacial tests. Here the important temperature is that of the actual interface, and an actual measurement in that layer would be preferred. However it was inconvenient and undesirable to place a thermocouple or other thermometer in each of the samples. Considerable additional sample preparation time and cost would be incurred, in addition to possible disruptive mechanical effects. Tests were carried out to determine the equilibrium time for bulk ice and interfacial test samples. In both cases the time constant involved in the exponential approach to equilibrium was about 20 minutes. Thus samples are now maintained at the test temperature for a period of 1 hour prior to the test to ensure that the whole of the sample has acquired the desired temperature.

4). Results

The results obtained to date are summarized in Tables 2, 3 and 4. All bulk tests were carried out at nominally -5, -13, and -21°C; all tests were within 1° of these temperatures. A few additional tests are in progress; at -13°C compressive tests; flexural and ring tests at -5°C.

As noted above, all the interfacial tests shown in Table 3 utilized the rope method. It is important to note that all failures have been of the cohesive type[8,10]; not one breakage has occurred leaving the concrete surface clear of ice. This is also true of the smoothness tests using the concrete support (Table 4). It was also noted that, especially at the warmer temperature, the ice remaining on the samples after fracture was crazed. Cracks could be seen to penetrate down to the concrete surface, eminating therefrom at angles varying from small to near perpendicular.

Also Table 4 indicates that, in the cohesive failure range, the rate of freezing of the interfacial ice does not influence the interfacial strength. Tests in the adhesive failure range are in progress.

Micrographs and S.E.M. images of the concrete surfaces have been taken and are being analysed.

Table 2 - STRENGTH OF PURE ICE

Temperature	-5°C	-13°C	-21°C
COMPRESSIVE STRENGTH (Kg/cm^2)	32.4	25.9	37.4
	38.6	46.8	31.8
	38.8		15.4
	35.0	45.8	39.8
	19.7	37.2	37.8
	30.8	39.1	63.7
	26.4		
Average Values	31.7	38.9	37.6

Temperature	-5°C	-13°C	-21°C
FLEXURAL STRENGTH (Kg/cm^2)	10.6	12.7	7.1
	16.9	7.4	8.7
	6.3	15.3	14.2
	14.2	5.8	8.4
	10.6	20.0	11.6
Average Values	11.7	12.2	10.0

Temperature	-5°C	-13°C	-21°C
RING TENSILE STRENGTH (Kg/cm^2)	11.8	13.7	12.4
	10.9	11.6	17.0
	5.4	13.5	16.5
	13.8	11.8	16.1
	10.7	10.7	11.6
		13.4	24.7
Average Values	11.8	12.5	14.7

The load rate for all the above tests was 0.2 Kg cm^{-2} sec^{-1}.

Table 3. TENSILE STRENGTH OF ICE-CONCRETE SAMPLES

PERCENT AIR ENTRAPMENT	TEMPERATURE (°C)	NUMBER SAMPLES	AVERAGE TENSILE STRENGTH (Kg/cm^2)
2	-3	7	6.2
2	-8	4	8.80
2	-12	5	8.06
2	-15	4	8.88
2	-19	4	8.03
4	-3	6	6.01
4	-8	4	8.21
4	-12	4	7.40
4	-15	4	7.73
4	-19	4	8.45
8	-3	5	5.92
8	-8	4	7.58
8	-12	4	8.08
8	-19	3	10.97

A loading rate of 0.2 Kg cm^{-2} sec^{-1} was used. The average deviation of Tensile strength measurements was 1.1 Kg cm^{-2}.

Table 4. FREEZING RATE AND SMOOTHNESS TESTS

Freezing Rate Test

Concrete Sample, 2% air content, Nylon Rope System. Load Rate 0.2 Kg cm^{-2} sec^{-1}

T	Growth Rate of Ice (cm/min)	$\bar{S}$ (Kg/cm^2)	No. of Samples
-19°C	0.037	9.91	3
-19°C	0.008	9.55	3
-3°C, -3°C	IN PROGRESS		

Smoothness Test

Concrete Sample, 2% air content, Concrete System. Load Rate 0.05 Kg cm^{-2} sec^{-1}

T	Surface Condition	$\bar{S}$ (Kg/cm^2)	No. of Samples
-11°C	Rough cut	10.4 ± 1.2	3
-11°C	Machine Polished	10.2 ± 3.5	3
-3°C, -3°C	IN PROGRESS		

5) Discussion and Conclusions

Little needs to be said regarding the bulk tests. The results are in excellent agreement with previous ones. Particularly, their agreement with data for lake ice indicates that our sample preparation technique produces ice of comparable quality to natural ice.

Results obtained for interfacial strength are intriguing. As can be seen from Table 3, there does not appear to be any significant dependence of S upon the percentage air entrapment in the concrete. This would suggest that the total adhesive force is not strongly dependent upon the pore structure of the concrete.

Our main initial goal was to define the relative role of surface cohesive forces and the interlocking forces. At first sight there appears to be little information in Table 3 to help towards this goal. However, when the data is plotted as a function of temperature (as in Figure 6) three possibly significant points are noticed; below $-7^{o}C$ the results are ostensibly independent of temperature; the data at $-3^{o}C$ are significantly lower than the other data; and the data at $-3^{o}C$ has significantly less scatter than data at other temperatures.

Clearly, additional data is needed before a proper interpretation can be attempted. Particularly, more data is needed close to $0^{o}C$. This requires improvement of temperature control and mounting technique, particularly at -1 or $-2^{o}C$. Nevertheless the following speculative interpretation can be given to illustrate the discriminative process which may be applied.

Adhesive strengths for ice on metals and plastics have a well defined temperature dependence [8,10]. For shear tests and smooth surfaces, S is virtually proportional to $|T|$ up to the point where the failures change from adhesive to cohesive. Data for ice on stainless steel and polystyrene are shown in Figure 6; curve c) is for ice-stainless steel by shear, d) and e) are for ice-polystyrene by shear and tension respectively. The physical mechanisms responsible for this dependence are not yet understood. Assuming that adhesion between ice and concrete due to cohesive forces would have the same type of temperature dependence, it is to be expected that S would decrease linearly as T tends to zero; this would produce a dependence as depicted by curve (a) on Figure 6 for a shear test. Alternatively, adhesion forces due to mechanical interlocking would be expected to exhibit the same temperature dependence as the tensile strength of ice, which is only small (curve b). Thus the form of S at higher temperatures will give an indication of the role of the two mechanisms. Temperature independence suggests mechanical interlocking; temperature proportionallity suggests cohesive surface bonds.

At present we tend towards the opinion that both mechanisms are present and significant. That there is no mechanical interlocking of ice in the pores is inconsistent with the wetting of the concrete surfaces and moisture absorption into the material. The lower values of S at $-3^{o}C$ do suggest some temperature dependence. And the decreased scatter suggests the onset of a mechanism of more precisely defined character than the statistical nature of imperfections in the ice. The nature of the failures must also be kept in mind.

A model is suggested in which interlocking and cohesion is involved. As the temperature is raised, the cohesive strength to some components of the matrix become inadequate to support the stress and plastic flow occurs in these regions. Deformations then cause increased stress on the other components, with stress concentrations occurring at the junctions of the materials. Thus, rather than a clear break occurring between the ice and the surface, cracks are developed and propagate into the bulk ice, causing failure.

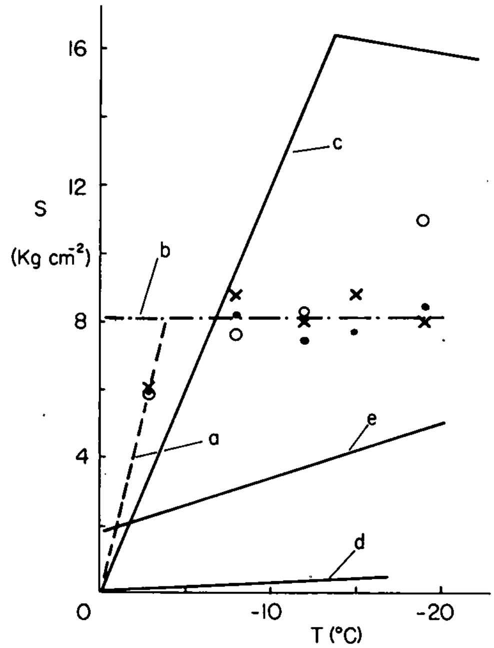

Figure 6.- Strength of Ice-Concrete Interface.

x - Tensile test, 2% entrained air
• - Tensile test, 4% entrained air
0 - Tensile test, 8% entrained air
Curves a) and b) - see text
Curve c) - ice-stainless steel, shear test[8]
Curve d) - ice-polystyrene, shear test[8]
Curve e) - ice-polystyrene, tensile test[8]

Our principle conclusion, drawn from this speculative model, is that further measurements are needed and they should include both shear and tensile tests. When completed they will probably provide a clear conclusion. The measurements should concentrate on the higher temperature range, ($-10^{o}C$ to $-1^{o}C$) and should include separate tests on the various components of the concrete.

6) Acknowledgements

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Adhesive Strength of Contaminated Ice

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Temperature dependence of adhesive strength of ice containing KCl was measured using centrifugal force in examination of an area occupied by a solution at an substrate/ice interface. The $AgNO_3$ replica technique developed by Prodi and Nagamoto was applied to examine the solution-occupied area on the surface of ice broken off from a substrate and the counterpart surface remaining on the substrate. Decrease of adhesive strength of KCl-ice at temperatures higher than the eutectic point could be interpreted by the reduction of the real contact area between ice and the substrate due to examination of a liquid solution at the interface.

Adhesion of ice on a solid surface is of practical importance. But, as has been pointed out by Jellinek(1) in 1970, precise measurement of an adhesive strength between ice and a substrate presents a real difficulty in that a number of factors influence this strength. Important among them are how broad a contact area is between ice and the substrate and whether or not liquid-phase solution layers exist at an interface between them.

Measuring the adhesive strength of a polycrystalline ice frozen from a dilute electrolyte solution by applying a shear stress on such an interface, Jellinek(2) suggested that the strength of shear adhesive force of a contaminated ice is due to the shearing of an interfacial liquid solution layer which has been formed during freezing, whereby be assumed that the thickness of a liquid solution is equivalent to that of a solution segregated at grain boundaries.

When a polycrystalline ice is formed from a dilute solution, a large part of solute molecules are segregated at grain boundaries. They can exist as a liquid solution at temperatures higher than the eutectic point of the solute and ice, when an ice containing a water-soluble impurity adheres on a substrate. Then, the adhesive strength of this ice must be greatly weakened under the influence due to the existence of a liquid solution at the substrate/ice interface, because the real contact area of ice at the interface is reduced by the presence of such a solution film. Therefore, it is important in the measurement of adhesive strength of ice to examine directly the area occupied by the liquid solution at the interface.

The present paper aims to study temperature dependence of relative strength of adhesion of ice containing potassium chloride relating it with a change of the area occupied by a liquid solution at the interface, using a replica technique which allows to visualize the existence of a solution film. Sea ice is a contaminated ice found in abundance in nature, but both the contaminants, NaCl and $MgCl_2$, have relatively low eutectic points. As KCl has a relatively high eutectic point of -10.7 °C, it was used as a contaminant.

Experimental Procedure

Measurement of Adhesive Strength

Measurements in this experiments of adhesive strength of ice containing KCl were made by applying a tension force, because the surface of an ice specimen broken off vertically from a substrate by the tension allows an accurate examinations of the area occupied by solution film at a substrate/ice interface without any disturbance. If an ice specimen is sheared off from the substrate, the area which has been occupied by a solution film at the interface must be disturbed by friction, making it impossible to accurately examine the initial distribution of the area occupied by the solution and the otherwise area, i.e. the real contact area of ice.

A centrifugal device was used, as shown in Figure 1, to have a tension force applied in a simple manner to an ice specimen adhering on a brass substrate. Two ice specimens prepared in the same size are individually frozen on the surface of two brass substrates (0.03m in diameter) and they are mounted at both ends of a revolutional arm driven by an electric motor. Figure 2 illustrated a detailed structure near the end of the revolutional arm where an ice specimen is mounted. When a centrifugal force acting on the ice specimen exceeds an adhesive force, the specimen is broken off from the brass substrate. As seen in Figure 2, the ice specimen is protected by a cylindrical lucite cover in such a way that the specimen broken off from the substrate does not scatter by the action of centrifugal force. This lucite cover also keeps the specimen free from a wind pressure created by the revolution. The angular velocity at a moment in which the ice specimen is

Figure 1. Experimental device for measuring adhesive strength of ice by centrifugal force.

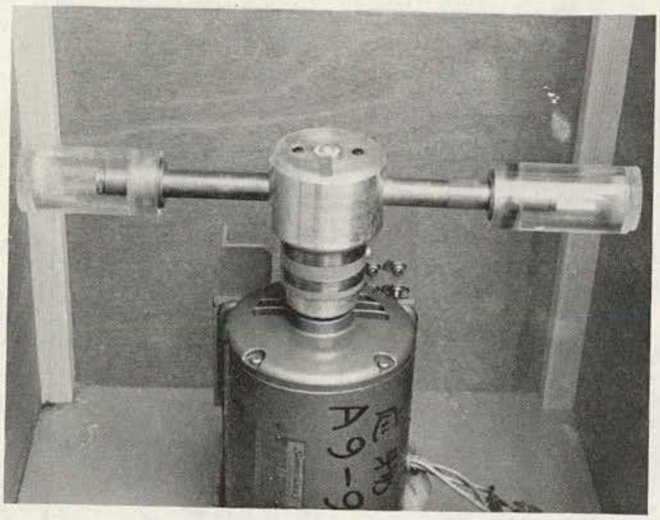
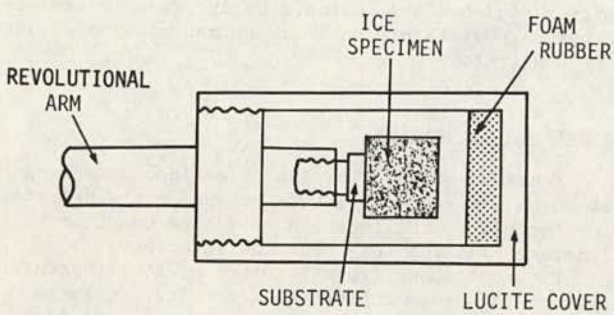


Figure 2. Schematic diagram of a brass substrate and an ice specimen mounted at the end of a revolutional arm



broken off from the substrate is measured by the aid of a stroboscope. The strength of adhesive force is obtained by dividing the value of centrifugal force by the apparent contact area of ice.

Examination of Solution-occupied Area at an Interface

For the examination of a distribution of areas occupied by a KCl solution segregated at a substrate/ice interface, a replica tecnique developed by Prodi and Nagamoto(3) was used in this experiment. Their technique was designed to examine chrodides, e.g. sea salts, contained in a natural hailstone. Namely, onto a sectioned surface of a hailstone, they applied a piece of millipore filter paper (0.8 μm in pore size), which was previously soaked in a concentrated $AgNO_3$ solution and dried up. Since sea salts segregated at grain boundaries in the hailstone are in a liquid state, i.e. a brine, at temperatures higher than the eutectic point, brine solutions transferred to the milipore filter paper exhibited brown patterns of AgCl as a result of chemical reaction, allowing the examination of distribution of sea salts in the crystalline structure of the hailstone.

Preparation of KCl-Ice and Substrate Surface

Polycrystalline ice containing KCl, which is called KCl-ice hereafter, was formed by freezing of a KCl solution ranging in 0.05% ~1% in concentration. For Preparation of a fine grained polycrystalline ice, a cylindrical container packed with fine disintegrated snow grains was soaked in a KCl solution cooled near 0°C, air having been expelled from the solution. Then the container was placed in a cold room to freeze a mixture of snow grains and the KCl solution. Figure 3 shows a typical crystalline structure of fine grained ice thus formed. The ice

Figure 3. Crystalline structure of ice containing KCl.

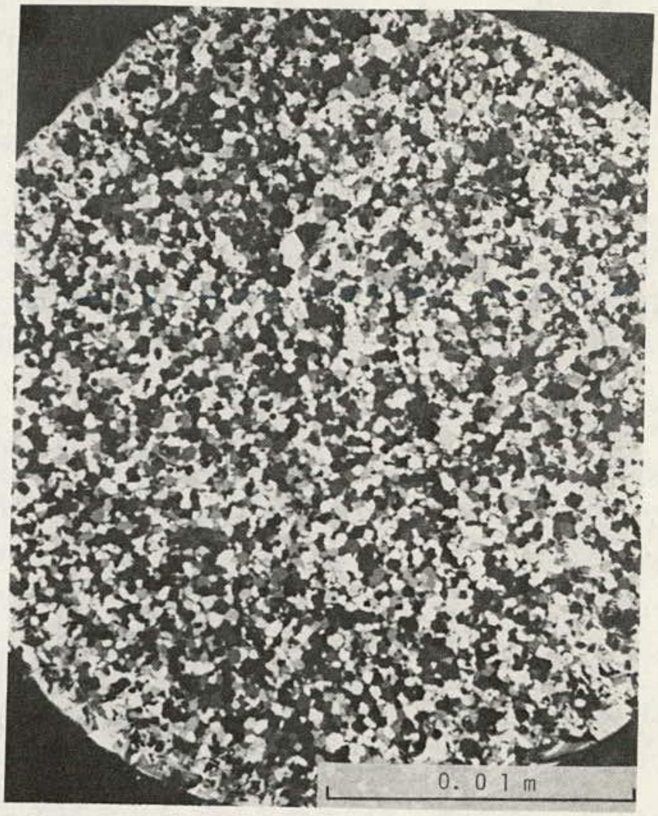


Figure 4. Ice fragment left on a brass substrate surface.

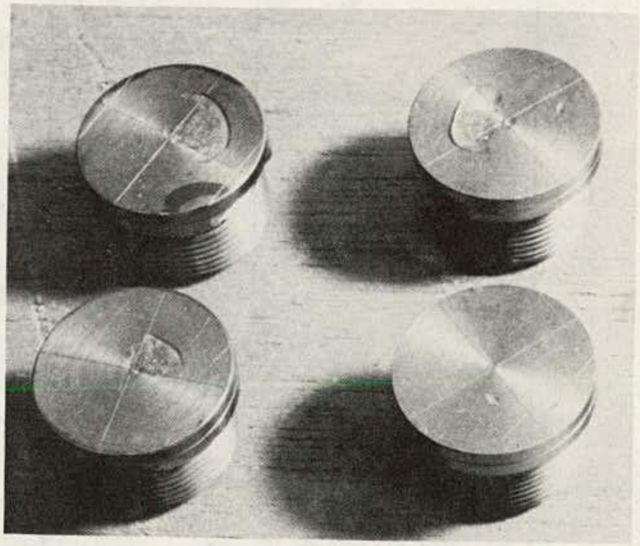


Figure 5. Temperature dependence of adhesive strength of pure ice.

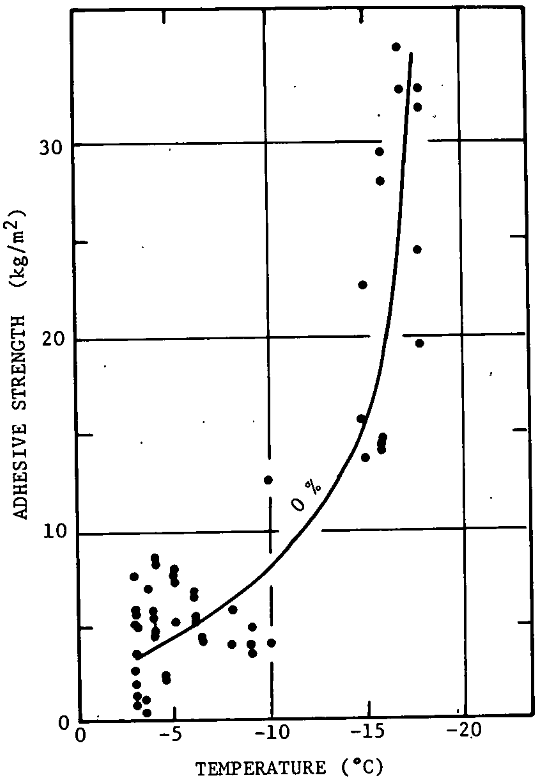
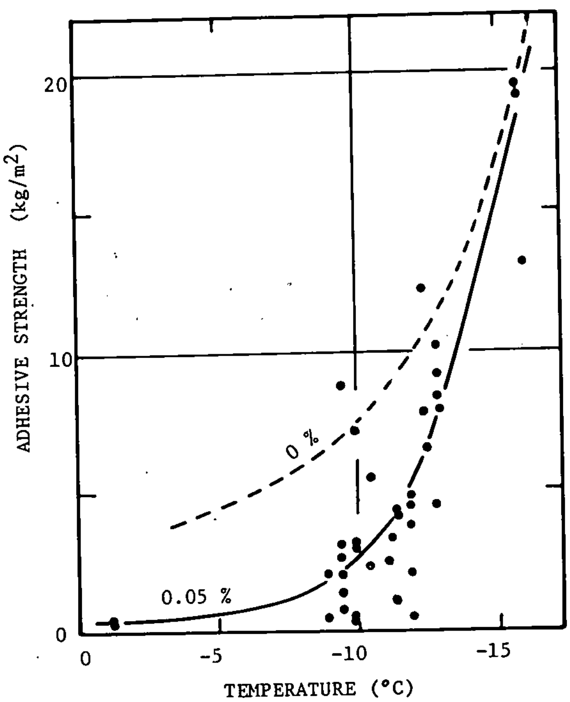


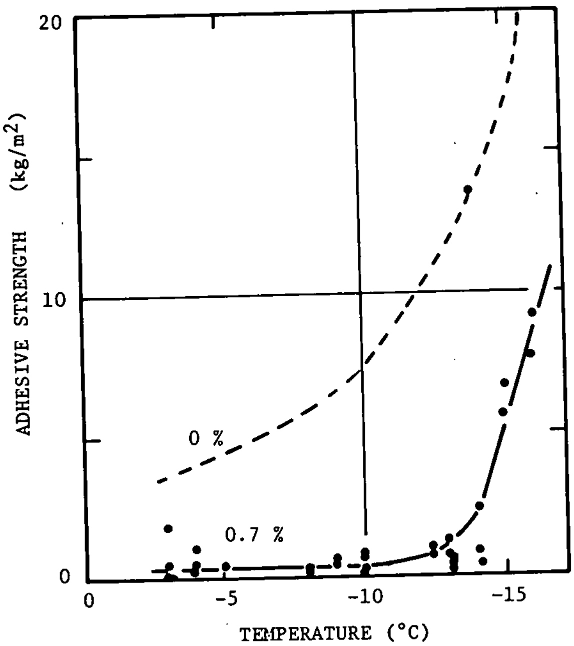
Figure 6. Temperature dependence of adhesive strength of KCl-ice frozen from a 0.05% solution.



specimen prepared for the measurement of adhesive strength had the weight of $8 \sim 15 \times 10^{-3}$ Kg and the apparent contact area of $0.7 \sim 3.5 \times 10^{-4}$ m^2, which depended on the ambient air temperatures adjusted.

The surface of the brass substrate used was not

Figure 7. Temperature dependence of adhesive strength of KCl ice frozen from a 0.7% solution



mirror finished, but cleaned by absorbent gauze with ethyl alcohol before an ice specimen was frozen onto the substrate.

Experimental Results

Adhesive strength of ice is defined as strength at which a break or fracture occurs at a substrate/ice interface, the location of such a break or fracture existing very near the interface.

Figure 4 shows typical shapes of ice fragments left on the brass substrates after ice specimens were broken off by the action of centrifugal force at -15°C. As seen in this figure, breaks or fractures of pure ice occured partly within an ice mass very near the interface (cohesive breaks), in which term "pure ice" means the ice frozen from a water distilled twice. However, most of breaks of KCl-ice occurred at the interface at temperatures higher than the eutectic point (adhesive breaks). Figure 5 shows adhesive strength of pure ice measured as a function of ambient air temperature. As seen in this figure, measured values were widely scattered, suggesting that the scattering of data may be caused by non-uniform breaks at the substrate/ice interface as shown in figure 4. In spite of the fact that breaks at the interface were not uniform, the adhesive strength of pure ice showed a tendecy of increase with the lowering of temperature as shown by a solid curve in Figure 5.

Figure 6and 7 show temperature dependence of adhesive strength of KCl-ice. Values of percentage labeled to an individual curve in the figures indicate the concentration of KCl in the initial solution in which ice was frozen. As shown in these figures, the adhesive strength of KCl-ice decreased with an increasing concentration of KCl in the initial solution. It is interesting to note here that the value of adhesive strength of KCl-ice frozen from a 0.05% solution decreased at temperatures higher than around -11°C, and that it increased sharply with lowering of temperature below -11°C as shown in Figure 6. In the case of KCl-ice frozen from a 0.7% solution, the critical temperature

Figure 8. $AgNO_3$ replica of a KCl-ice surface broken off vertically from a substrate. Replication temperature: -8°C; KCl concentration of initial solution: 0.7%.

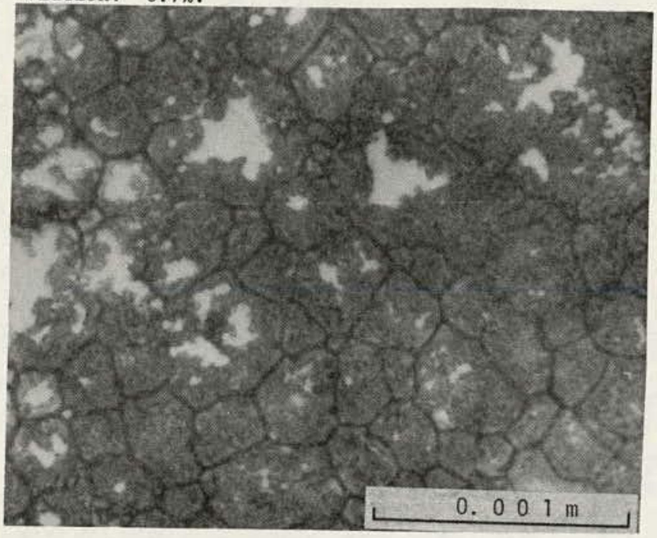
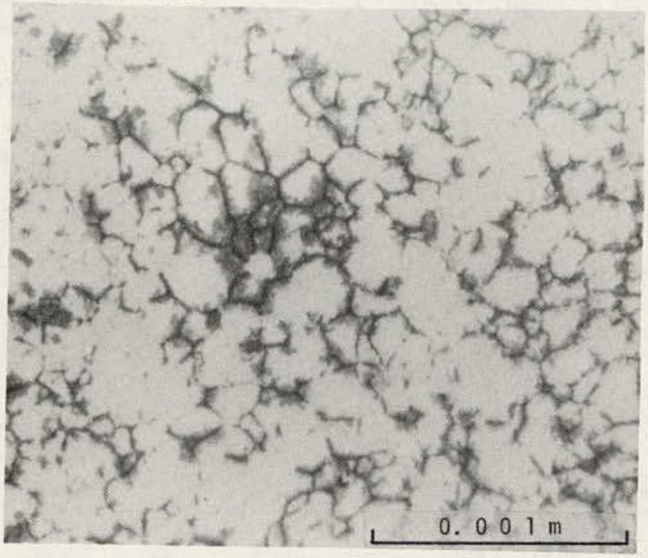


Figure 9. $AgNO_3$ replica of a KCl-ice surface broken off vertically from a substrate. Replication temperature: -14°C; KCl concentration of initial solution: 0.7%.

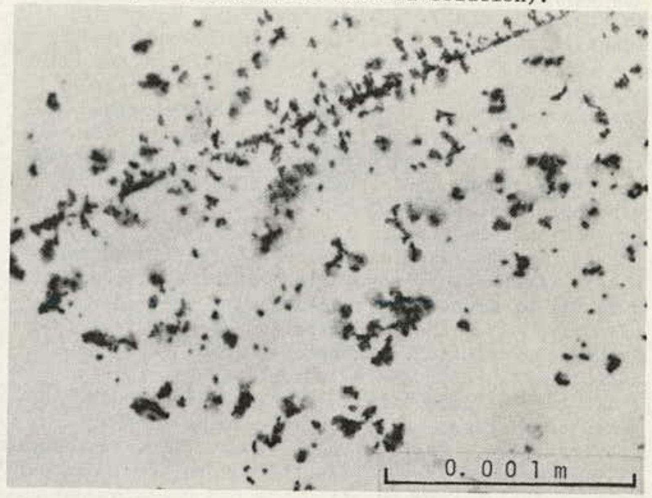


shifted slightly to a lower temperature than -11°C as shown in Figure7.

According to the International Critical Table, the eutectic point of the KCl-ice system is reffered to be -10.7°C. Hence, a drastic reduction of adhesive strength observed at temperatures higher than -11∿-13°C can be explained by an interpritation that a thin solution film existing at the substrate/ice interface may contribute to the reduction of the real contact area of ice.

This interpritation was tested by placing a piece of millipore filter paper containing $AgNO_3$ on the surface of an ice specimen broken off from the substrate and applying a slight pressure onto the surface of the millipore filter paper to make its contact with the ice surface closer. The distribution of a solution film segregated at the substrate/ice interface was successfully replicated through chemical reaction between $AgNO_3$ and a KCl

Figure 10. $AgNO_3$ replica of a brass substrate surface taken immidiately after the removal of a KCl-ice specimen (0.7% in initial solution).



solution.

Figures 8 and 9 show photomicrographs of replica of an ice surface taken at -8°C and -14°C respectively. The specimen was KCl-ice frozen from a 0.7% solution. From these two photomicrographs, it is clear that the solution-occupied area at -8°C is much broader than that at -14°C. It is interesting to note that KCl molecules segregated at grain boundaries were still in a liquid state even at -14°C, which is lower than the eutectic point as seen in Figure 9.

Figure 10 shows an $AgNO_3$ replica of the surface of the brass substrate matched with Figure 8, where the ice specimen which adhered was broken off vertically by the action of centrifugal force. Immediately after the breaking off of ice, a piece of millipore filter paper was applied on the substrate surface to examine a distribution of a solution film which was left on the surface. Unlike the replicated pattern of a solution film on the ice surface shown in Figure 8, a liquid solution was dispersed in the form of patches or microscopic droplets on the substrate.

Discussion and Conclusion

As has been pointed out by many authers, the adhesive strength of ice is greatly influenced by a number of factors including ambient air temperature, rate of stress applied, physical properties of a substrate surface and purity of ice. This study focused on how the adhesive strength of ice is influenced by the existence of a liquid solution at the substrate/ice interface. When an ice containing a water-soluble impurity adheres onto a substrate surface, a solution film exists usually at an interface between ice and the substrate, reducing the real contact area of ice. It was found useful to select KCl as a convenient contaminant of ice and adopt the $AgNO_3$ replica technique developed by Prodi and Nagamoto(3) in the examination of the area occupied by a liquid solution film and the otherwise area, i.e. the real contact area of ice at the interface.

Adhesive strengths of KCl-ice were measured by the application of a tension using a simple centrifugal device. As was expected, the relative strength of a adhesive force of KCl-ice decreased with the increasing concentration of KCl in the initial solution from which ice was formed.

When ambient air temperature shifted from a higher range than the eutectic point to a lower range, the adhesive strengthof KCl-ice changed sharply as seen in Figures 6 and 7. This temperature dependence of adhesive strength of KCl-ice could be explained by the existence of a liquid solution film at the substrate/ice interface, as was proved by the $AgNO_3$ replica technique. The estimation of Chloride reaction areas seen in Figures 8 and 9 was made by the aid of a photo pattern analyzer. The following results were obtained: the solution-occupied area was approximately 87.8% and 27% for the replica taken at -8°C and -14°C respectively.

As the first approximation, it is allowed to say that a darkness of brown color exhibited by AgCl as a result of a chemical reaction with chlorides is proportional to the concentration of chlorides in a segregated solution. Therefore, $AgNO_3$ replicas shown in Figures 8 and 9 indicate that a fairly thick concentrated liquid solution is segregated at grain boundaries, wherefrom it extends to the substrate/ice interface in the form of a thin solution film, resulting in the reduction at the real contact area of ice. Consequently, the thickness of an extended solution film at the interface is not equivalent to that of a solution segregated at grain boundaries as has been assumed by Jellinek(2). Since the contact between grain boundaries and the substrate is almost completely broken by the existence of a thick concentrated liquid solution, grain boundaries do not contribute to the adhesive strength of ice, but a thin solution film which extends from grain boundaries to the substrate/ice interface reduces the adhesive strength of ice, depending on its thickness. Though an ionic difusion can occur at the substrate/ice interface as shown by Murrman et al.(4) the authors believe that the filmy extension of a liquid solution at the interface observed in this experiment is accelerated by a pressure applied on an ice specimen in the freezing of it on the substrate surface.

Acknowledgement

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Electrical Properties of Ice-Solid Interfaces

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In the ice-water system, the principal mechanical difference between the liquid and the solid, the inability of the liquid to support a shear, is reflected in the dielectric properties. In the liquid, the molecular dipole moments easily follow electric fields up to frequencies above 10^9 Hz. In the solid, the structure prevents them from following fields above frequencies in the audio range. Thus dielectric measurements can tell us rather directly about a particular property which is important in determining the adhesive properties of ice, the rotational mobility of the molecules in the interfacial layer. We have used electrical measurements to study the nature of the molecules at two different ice-solid interfaces. One is the ice-ice interface which occurs between differently oriented grains of ice. The other is the ice-quartz interface. Measurements have been made over a frequency range of d.c. to 10 MHz and over a temperature range 0 to -20°C on both pure and NaCl doped samples. We find that the apparent thickness of the interfacial region depends on the frequency of measurement. That is, more molecules can follow a field of 100 kHz than of 1 MHz. It also depends strongly on temperature and impurity content. Trace impurities appear to play a dominant role in the d.c. conductivity at an ice-solid surface interface even when care has been taken to ensure clean surfaces.

A knowledge of the molecular interactions in the interfacial region between two materials is essential to understanding the adhesive forces between them. When two materials adhere due to an interlocking structure, they are held together by the cohesion of whichever material breaks first. This is a special case of adhesion in which both materials are the same.

If one is to modify the adhesive forces and control them, one must alter the molecular interactions in this interfacial region. Because the region is usually very thin, the energy cost of modifying it is small compared to that of most mechanical processes associated with the separation of two materials such as ice and pavement. This situation is illustrated in Table 1 which shows the energy costs for various operations and compares them to the energy costs of simply driving a small truck down the highway without doing anything with it. It is clear that one would like to discover a way of altering this region to reduce adhesion without dissipating much energy in the bulk. A mechanism for selectively depositing high energy density in this layer would be particularly exciting. Thus it is important that we understand fully the electrical and mechanical properties of the interfacial region.

Table 1. Energy costs of various processes.

PROCESS	ENERGY COST J/m^2
"Melt" 1 monolayer of ice	.096
"Vaporize" 1 monolayer of ice	.87
Deposit 1 eV per surface molecule	1.54
Heat a 1μm layer of ice 1°C	4.0
Melt a 1μm layer of ice	316
Vaporize a 1μm layer of ice	2860
Driving a small truck (It is assumed that the truck travels ten miles per gallon of gasoline and sweeps an area 2 m wide).	4700

We are concerned here with ice (water)-solid systems. For water, the principal difference between the liquid and the solid state (the inability of the liquid to support a shear) is directly reflected in the dielectric properties. Figure 1 (from Camp et al. 1967) shows the capacitance, which is proportional to the dielectric constant, and the conductance, which is proportional to the electrical conductivity, of a sample of pure ice as a function of frequency. A temperature dependent audio-frequency dispersion is the dominant feature. By contrast, the dielectric constant of water remains almost unchanged up to a frequency of above 10^9 Hz (illustrated by the dashed horizontal line in Figure 1). At frequencies of the order of 10^{10} Hz, water shows a dispersion similar to that of ice at 10^3 Hz. The difference in the two cases is that the water molecules can rotate much more easily under the influence of an applied electric field in the liquid than they can in the solid. Note that the average strength of the intermolecular bond in ice is changed by only about 10% when it melts. But the physical characteristics are changed dramatically and the dielectric relaxation frequency is shifted by seven orders of magnitude. Thus dielectric measurements tell us rather directly about a particular property which is important in determining the adhesive characteristics of ice. For a fairly current review of the dielectric properties of ice see Hobbs (1976). Some recent developments are reported by Granicher (1977).

In the interfacial, ice-solid region we have water molecules which are influenced both by the ice structure and by the solid structure. We expect that this interaction will disorder the local ice structure and create a more water-like interfacial region. (One must admit the possibility in certain conditions of creating a more rigid rather than a less rigid structure). Such a state, intermediate between ice and water, should exhibit a dielectric response also intermediate between ice and water. If as seems probable, there is a series of layers each having different properties, there will be a series of dispersions and the total dispersion curve will be broadened. Thus dielectric measurements would seem to provide a fairly sensitive test for water molecules in different states. For example, at a frequency of 10^5 Hz, the dielectric constant of pure ice is about 3.2 and that of water is about 80. Water-like molecules whose dispersion frequency is well above 10^5 Hz will respond as water. Thus the ratio $82/3.2 = 25$ works in our favor: one water-like molecule has as much effect as 25 ice-like molecules. It turns out that in certain frequency regions, one has a still larger sensitivity through the measurement of conductance. Thus electrical measurements can contribute information about the thickness and properties of thin interfacial layers.

We report below studies of the properties of this interfacial region as inferred from the electrical properties of various ice-solid configurations. Since interfacial regions are very thin, it is important to have large surface-to-volume ratios to provide enough molecules to give a measureable signal even with sensitive apparatus and the advantages cited above.

The Ice-Ice Interface

One way of obtaining large surface to volume ratios is to create ice having very small grains. Thereby one creates a large grain boundary surface area. This is an interesting approach also because it allows us to study what may be the simplest ice interface, namely the ice-ice interface. This is important in cohesion and therefore may be important in the adhesion of ice under conditions in which fracture occurs at grain boundaries rather than at the actual interface, for example when ice interlocks the solid. The analysis of a complex grain structure would be very difficult. However, if the grains can be made columnar, the grain boundaries are electrically in parallel with the grains themselves, and the analysis is simplified greatly.

Fine Grained Sample Preparation

We have developed a technique for making fine grained structures in which most of the grains are perpendicular to a given plane. This is accomplished by nucleating the growth at a very large number of sites on a plane surface. Then the surface is covered with a thin layer of water and cooled from the substrate. Because the heat of fusion is extracted through the base, the grains grow into the melt at the same rate with nearly perpendicular grain boundaries. The arrangement is illustrated in Figure 2. The myriad of small nuclei may be created by breathing on the cold substrate.

When a sample of the desired thickness has been prepared, it is melted free from the base and mounted in the measuring cell as shown in Figure 3. Our experience shows that, as a practical matter, grain sizes having a typical dimension of less than .01 mm are not easy to produce and use. This is because of the very rapid grain growth which occurs at temperatures close to melting (see Jellinek 1969). Another experimental matter which should be noted is the necessity of eliminating all air gaps between thin samples and the electrodes. A gap of 10μm with a 1 mm thick sample can seriously distort the measurement.

Fine Grained Sample Measurements

Several samples prepared and mounted in this manner have been studied and compared to similar samples of pure, single-crystal ice. From replicas of the samples taken after the measurements, we find typical grain sizes ranging from .05 mm on one sample to .12 mm on another.

At low frequencies and $-1°C$, we find the conductivities of the different samples vary, one being just about the same as that for pure ice and others being several times as large. We attribute this variation to slight traces of impurity in the melt water. This suggests that for the purest ice, low frequency grain boundary conduction is very small. In the pure ice dispersion region (1 - 30 kHz), the bulk properties of the ice dominate our measurements and little information about the interface can be inferred.

At high frequencies one finds a significant increase in the conductivity for all samples and for some, a measurable decrease in the dielectric constant. The latter indicates that as the frequency increases, fewer and fewer molecular dipoles are able to follow the field. Thus at any given frequency the excess dielectric constant over 3.2, (the contribution due to the polarizability of the molecule itself, independent of rotation) provides a measure of the fraction of the dipoles which can follow the field. The argument is as follows: The measured dielectric constant, K_{eff}, is made up of two parts, a part due to a fraction, f_1, of molecules which rotate easily and are associated with the presence of grain boundaries, and a fraction f_2 which are normal bulk molecules. The mobile molecules have a dielectric response similar to that of water (K = 80) and the immobile molecules a dielectric response due only to their polarizability (K = 3.2). Thus

$$K_{eff} = 80\ f_1 + 3.2\ f_2 \text{ and } f_1 + f_2 = 1 \quad (1)\ (2)$$

and therefore

$$f_1 = (K_{eff} - 3.2)/76.8 \quad (3)$$

If the change with frequency of the dielectric constant (well above the ice dispersion) is too small to measure but the change with frequency of the conductivity is large, we can also use this to give a rough value of f_1.

The electrical analög of a Debye dispersion is a pure resistance, R, in series with a pure capacitance C. At any frequency, this can be expressed as a frequency dependent conductance, G_p,

Figure 1. Debye dispersion for high-purity single crystal ice.

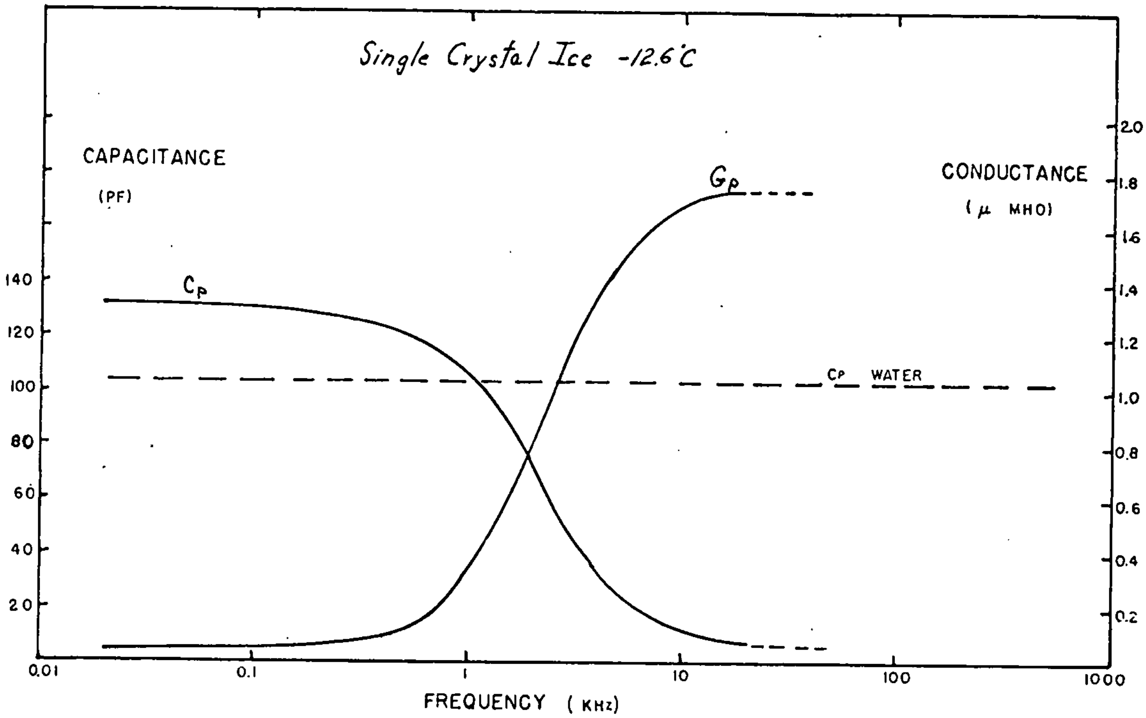


Figure 2. Technique for growing fine-grained ice with columnar grains perpendicular to the surface.

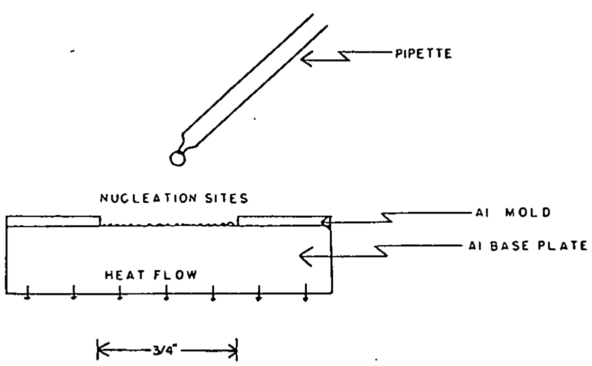
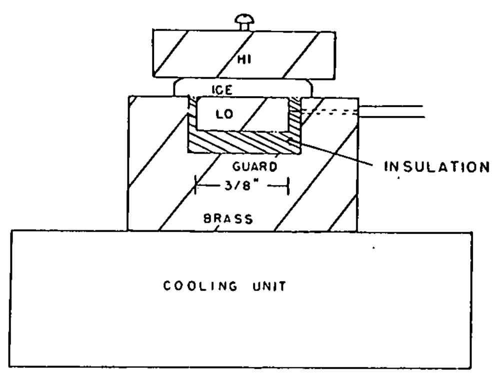


Figure 3. Measuring cell for fine-grained samples.



in parallel with a frequency dependent capacitance, C_p. They are related by the following equations:

$$G_p = \frac{1}{R}\frac{\omega^2}{\omega^2 + \omega_D^2} \qquad C_p = \frac{\omega_D^2\, C}{\omega^2 + \omega_D^2} \tag{4}$$

where ω_D is the Debye frequency in radians/sec, $\omega_D = \frac{1}{RC}$. This may also be written in terms of a complex permittivity $\varepsilon^* = \varepsilon' - i\,\varepsilon''$ (Smyth 1955).

$$\varepsilon' - \varepsilon_\infty = \frac{(\varepsilon_o - \varepsilon_\infty)\,\omega_D^2}{\omega^2 + \omega_D^2} \tag{5}$$

where ε_∞ is the permittivity at frequencies large compared with ω_D

$$\varepsilon'' = \frac{(\varepsilon_o - \varepsilon_\infty)\,\omega\,\omega_D}{\omega^2 + \omega_D^2} \tag{6}$$

Granicher (1957) has related ω_D to the average rate of dipole rotation W_o, by $\omega_D = 2\,W_o$

We assume that the rise in the conductivity over one decade of frequency is due to a single Debye dispersion having a dispersion frequency ω_d in the middle of the decade. (For these rough values, the results are not very sensitive to the details of the assumption such as whether a single dispersion or a distribution of dispersion should be used). If we call this change in conductivity $\Delta\sigma$ and the related change in dielectric constant Δk, we have from equation 4,

$$\frac{C_p}{G_p} = \frac{\varepsilon_o \Delta k}{\Delta\sigma} = \frac{\omega_D^2}{\omega^2}\ RC.$$

Since $RC = \frac{1}{\omega_D}$ and choosing $\omega = \omega_D$ we have

$$\omega_D = \frac{\Delta\sigma}{\varepsilon_o \Delta k},\ \Delta k = \frac{\Delta\sigma}{\omega_D\,\varepsilon_o} \tag{7}$$

This is the contribution to K_{eff} of the mobile molecules in the frequency region chosen and thus is equal to 80 f_1.

For a square grain, each of the four boundaries is shared by 2 grains. Thus if t is the length of a side and δ is the thickness of the boundary region, $f_1 = 2\,\delta/t$. This same relation may be used for irregularly shaped grains if t is a suitable "characteristic" dimension of the grain.

For the sample which, from low frequency measurements, we believe to have been our purest fine grained specimen, we have a $\Delta\sigma$ at 5×10^6 Hz and -1°C of about 8.5×10^{-6} (ohm m)$^{-1}$. The typical grain dimension, t, was about 0.05 mm. This leads to a grain boundary thickness at 5×10^6 Hz of about 100 Angtroms. The argument is approximate (factor of 3) but it does show very thin grain boundaries even close to the melting point when the impurity content is low. This is in general agreement with grain boundary theory (Woodruff 1973). At 10^8 Hz, one would expect even thinner boundaries.

It has been remarked earlier that the low-frequency conductivity of the fine-grained samples varied from values close to those for pure ice to values several times larger. The extreme low-frequency case is direct current. Figure 4 (a) shows a plot of d.c. conductivity of fine-grained sample number 3 as a function of temperature from nearly 0°C to -20°C. It is seen that the conductivity rises rapidly as the temperature approaches 0°C. This indicates very rapid thickening of what are probably still very thin grain boundaries. Figure 4 (b) shows similar data for a sample of fine-grained ice grown from a 0.01 molar solution of NaCl. Note that the scale is roughly 2 orders of magnitude larger. The grain boundary effect decays much more slowly as the temperature is lowered. The two curves are well described by the emprical relations

$$\sigma = 1.18 \times 10^{-6} \exp(-0.340\theta)(\text{ohm m})^{-1} \text{ for Sample 3}$$
$$\sigma = 2.8 \times 10^{-4} \exp(-0.101\theta)(\text{ohm m})^{-1} \text{ for doped ice} \tag{8}$$

(Note: conductivity here means the grain boundary conductance per square meter of a sample one meter thick).

We would like to be able to interpret these numbers as being directly proportional to grain boundary thickness. However, because impurities segregate out along the grain boundaries, the concentration of impurities in the grain boundaries will tend to decrease as the boundary region thickens. This will tend to make the true grain boundary thickness curves somewhat steeper than the conductivity curves. We conclude that the grain boundaries of the deliberately doped sample are at least a factor of 50 thicker than those of the relatively pure sample # 3.

As will be shown shortly, we believe that the grain boundary width at -1°C for the doped sample as measured at 10^6 Hz is of the order of 12µm. This means that about 6% of the sample is grain boundary region. The total d.c. conductivity at this temperature is about 2.5×10^{-4}(ohm m)$^{-1}$. Thus, the conductivity of the grain boundary region must be about 4×10^{-3}(ohm m)$^{-1}$. This is substantially less than we would expect if the grains were composed of a .01 molar solution of NaCl. It seems probable that the effective grain boundary width for d.c. conduction is significantly smaller than that for 1 MHz relaxation or that ions are strongly rejected to the melt from the grain boundary regions.

A frequency scan for the doped, fine-grained ice is shown in Figure 5. This is very different from that for pure ice. At the low frequencies we find a much larger conductivity, which is expected for relatively thick grain boundaries containing fairly significant concentrations of impurities. The apparent low-frequency dielectric constant,K, is anomalously high which is characteristic of an electrode effect, often referred to as "polarization", which is frequently a problem in working with doped samples.

In the middle frequency range there appears to be a Debye-type dispersion with a dispersion frequency of about 4×10^4 Hz and a dielectric strength of the order of 100. We believe this to be a true Debye dispersion for doped bulk ice. At the high frequencies, we see a rapidly rising conductivity and a decreasing dielectric constant, K. Here the change in K is quite resolvable and we can infer directly from it something about the fraction of water molecules which are in a more mobile state than they would be in the ice lattice.

At 1 MHz (-1°C), well above the Debye dispersion, we measure a K of 7.74. Since K for pure ice at high frequency is 3.2, we have an excess of 4.64 which we attribute to dipoles which are able to rotate easily. Assuming the model in which the grain boundary region is in parallel with the bulk

Figure 4. A pure fine-grained sample #3, d.c. conductivity vs. temperature.
B Doped Sample (.01 M NaCl), d.c. conductivity vs. temperature

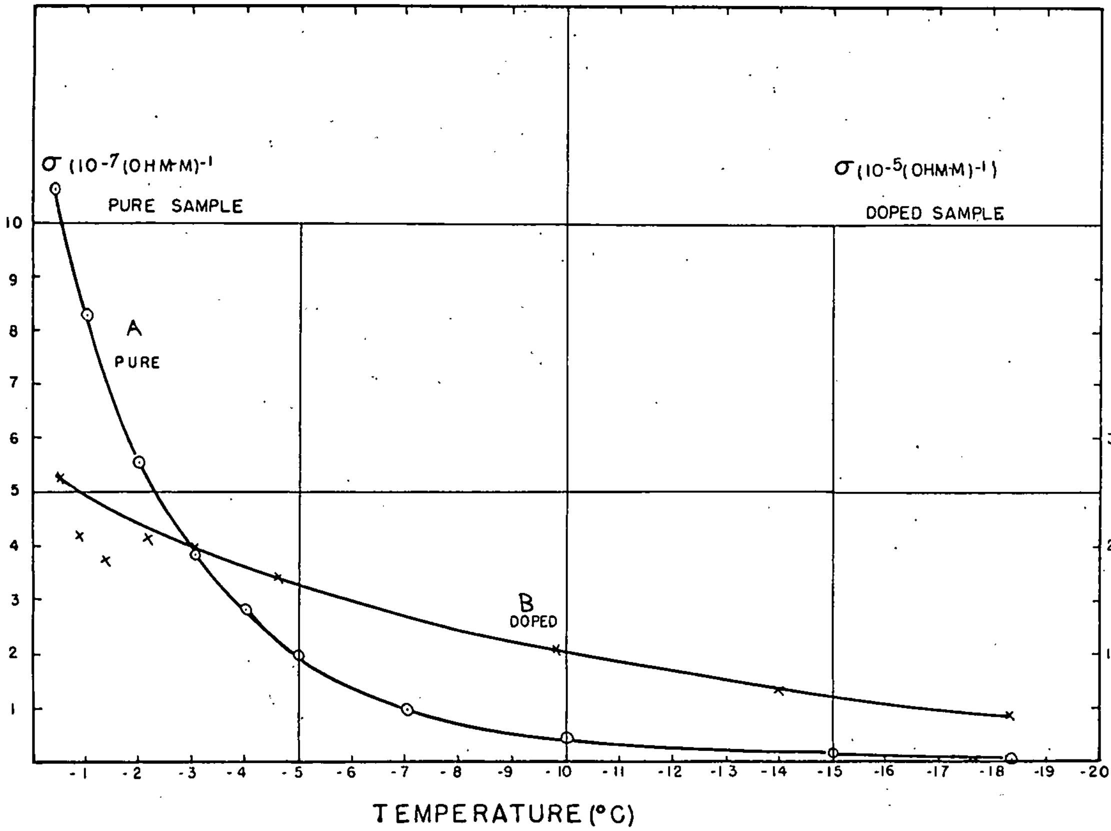
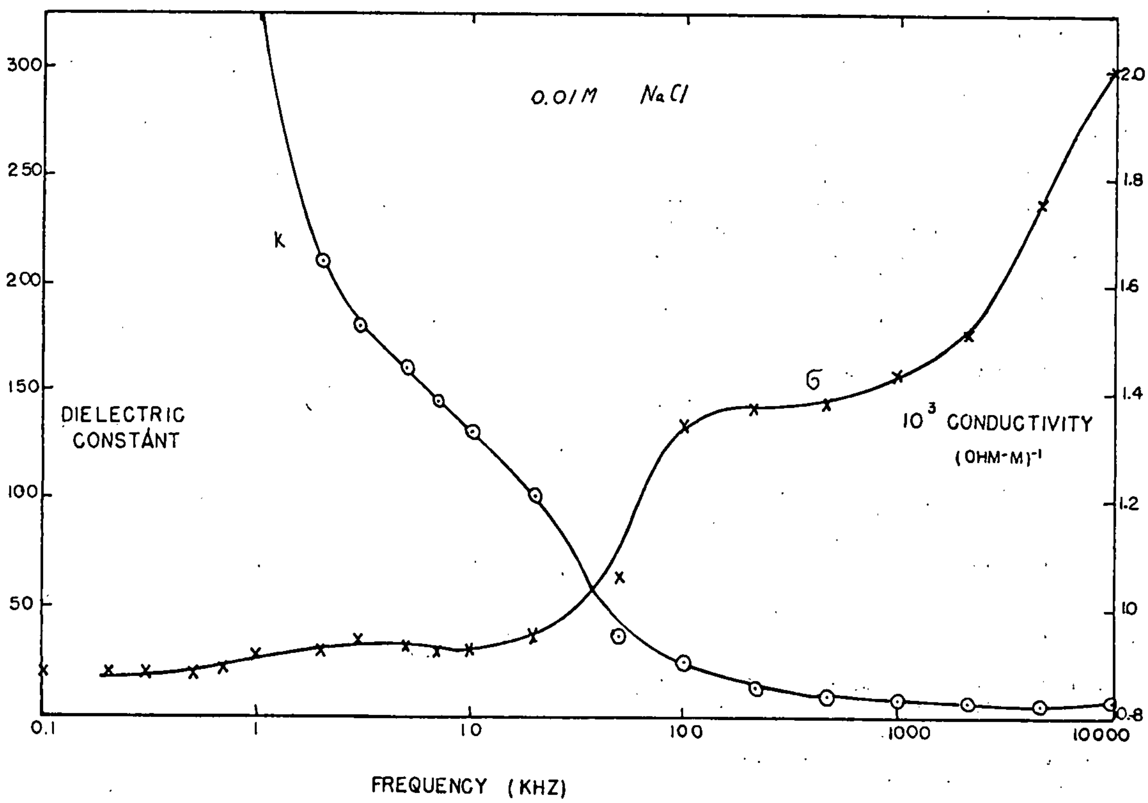


Figure 5. Frequency dependence of dielectric constant and conductivity of fine-grained ice grown from a .01 M NaCl solution (-1°C).



we find from equation 3 that at -1°C and 1 MHz, f_1 = 0.059. Similily at 10 MHz K = 5.08 and f_1 = 0.024. It follows that about 6% of the molecules can easily follow the field at 1 MHz and only about 2.4% at 10 MHz. From the previous analysis and the measured t of 0.4 mm for this sample, we conclude that the effective thickness of the grain boundaries in which the molecule can follow a 1 MHz field is about 12 μm and that for which they can follow the field at 10 MHz is about 5 μm. As might be expected, the grain boundaries comprise an inner core of very mobile molecules surrounded by layers of molecules which are successively more ice-like.

Similar measurements made on this sample at -14°C give a K at 1 MHz of 4.88 and a K very close to 3.2 at 10 MHz. Thus the core which is mobile at 10 MHz is too thin to resolve in this way (less than .3 μm) and that which responds at 1 MHz has a thickness δ = 3 μm.

The temperature dependence of the conductance and the capacitance of this sample was measured at a frequency of 1 MHz. From these measurements, the effective grain boundary thickness for this frequency was evaluated as above. The results are shown in Figure 6. Because the analysis at low temperature involves the differences of nearly equal numbers, the base-line error is large and we cannot say, at this stage, whether or not the thickness is characterized by a single activation energy.

Ice-Quartz Interface

A series of experiments has been conducted on thin films of ice sandwiched between quartz plates. The basic experimental cell is shown in Figure 7. The quartz plates are separated by platinum spacers to which the lead wires are connected. However, to ensure good contact to the ice regardless of thermal contraction as the temperature is lowered, the actual electrodes are very thin layers of tin evaporated onto the quartz. Thus the ice makes a lap joint to the actual contacts. The cell is guarded and placed in a temperature controlled chamber.

Sample Preparation

Sample lengths of 3 mm and 15 mm and thicknesses of 10 μm and 40 μm were used. All samples were 6 mm wide. The samples were prepared by cleaning the cells and leaching them in demineralized distilled water. They were then filled from the side with a medicine dropper, capillary action drawing the water in. After filling, they were cooled to 1 or 2 degrees below freezing and then nucleated from the side with an ice crystal. In this way, they grew with relatively large regions nearly single crystalline as revealed by examination in polarized light. The direction of the c-axis relative to the direction of the applied field was not known. Both a.c. and d.c. measurements were made on a number of samples.

Measurements on Thin Films

The a.c. measurements showed a low frequency capacitance characteristic of an electrode process falling monotonically to what was probably a stray capacitance of a few tenths of a picofarad at 100 KHz. The conductance rose monotonically with frequency but, because samples of this geometry do not lend themselves to a.c. measurement, we cannot clearly separate the part which is due to the electrode effect from that due to the ice surface. This sample geometry is primarily intended for d.c. or low frequency a.c. conductance measurements.

A typical value for conductivity at 100 KHz was 6 x 10^{-4}(ohm-m)$^{-1}$ at -18°C, dropping off to a nearly constant value of 10^{-4}(ohm-m)$^{-1}$ at 1 KHz. The high frequency value is about two orders of magnitude greater than that found for pure bulk ice. This indicates a substantial surface effect.

Direct current measurements showed conductivities at -18°C which varied from sample to sample. The highest was about 8 x 10^{-5}(ohm-m)$^{-1}$ and the lowest about 10^{-5}(ohm-m)$^{-1}$. This is expected because d.c. conductivity is extremely sensitive to trace impurities. For high purity ice, the d.c. conductivity of the bulk should be less than 10^{-8}(ohm-m)$^{-1}$ (Camp 1967, Von Hippel 1971).

Figure 8 shows the temperature dependence of the d.c. current (proportional to conductance) as a function of temperature for four samples of different geometries. Note that the values for the 3 mm by 10 μm sample (indicated by the symbol, ʘ), have been divided by four to make the curve shape comparison easier. All samples show a very sharp increase in conductance as the melting point is approached and a much slower decay at lower temperatures. The process is not a simple, thermally activated one and the range of temperatures accessible does not permit a resolution into two activated processes. However we can say that if there is a characteristic activation energy for the high temperature process, it is larger than 40 K-cal/mole. We find that the variation of sample length is in the right direction but that the variation with thickness is not consistent. This is what we would expect for a process in which the surface contribution was much larger than that of the bulk. Trace impurities would tend to segregate to the surface where they would have a large effect. Since thicker samples would contain more total impurity, they could easily have a larger surface conductance. From these thin-film experiments, we conclude that even for samples prepared under clean conditions, trace impurities are important and that the surface process dominates. There seems to be a very strong temperature effect close to the melting point. It is apparent that, for experiments with paving materials, much thicker ice layers can be used because of the impurities that will be present. This should simplify such measurements.

Conclusions

By electrical measurements, we have been able to show that the ice-ice interface comprises a core of molecules which are much more fluid than are those of the bulk ice. They are surrounded by molecules having less and less mobility as one progresses away from the core toward the ice. Thus the effective grain boundary thickness depends on the frequency at which it is measured. At the specific frequency at which the thickness is defined, most of the molecules within this thickness can rotate to follow the a.c. field. For pure ice, the grain boundaries are probably so thin even at -1°C that only molecules in a layer a few tens of monolayers thick are able to rotate at frequencies significantly above those of the bulk ice dispersion. Even trace impurities contribute significantly to the thickening of the grain boundary and with the deliberate addition of .01 M NaCl, the grain boundaries thicken to the order of micrometers. Typical values are reviewed in Table II. Under these conditions, it is possible to show how the thickness of the interfacial layer varies both

Figure 6. Grain boundary thickness vs. temperature for doped fine-grained ice.

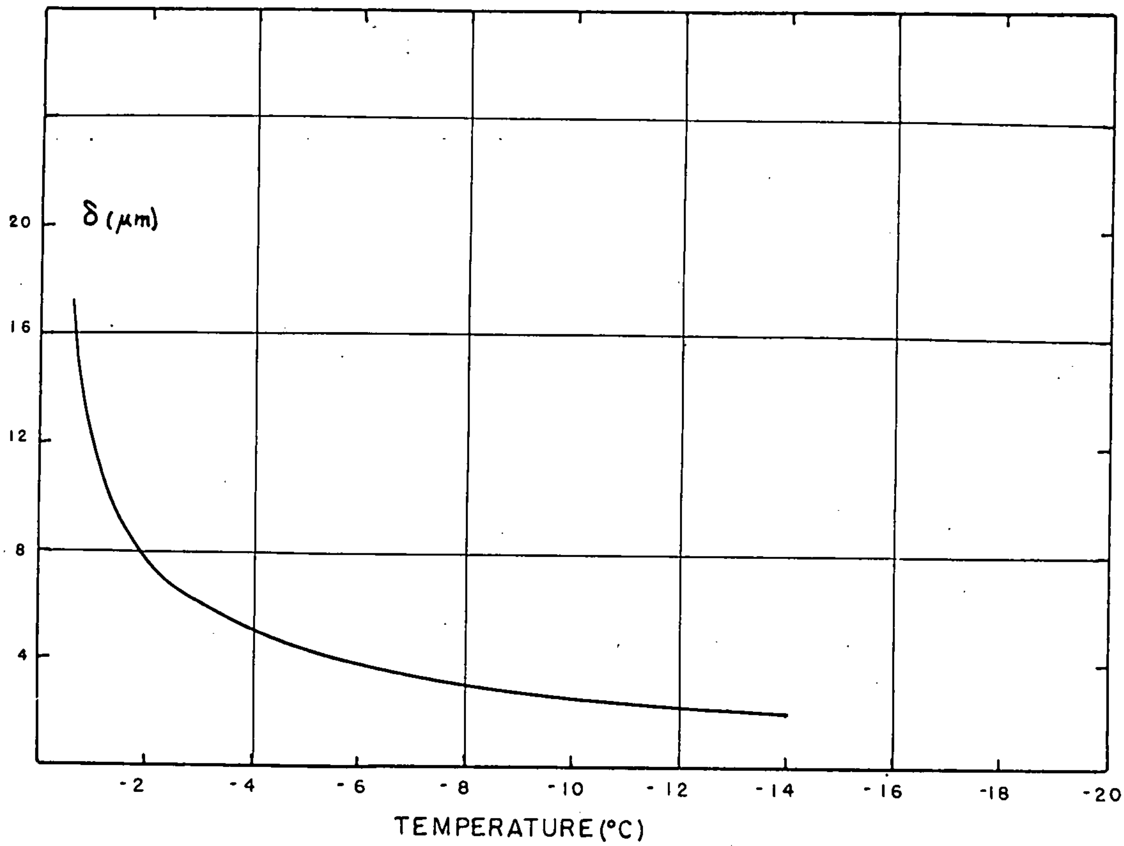


Figure 7. Cell and cell holder for thin film experiments.

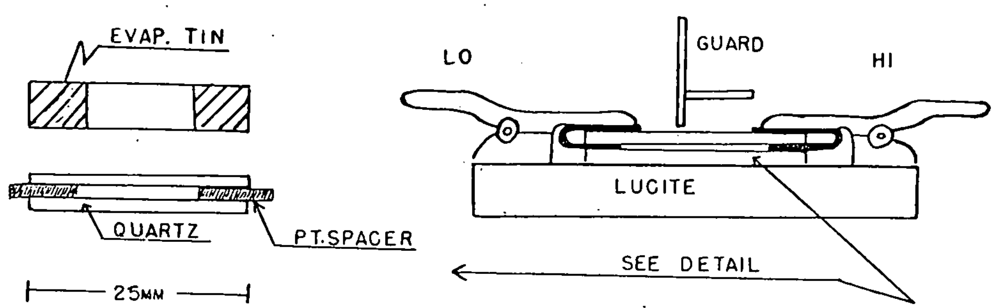
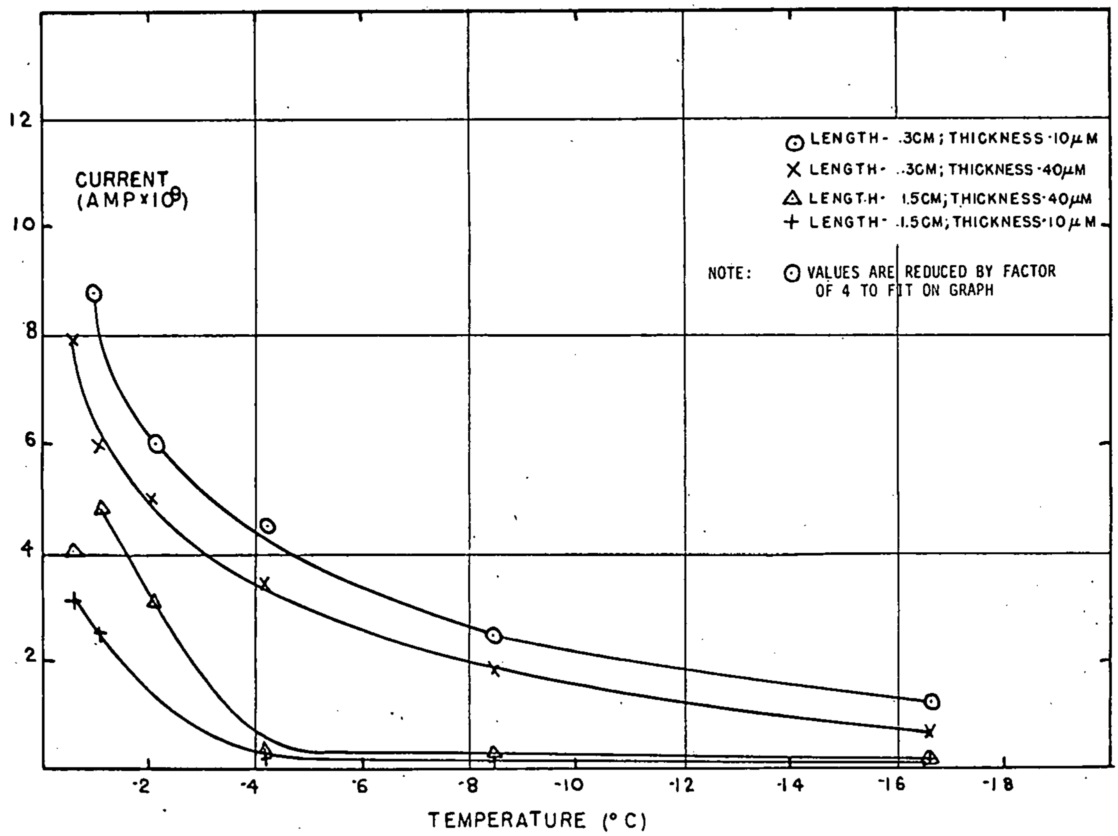


Figure 8. Temperature dependence of d.c. current for four thin film samples of different geometry with 3 volts applied.

⊙ length 3 mm, thickness 10μm, x length 3 mm, thickness 40μm,
+ length 15 mm, thickness 10μm, △ length 15 mm, thickness 40μm.



with temperature and with the frequency at which the measurements are made.

Table 2. Summary of Estimates of Grain Boundary Thickness.

SAMPLE	TYPE OF MEASUREMENT	EFFECTIVE GRAIN BOUNDARY THICKNESS -1°C	
Pure # 2	From High Frequency	δ (5 x 10^6) 100 Å (Order of Magnitude)	
Pure # 3	From Capacitance Data	δ (10^6) = 700 Å	
	From d.c. Compared to Doped	δ (d.c.) = 2400 Å (Order of Magnitude)	
Pure # 1	From Capacitance Data	δ (10^6) = 1000 Å	
		-1°C	-14°C
Doped	From Capacitance Data	δ (10^6) = 12 μm	3 μ
		δ (10^7) = 5 μm	0.3 μ

Unless otherwise noted, values are believed to be within a factor of 2.

Direct current measurements show the grain boundary conductance dropping off with decreasing temperature, but not as rapidly as does the grain boundary thickness. Perhaps this is due to the increasing concentration of ions as the grain boundary grows thinner. The d.c. conductance appears low for the salt concentration used, suggesting that the region in which ions are easily transported is much thinner than that in which dipole rotation at 1 MHz is easy, or that even in the grain boundaries significant rejection of impurities to the melt takes place.

Thin film experiments also show a strong temperature dependence of the conductivity of the surface region. They substantiate the importance of trace impurities and indicate that valid measurements can be made on practical (dirty) interfaces, such as paving materials, using fairly thick ice layers. This fact should greatly simplify such measurements.

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Numerical Simulation of Atmospheric Ice Accretion

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Time-dependence enters into calculations of ice accretion on objects primarily through terms dependent on the initial conditions and size and geometry of the object. A numerical technique to include the time-dependence is described here as well as simulation of complex situations where the conditions vary, for example, along a helicopter rotor blade. Some results of varying droplet sizes, velocity, and droplet distributions are presented. These indicate the general dependence of ice accretion on these parameters as well as illustrate the utility of numerical techniques in seeing how these effects can influence the rates of ice accretion for particular initial conditions.

In this paper, we point out those features in the governing relationships for ice accretion that require special treatment because they implicitly contain time dependence leading to feedback effects. We then show how the time-dependent formalism can be solved by using numerical methods to more correctly account for these feedback effects and include them in calculations of ice accretion on objects, given the atmospheric conditions and object parameters. The computer model is useful as a simulation tool to provide input for design purposes such as helicopter deicing design or structural applications such as power line or tower icing prediction, or as a research tool to examine the sensitivity of the icing process to variations in the input variables. These simulations may assist in the extension of limited laboratory and field testing, lending some generality to the understanding of ice accretion processes, and extension to applications where data are limited, for example, the case of power line icing in remote locations.

Physics of Ice Accretion

The primary sources of icing conditions are clouds and fog since the smaller droplets present in those configurations can sustain substantial supercooling over a wide temperature range. The six parameters necessary for quantifying the problem can be conveniently divided into three properties of the atmosphere (the ambient temperature T_o, the liquid water content lwc, and the droplet radius distribution R_{drop}) and three of the accreting object (its cross section diameter, 2a, velocity u, and shape, e.g. cylinder, airfoil, etc.).

If we move an object relative to a supercooled cloud, the rate of ice accretion depends on two factors. First, the icing rate depends on the kinematic interaction between the object and the droplets in the cloud. This relation determines whether particular droplet sizes are captured. Second, it depends on the thermodynamic processes at the object surface. Here, a balance is obtained between the rate of heat release necessary to freeze all or part of the impinging water and the rate at which heat can be carried away from the surface into the flow field by the processes of convection, evaporation, radiation, etc. We first consider the kinematic interaction.

In determining the interaction between the droplets and the flow field, we integrate the equation of motion for the droplet in the flow field. Following Brun (1), the assumptions for this formulation are: a) the streamlines determined for clear air are valid, i.e. the droplets are not sufficiently numerous to perturb the flow, b) gravity forces are significantly less than the inertial forces, so as to be neglected, c) the pressure forces on a droplet are equivalent to those on an equal volume of air at the same location, consequently they may also be neglected compared to the inertial forces because of the much greater density of water with respect to air.

Neglecting terms due to these factors, the motion of the droplet therefore results primarily from the inertial and viscous drag forces as it drifts with the fluid streamline. The drag force is proportional to the velocity and the drag coefficient, c_d, the droplet sees at any given time. Newton's second law in dimensionless form for the droplet, after Langmuir and Blodgett (2), therefore becomes, for the circular cylinder case:

$$k \frac{d\bar{u}_d}{dt} = \frac{c_d \, Re}{24} (\bar{u}_d - \bar{u}_o) \qquad (1)$$

Here $\bar{u}_d$ is the dimensionless velocity of the droplet at any point, $\bar{u}_o$ the dimensionless streamline velocity at the same point, Re the Reynolds number = $2 R_{drop} \rho_{air} \frac{(\bar{u}_d-\bar{u}_o)u}{\eta}$, c_d the drag coefficient, and k the inertial parameter (analogous to mass in dimensionless form) = $2 \rho_w R^2_{drop} \frac{u}{9\eta a}$.

The drag coefficient of a spherical drop, c_d, in general also exhibits a functional dependence on Reynolds number (3).

The calculation of droplet trajectories, therefore, involves considerable computation time since the equation of motion has to be integrated numerically with respect to time to fully assess the degree to which the droplet deviates from the fluid streamlines.

Langmuir and Blodgett (2) compile these computations into curves of the collection efficiency, E, as a function of two dimensionless parameters, each depending on the free-stream velocity, droplet radius, and cylinder radius. Collection efficiency is defined as the fraction of the distance from the centerline of the cylinder axis that a droplet can be and still be captured by the cylinder, i.e. the far field position of the droplet trajectory that is tangent to the cylinder (Fig. 1). It also refers to the fraction of the total possible droplets that is collected. Under natural conditions, there is usually a distribution of droplet sizes, so the computations become lengthy since an equation of motion has to be integrated separately for each size category. The total collection efficiency is then the sum of the collection efficiencies for each size times the fraction of the total lwc represented by that droplet size.

Time-Dependence in the Droplet Trajectories

The first of the time dependent effects that have not been treated in detail in earlier work is that of the droplet trajectories. As ice accretes on the front surface of the cylinder it is apparent that the cylinder cannot maintain its initial circular shape. The streamline characterized by the boundary of the object is, therefore, no longer the same as it was initially and the velocity field in other regions is proportionally distorted to maintain continuity. From equation 1, the change in velocity of the droplet depends on the streamline velocity in that location. The trajectory and velocity of a given droplet size will therefore be modified over the initial value prior to the ice accretion, thereby changing the collection efficiency, E, as ice accretes. This effect has not been included systematically before because of the length of the computations required to get the initial pre-icing values of the collection efficiency. With a digital computer of sufficient power, however, this effect can be taken into consideration as we show in a later section.

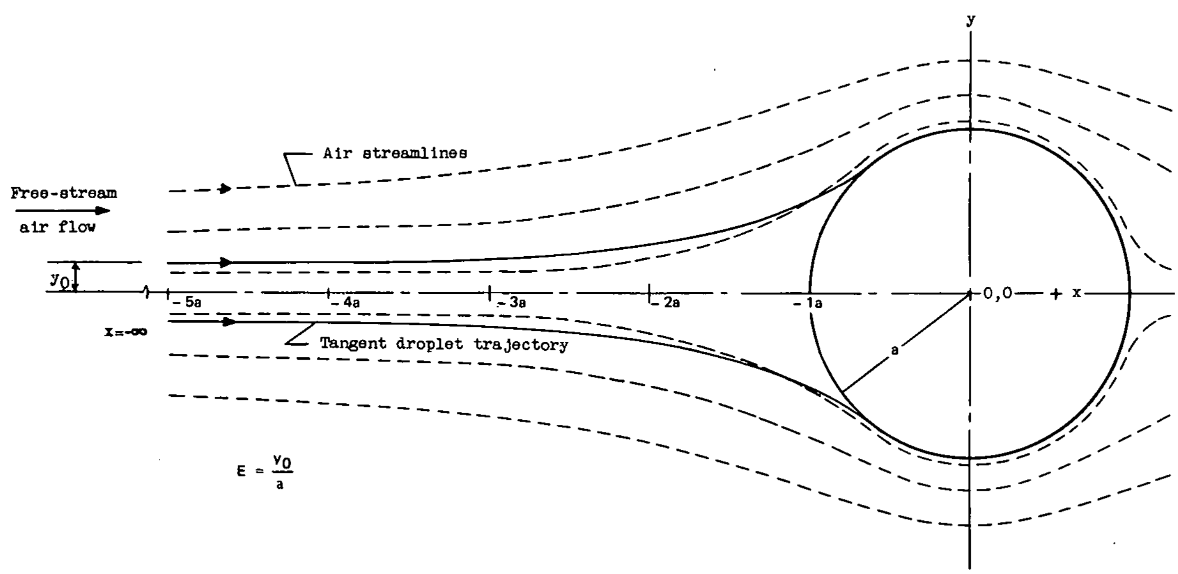
Thermodynamic Processes at the Object Surface

In general, the mass rate of water arriving at the object surface (per unit length) can be written as:

$$\dot{m} = E \text{ lwc } u \ (2a) \qquad (\frac{kg}{m\text{-}s}) \tag{2}$$

where E, the collection efficiency as described, depends on the velocity, droplet size, object cross-sectional diameter, and object's characteristic dimensions, lwc is the volumetric liquid water

Figure 1. Air streamlines and droplet trajectories with respect to a right circular cylinder. Collection efficiency $E=y_o/a$ where y_o is the initial far-field y location of the droplet trajectory that is just tangent to the cylinder and a is the radius of the cylinder.



content (kg/m^3), u is the free stream velocity (m/s), and 2a is the object cross section to the flow (m). However, the mass of ice accreted will not in general be equal to this quantity if heat transfer processes cannot adequately freeze all of the accreted water.

The heat transfer controlled by the properties of the flow is taken as the sum of the convective and evaporative fluxes, and the aerodynamic heating of the incoming air (1):

$$q_{surf} = -H\left[(T-T_o) - \frac{Ru_o^2}{2c_{p\ air}} + \frac{.6L_o}{pc_{p\ air}}(E'-E_o)\right] \quad (3)$$

New terms are H, the convective heat transfer coefficient, R, the surface recovery factor, $c_{p\ air}$, the heat capacity of air, L_o, the latent heat of water vaporization, E', the vapor pressure of water at surface temperature T, E_o, the vapor pressure of water at the ambient temperature T_o, and p, the atmospheric pressure. The factor $\frac{.6}{p}$ converts the mass flux from weights of water vapor to the more convenient vapor pressure form and uses the relationship of latent and sensible heat transfer coefficients of $\frac{H_m}{H} \approx \frac{F(Le)}{c_{p\ air}}$ where F(Le), a function of the Lewis number Le (ratio of the diffusion coefficient to thermal diffusivity), is approximately 1. Therefore,

$H_m \approx \frac{H}{c_{p\ air}}$, as indicated in equation 3.

The total heat balance at the blade surface between the flow and that given up by the incoming droplets is shown schematically in Figure 2. Three cases of surface temperature define specific terms related to the droplets' heat transfer terms: 1) T>0°C, 2) T = 0°C, 3) T<0°C.

Case 1. T>0°C. In this case, the heat flux is due to the temperature difference between the collected water and the droplet temperature in the flow plus the conversion of the droplet kinetic energy into heat. No ice is accreted if the surface temperature T>0.

Case 2. T = 0. In this case, a fraction F of the accreted water is converted to ice, adding the latent heat of fusion (L) to the heat flux.

Case 3. T<0. Here all the accreted water is frozen as ice, and a second additional term is added to account for the difference in specific heat between the incoming water and resulting ice at temperature T. The heat balance as shown schematically in Figure 2, after Messinger (4), can be taken for any of the three cases, and the residual heat, ΔQ, can then be used to modify the surface temperature by

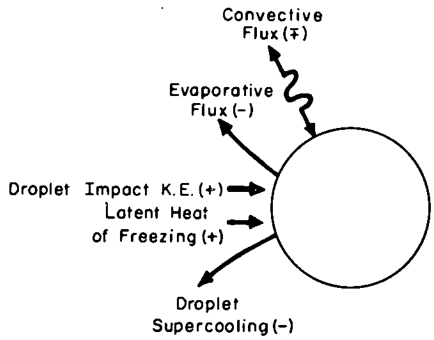
$$T_{new} = \frac{(T\ c_{pm\cdot blade} + \Delta Q)}{c_{pm\cdot blade}} \quad (4)$$

Here,

$$c_{p\ m\cdot blade} = c_{(pm\cdot blade)_o} + m\cdot F\cdot c_{p\ ice} \quad (5)$$

i.e. the heat capacity of the object (blade) plus the heat capacity of any accreted ice. The new temperature T_{new} can then be checked to see if it is above or below 0°C and the appropriate terms in the heat balance selected. In going across 0°C, the appropriate balance is chosen based on the value of the accreted ice fraction F. F must lie within the range 0≤F≤1 in order for the T = 0 thermodynamics to be chosen.

Figure 2. Schematic indicating the five terms and in the heat balance and whether they are carrying heat toward (+) or away (-) from the freezing surface. Convective flux usually takes heat away from the surface (-) but at high velocities adiabatic compression of the flow dominates and the convective heat flux is then given positive towards the surface.



Time Dependence in the Thermodynamics

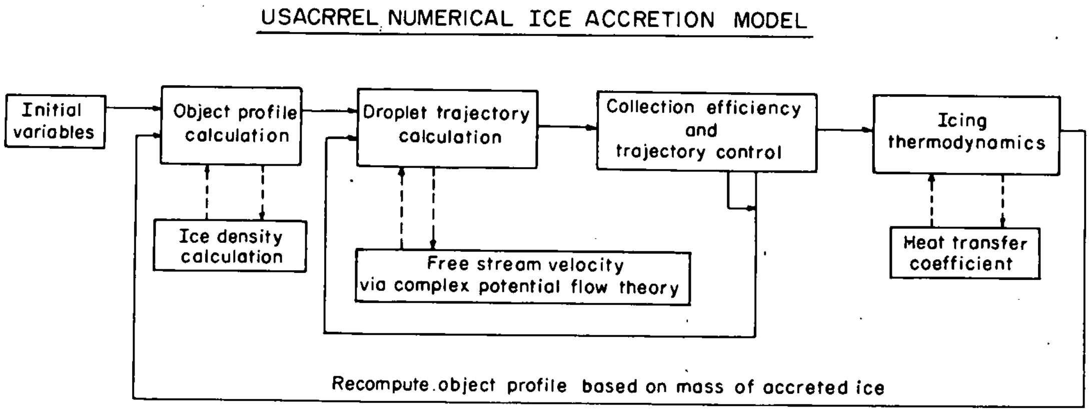
As with the droplet trajectories, the time dependence of the thermodynamics associated with ice accretion results from the distortion of the object's size and shape as ice accretes. The mass rate of water collected contains this dependence in the collection efficiency term which changes as the flow field responds to the increasing accretion. The heat flux from the surface into the flow varies with the change in heat transfer coefficient which in turn varies through the changes in surface area and shape with time as well as with the mass rate terms. In general, then, the correct form of the equations exhibits significant time-dependence. A scheme to update the time-dependent parameters as ice accretion proceeds is described next.

Numerical Ice Accretion Model

In a first attempt to include time-dependence and its subsequent effects on later ice accretion, a numerical model of the ice accretion processes described has been programmed on a digital computer. The model is programmed in the language BASIC on the Dartmouth Time Sharing System (DTSS), which uses a Honeywell 66/40 computer. Hook-up is through an acoustic coupler connected by telephone line to the computer. The model includes software using DTSS subroutines for graphical display of the results using a Tektronix Model 4013 CRT display. A more extensive description of the program and its underlying physics is given in (5).

Figure 3, a block diagram of the numerical model, indicates how the time dependence is accounted for by the loops indicated by the various arrows. The major one is the recomputation of the object profile after ice accretes, based on the mass of accreted ice. The new profile is then used to update the flow field and determines

Figure 3. Block diagram of the numerical model for calculating ice accretion. Each block represents a subroutine of the program.



changes, for example, in the collection efficiency, E, and heat transfer coefficient, H, for the next timestep.

Figure 4 shows the subroutine for the icing thermodynamics. This routine takes the output of the collection efficiency routine and the initial variables to compute the mass of ice accreted based on the thermodynamic balance. The temperature of the object surface is initialized in the control program at the recovery temperature of a non-icing flow at the same velocity.

The model proceeds through the icing thermodynamics based on the pseudo steady-state temperature hypothesis--i.e. over a small enough increment of time, the temperature of the object does not change. So, before the thermodynamic balance is initiated, the heat transfer coefficient is calculated using the current value of the surface temperature. Then, based on the current surface temperature, it branches to the appropriate thermodynamic expression. The complete thermodynamic balance yields the new surface temperature, or new ice fraction accreted, if in the $T = 0°C$ temperature regime. Of course, care must be taken to maintain physical as well as thermodynamic continuity as the temperature proceeds through the limits of each thermodynamic argument. The program naturally checks for errors in continuity and redirects execution at the appropriate level.

At the end of the icing thermodynamics, the output is given as new ice mass, total heat capacity, and surface temperature. After several iterations of the thermodynamics, the new total ice mass is fed back to the object profile calculation (Fig. 3) to recompute the object size, flow field characteristics, and surface area for the next time period of the calculation.

Helicopters flying in icing conditions have presented a continuing problem since they normally operate at altitudes where icing conditions occur more often. They also have the interesting characteristic that the linear velocity of the rotating blade varies over a large range, from essentially near zero in the hub region to nearly sonic velocities at the blade tip. This is given by

$$v_i = R_i \omega \tag{6}$$

where v_i is the velocity of the segment, R_i the distance from the rotor hub and ω the angular velocity of the rotor. Interest in how these changing conditions influence ice accretion processes was a continuing impetus in the development of this numerical scheme. Two options to include the velocity variability were therefore built into the program.

The first of these selects specific values of the velocities (or equivalently, position along the rotor) and computes the ice mass and profile changes as a function of time. Figure 5 shows such a calculation for a velocity of 10 m/s and initial conditions of 1.43 g/m^3 lwc, droplet radius of 45 μm and T_a= -17.7°C. Any number of velocities can be selected, allowing details of the ice accretion process to be seen, such as the time-dependence of the collection efficiency or heat transfer. The heavy black line is the tangent trajectory used to compute the collection efficiency for this case. The figure is illustrative of the three main time intervals of the calculation. The spacing of the dots in the temperature plot indicates the time period (2 s) that we take for the pseudo steady-state heat balance, i.e. in the 2-s time interval it is assumed the thermodynamic properties of the system do not change significantly. After 25 repetitions of the thermodynamic balance with successive updates of the heat flux, the profile dimensions are sufficiently changed to then require the updating of the collection efficiency, ice mass and profile shape characteristics. The time periods of these are 50 s and are indicated by the hacks on the time scale. The changes in the profile dimensions indicated on the figure take place at these intervals. The third interval is the total time of the calculation, indicated by the full length of the time scale (300 s). Programming mechanics dictate that these times be integer multiples of the smallest value. However, they can be modified within this constraint.

The second display option is shown in Figure 6. Here the quantities final surface temperature, leading edge (maximum) ice thickness, and variations of collection efficiency and fraction of collected water accreted as ice are given as a function of velocity along the blade from 0 m/s to 250 m/s. The program computes and stores the heat balance, ice thickness, and collection efficiency for each 10-m/s velocity interval for a period of 300 s and steps to the next velocity value. At the end of the 25 values (0 to 250 m/s in 10-m/s intervals), the information saved at the end of each calculational step is then displayed. Straight lines are drawn between the points to complete the

Figure 4. Subroutine THERMO calculates mass of water arriving and converted into ice or shed as unfrozen water if (>0°C).

Icing thermodynamics
[THERMO]

1 Calculate the ambient water vapor pressure (E_0)
Smithsonian Meteorological Tables, 1951

2 Call: subprogram HTTRANS1 for calculating heat transfer coefficient
[watts/°C (meter of blade/2) sec]

3 Calculate mass of water collected/meter of blade · sec

$$m = E \cdot lwc \cdot u \cdot b$$

4 $T < 0$, $T = 0$, $T > 0$ — branch to appropriate thermodynamics (see E.A. Brun, 1957)

[initially, $T = T_0 + \frac{u_0^2}{2000}$ i.e. recovery temp]

5 $T > 0$ what is Q?

a) $$Q = -H\left[T - T_0 - \frac{Ru_0^2}{2c_{p\,air}} + .6\,L_0(E' - E_0)/p\,c_{p\,air}\right] - m\,c_{pH_2O}\left(T - T_0 - \frac{u_0^2}{2c_{pH_2O}}\right)$$

R = surface recovery factor
L_0 = latent heat of vaporization of water @ 0°C
E' = vapor pressure of water at surface temperature

b) Calculate new T

$$T = (T\,c_{pm\,blade} + Q)/c_{pm\,blade}$$

c) Is T still above 0°C? No
** end THERMO **

6 $T = 0$

a) $$Q = -H\left[-T_0 - \frac{Ru_0^2}{2c_{p\,air}} + .6\,L_0(E' - E_0)/p\,c_{p\,air}\right] - m\,c_{pH_2O}\left(-T_0 - \frac{FL}{c_{pH_2O}} - \frac{u_0^2}{2c_{pH_2O}}\right)$$

F = fraction of collected water accreted as ice
L = latent heat of freezing

b) $F = F - Q/Lm$

c) is $F > 0$ Temperature above 0°C No

d) is $F < 1$ Temperature goes below 0°C No

e) $c_{p\,m\,blade} = c_{p\,m\,blade} + m\,F\,c_{p\,ice}$

** end THERMO **

7 $T < 0$

a) $$Q = -H\left[T - T_0 - \frac{Ru_0^2}{2c_{p\,air}} + .6L_0(E' - E_0)/p\,c_{p\,air}\right] - m\,c_{pH_2O}\left(T\frac{c_{pice}}{c_{pH_2O}} - T_0 - \frac{L}{c_{pH_2O}} - \frac{u_0^2}{2c_{pH_2O}}\right)$$

b) $T = (T\,c_{pm\,blade} + Q)/c_{pm\,blade}$

c) $c_{p\,m\,blade} = c_{p\,m\,blade} + m\,c_{pice}$

SUBEND

curves as shown. In addition, the lowest plot shows the percentage of the accreted water that is frozen into ice. As shown for this particular plot, the fraction accreted and frozen drops below 100% at the point where the surface temperature goes to 0°C as the thermodynamic equations would indicate.

Results

In this section, we give some examples of the effects introduced by including the time-dependence as formulated previously. First, the effects of including collection efficiency feedback and a distribution of droplet sizes are shown in Figure 7.

Here the amount of ice accreted as time proceeds is plotted for the initial conditions of lwc = 1.08 g/m^3, initial ambient air temperature = -5.5°C, and velocity = 60 m/s. The droplet distribution selected is a Gaussian with six classes. The mean radius is 17 μm and the droplet radius standard deviation is 8 μm about the mean. As shown by the inset table listing the lwc amounts by droplet size, very little of the total water available is partitioned into the lower droplet

Figure 5. (Top) The change in profile dimension at 50-s intervals by ice accretion is indicated by the profile shapes on the initial half cylinder. The black line coming from the right is the tangent trajectory at the beginning (top of the black line) and end (bottom of the black line) of the icing period of 300 s. (Bottom) The surface temperature of the front half cylinder as a function of time is plotted. As seen, the surface temperature reaches an equilibrium value within about 30 s after the icing starts.

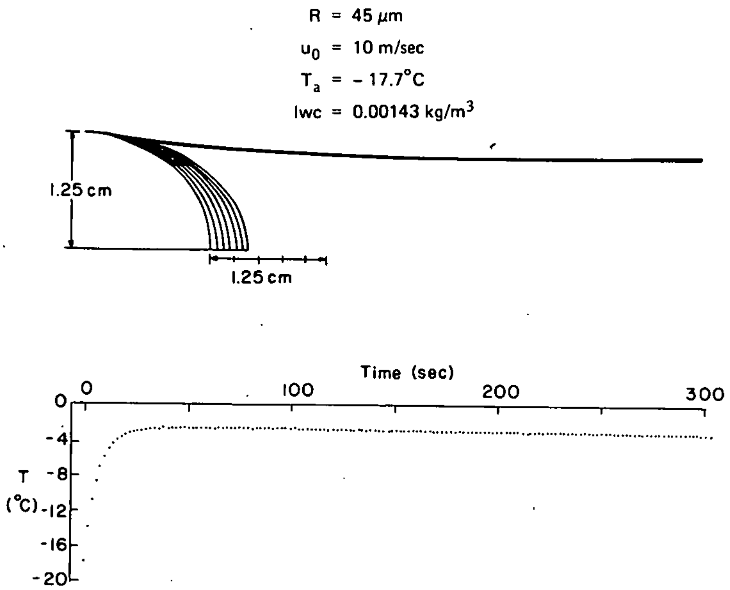


Figure 6. Numerical simulation of helicopter rotor blade icing showing the surface temperature, leading edge ice thickness, collection efficiency and fraction accreted (as ice) as a function of velocity for the initial conditions as shown. The maximum ice thickness occurs when heat transfer conditions optimize with amount of accreted water (equation 6) to form the most ice.

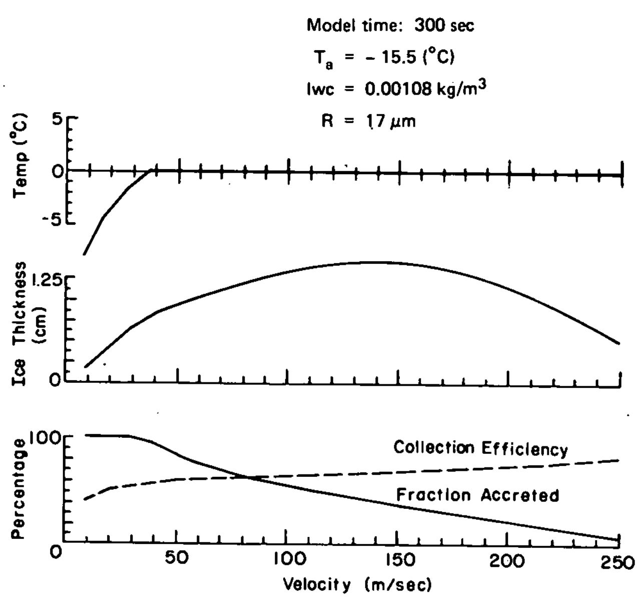
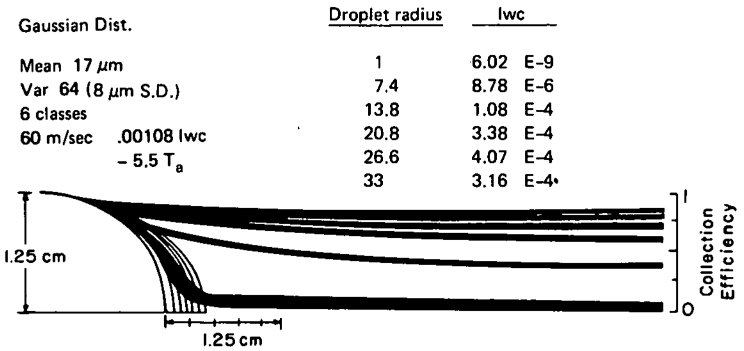


Figure 7. Droplet trajectories and ice profile changes for a Gaussian droplet size distribution. Droplet sizes and respective liquid water contents are given in the inset; collection efficiencies for the various droplet categories and their changes with profile dimension changes are given on the right hand scale. Profile ice thickness changes are shown at 50-s intervals. Thermodynamic conditions for this simulation are such that the surface temperature was at 0°C (equilibrium) and some accreted water was not frozen.



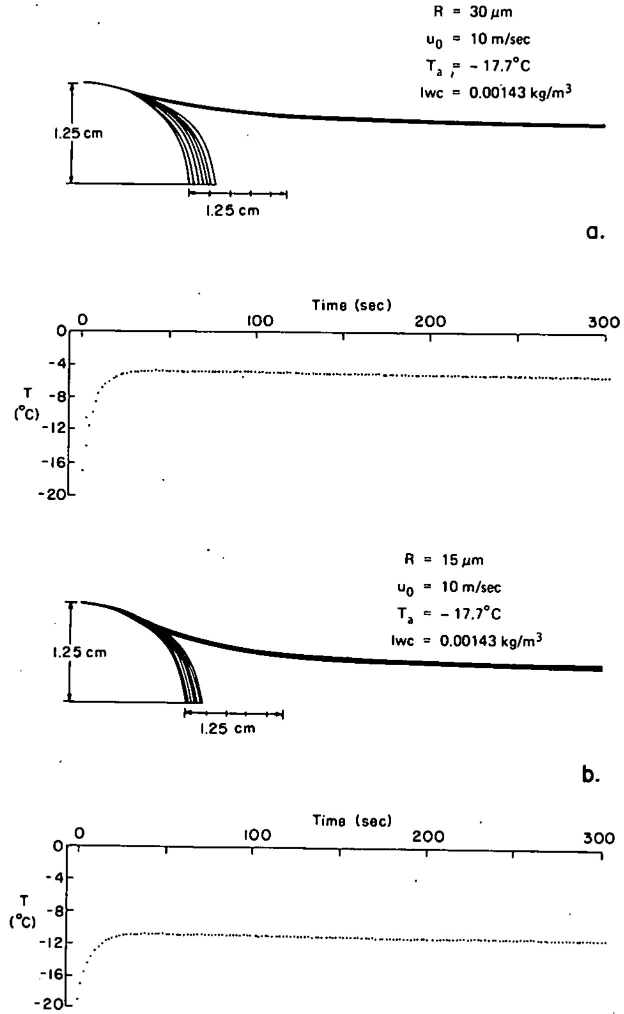
sizes (for the two lowest droplet sizes the lwc is two to three orders of magnitude lower than for any of the four highest classes). Referring to the profile plots, the dark lines originating at the right refer to the collection efficiency and its changes with time and droplet size as shown. The thickness of these lines results from "overprinting" on the display screen so the top of the line for any droplet class is the tangent trajectory that, when scaled to the object radius, gives the initial value of collection efficiency for that class (scale at right). The bottom of each thick line is the final collection efficiency value after 300 s of ice accretion has taken place. For the highest droplet sizes (>20.2 µm) the collection efficiencies are generally 0.75 or above for this velocity. The collection efficiency drops markedly for sizes below 20 µm and the decrease in collection efficiency with ice accretion (given by the distance between the top and bottom trajectories or thickness of each line) is also greater for the smaller droplets. The ice accretion rate does not change dramatically since 90% of the liquid water is concentrated in the top three droplet classes. The collection efficiencies for these vary by the smallest amounts (∿3 to 5%) at this velocity and object radius so the rate of ice thickness change is not substantial for the time period of this simulation. It is seen from this plot that a lowering of the mean droplet size, such that a significant shift occurs in the amount of lwc available in small droplets (< 14 µm radius), would substantially change the ice accretion rate. The collection efficiency and its change with object profile are both more markedly affected at the lower droplet sizes, for example, the collection efficiency of the 1-µm category decreases from 15% to 6%, a 60% change with object profile change.

We illustrate this further in Figure 8, where two profiles are shown for the same conditions except that the droplet size is given as 30 µm (a) and half that, 15 µm (b). From this figure we see that the total centerline ice thickness is reduced by 40% by changing the droplet radius, even though the ambient temperature and liquid water content are the same for both cases. Similarly, the calculated surface temperature is higher for the larger droplet size since more latent heat is liberated per unit time, increasing the heat flux to the object surface and increasing its temperature.

In Figure 9, we compare and discuss a simulation with experimental data to indicate both the general validity of the model and some specific differences that require more experimentation and better model parameterization. This figure, in the ice thickness distribution portion, shows the simulated and experimental results. The experimental arrangement is more fully described in Ackley et al. (7). Briefly, the measurements were taken from a rotating cylinder system at 3600 rpm in a coldroom at the ambient temperature shown. Water of the mean droplet size and lwc indicated was sprayed onto the rotor. Comparing the two ice thickness curves it is seen that the simulated ice thickness somewhat underestimated the experimental accumulation but is reasonable within the constraints imposed by both the assumptions in the simulation (e.g. one droplet size at the mean experimental value) and the errors in measurement in the experiment on both droplet size and lwc (∿25%). In the experiment, analysis of the ice properties showed a grain size change indicating a transition in surface temperature from below 0°C to 0°C in the vicinity of the blade where the linear velocity was 20 m/s. As shown by the calculated temperature distribution (top of Figure 9) the calculated rise to 0°C takes place in about the same velocity region. This agreement would indicate that the simulated heat transfer and thermodynamic relations are approximately compatible with the experimental measurements.

A difference between the two is the location of the maximum ice thickness in the experimental data when the simulation indicates the ice thickness should be increasing all the way to the tip of the experimental rotor (v ∿ 100 m/s) for this set of conditions. Other experiments indicate, however, the maximum position may possibly be controlled by a flow field perturbation induced by the blunt end of the cylindrical rotor. We plan further experiments at different rotation rates (i.e. changing the velocity distribution without changing the physical dimensions of the rotor) to see if this effect is modified and in what way. At this time, therefore, we assign no particular significance to the position of the thickness maximum differing between the experiments and the simulation until further experimental results are available that can test the possible end effects of the rotor tip.

Figure 8. Accreted ice thickness and temperature for ambient conditions indicated. The profile updates occur at 50-s intervals. The difference in accreted ice thickness for the two cases (a) and (b) occurs because of the change in collection efficiency for the droplet sizes 30 μm (a) and 15 μm (b).



In Figure 10 the relative contributions of the thermodynamic terms from the accretion shown in Figure 6 are shown. The heat balance requires the algebraic sum of the positive and negative contributions to the heat flux to equal zero as long as ice is accreting. If the balance goes positive, then the excess heat is taken up by a rise in surface temperature. At velocities below 50 m/s, Figure 10 shows the convective flux dominates, contributing about 50% of the necessary heat flux to freeze the accreted water with smaller and nearly equal contributions from droplet supercooling and evaporative heat flux of ∿ 25% each. At about 80 m/s, the convective flux is at its maximum negative value and it then becomes less negative with increasing velocity because of the contribution to this flux by adiabatic compressional heating of the flow, $\frac{Ru_o^2}{2\,c_{p\,air}}$ (Figure 4). Above 80 m/s, an additional positive term, the kinetic energy imparted by droplet impact, also becomes significant. The increasing positive contribution of these terms causes the latent heat of freezing to reach its maximum, since the other terms, the evaporative

Figure 9. Comparison between experimental data (ambient conditions inset) and model simulation of the same conditions. Agreement is reasonable considering experimental errors in lwc (∿ 25%) and use of a single droplet size (mean experimental size) in the simulation compared to a distribution in the experiment.

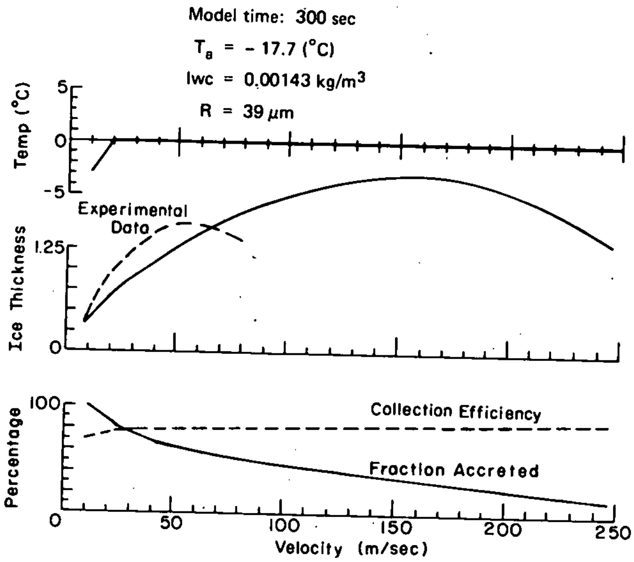
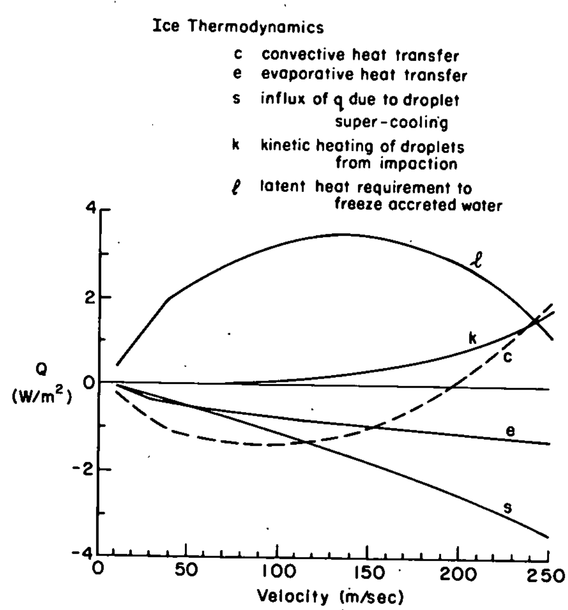


Figure 10. Magnitude of the individual thermodynamic terms as a function of velocity for the simulation shown in Figure 6. The terms are defined in Figure 4.



and supercooling influx, decrease more slowly with velocity than the positive terms are increasing. The maximum available latent heat requirement corresponds to the maximum ice thickness at 140 m/s. At the maximum ice thickness, the heat necessary to freeze the accreted ice is about 45% from droplet supercooling, 25% from evaporative flux and 30% from convective flux. Kinetic energy of the droplets consumes about 7% of the heat at this point, the remainder being balanced by the latent heat of freezing. No heat is available for freezing from convective flux above 200 m/s due to the heating effects of adiabatic compression. At about 240 m/s, the kinetic energy of droplet impact, the now positive convective flux, and the latent heat of freezing all consume equal amounts of the negative flux available from evaporative flux and droplet supercooling for this set of initial conditions.

Conclusions and Future Studies

As pointed out earlier, one important result of numerical methods is a more accurate comparison of theory with experimental results by including time dependence in a measurable way. These comparisons can provide more confidence in simulation of conditions that are not experimentally known. For example, it is clear from Figures 7 and 8 that a change in either mean droplet size or in the distribution such that large numbers of small droplets dominate the liquid water content can radically change the amount of ice accreted. Using the results of ground icing sprayers with large droplet sizes to test for cloud conditions may therefore be highly inaccurate. The change of collection efficiency with time as mass accretes is also a complex function of the initial conditions more strongly affected by droplet sizes, and the numerical solution graphically portrays how these conditions can affect the ice buildup.

In a situation such as a helicopter rotor blade, the thermodynamics determining the ice buildup at any particular linear velocity can show wide variability in which terms dominate, so a numerical solution and graphic display can provide a convenient method of seeing this variability. For design purposes, additional terms (for example, increasing the heat flux to the blade surface by electrical heating) can be evaluated to determine whether particular icing conditions would be relieved or unaffected by the extra heat flux. An optimization procedure could then be used with statistics on meteorological conditions to evaluate the likelihood of the design change significantly increasing the chances for successful operation.

At present, within the data limitations that have been used for its formulation, the model offers a significant method of evaluating time-dependence (or independence) of the various parameters that influence the icing process. With this information, extension to engineering design may be facilitated by easy access to a number of simulated "case histories" applying to aircraft icing or ground-based structural problems. For example, total icing loads on a structure with a variety of different shaped and sized struts can be computed by breaking the structure down geometrically, treating each shape individually, and summing up the individual loads into the total for the structure.

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Preliminary Assessment of an Ice Accretion System

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Climatic chamber tests of an off-the-shelf ice detection system manufactured by Rosemount Engineering Company were conducted at the Armament Development and Test Center, Eglin AFB, Florida. The purpose of the tests was to determine the feasibility of taking objective observations of ice accretion near the earth's surface. Data was collected for a variety of wind, temperature, and precipitation conditions which simulate natural icing. This paper presents the preliminary results of the tests.

Ice accretion can be a major destructive force to structures, such as towers, radar, elevated cables, etc. Concurrent, or more probably subsequent strong winds may be the critical factor in damaging equipment loaded with ice. Despite this, routine objective observations of ice accretion at the earth's surface have not been made by any national weather service.

Ice accretion studies have been carried out by independent organizations such as power and telephone companies. However, these have been limited in scope and geographic applicability. Many researchers (1, 2, 3), to name a few, have assimilated the available material on ice accretion and attempted to delineate the ice accretion hazard. Other researchers, (4, 5, 6, 7) have attempted to relate ice accretion to readily available climatological data. Unfortunately, current information is limited, and, in many instances subjective; consequently, these studies fall short of providing accurate and consistent design criteria.

The bulk of the work on ice accretion explores the theoretical relationships between ice formation and the parameters affecting its rate of accumulation, density, shape, etc. (e.g. 8, 9). These relationships are important to a complete understanding of ice accretion processes. They are, however, based on ideal steady state atmospheric conditions and are of limited use in calculating a realistic magnitude of ice accretion in the turbulent natural environment.

The methods used to measure ice accretion in the natural environment have been varied. The most objective measurements have been made using a cable suspended between two poles with a weight measuring device, or tensionometer, between one of the poles and the cable. This method has been used to collect data in the Soviet Union, (10). The Bonneville Power Administration, Portland, Oregon has many years of this type of data taken in mountain locations in the northwestern United States. Two shortcomings of this instrumentation that preclude its use at most observing sites are its size and its orientation which results in ice amounts being a function of the wind direction.

Due to the importance of ice accretion design criteria for exposed AF systems, the Air Force Geophysics Laboratory funded research to test the feasibility of taking objective observations of ice accretion using a sophisticated ice detection system marketed by Rosemount Engineering Company.

The Rosemount Ice Detection System

The Rosemount Engineering Company, Minneapolis, Minnesota markets a line of ice detectors which are used primarily to detect ice formation in the intake portion of turbomachinery. They are aerodynamically designed for use on aircraft, but they have been used to detect icing on towers.

The ice detector works by the magnetostriction principle. An oscillator forces a small closed cylinder (the sensing probe) to vibrate longitudinally, parallel to its axis. It is driven at its resonant frequency when dry, but accretion of ice will cause a shift in resonance corresponding to the increase in mass on the probe. After a small preset amount of ice has accumulated, the sensor is deiced.

Hill (11) and Chaine (12) conducted tests on Rosemount ice detectors in the natural environment. These tests indicated that the instruments operated satisfactorily. However, they did not determine whether they could be used to measure mass and thickness of accumulated ice.

The advantages of using a Rosemount ice detector to observe ice accretion, convenient size, durability, and the ability to perform with limited human involvement, are quite attractive compared to other methods and devices that have been tried. We decided that if the Rosemount detector were tested under controlled conditions in a climatic chamber, we could evaluate its ability to measure ice accretion.

Accordingly, four model 872DC ice detectors, a newer model than the ones tested previously were purchased from Rosemount. The main reason for choosing this model is the long strut, as can be seen in Figure 1. It was also necessary to purchase a model number 524H controller, which is kept remote from the detectors, to actuate the deicing system. An event recorder was used to count deicing cycles.

The Ice Accretion Tests

Testing of the ice detection system is being carried out in the climatic chamber at the Armament Development and Test Center (ADTC), Eglin AFB, Florida. Preliminary tests were conducted during two 3-week periods in April-May 1977 and January-February 1978.

Our goal was to evaluate how accurately the Rosemount system could determine ice accretion amounts on small simulated structural components. During the first test period, cylinders with four different diameters up to 50.8 mm (2 inches), in both the vertical and horizontal mode, were mounted in close proximity to three Rosemount ice detectors. Vertical and horizontal flat plates were also placed in the test area. One-hour tests were run for wind speeds of 5 to 35 knots, temperatures of -1°C to -7°C, freezing rainfall rates of 1.27 and 5.08 mm (0.05 and 0.20 inches) hr^{-1}, and 0.2g m^{-3} water content for freezing cloud/fog conditions.

Early in the testing, all three Rosemount 872DC detectors broke down due to overheating during the deice cycle. These were returned to Rosemount for repair, and we were loaned three model 871FA detectors. The major difference between these models is the length and shape of the strut on which the sensor is mounted. The detectors were set to deice with 0.5 mm (0.02 inches) of ice on the sensor.

For the second test period, two 872DC detectors and one 871FA detector were used. One-hour tests were run for wind speeds of calm to 35 knots, temperatures of -1°C to -10°C, freezing rain rates of 1.27 and 2.54 mm (0.05 and 0.10 inches) hr^{-1}, and 0.1 and 0.2g m^{-3} water content for freezing cloud/fog conditions. Additional, longer duration tests, some with varying conditions, were also run.

Test Results and Analysis

A. The April-May 1977 Tests

The initial tests were conducted in one of the climatic chambers at ADTC, with floor dimensions of 9.1 x 39.6 m (30 x 130 ft). A total of 39 1-hr tests were run. Measurements made on the simulated structural members included ice thickness, the mass of the ice on three removable cylinders, and the ice density using a rotating cylinder 3.2 mm (1/8 inch) in diameter. Figure 2 shows the arrangement on the test stand. The linear least squares regression of the ice thickness on the 25.4 mm (1-inch) cylinder versus the number of instrument cycles for the 39 test points is shown in Figure 3. Although the correlation of .915 is quite good, the standard error of the ice thickness, about 4 mm, is fairly high.

The first round of testing involved several problems which limited our capability to evaluate the Rosemount detectors. The most important of these were: (1) the strut on which the sensor is located was not long enough to keep accumulated ice on the mounting plate from interfering with the flow passing the sensor, (2) the area of uniform icing was smaller than the area covered by the instrumentation, (3) the vertical flat plate, see Figure 2, caused enough turbulence at wind speeds in excess of 15 knots to interfere with ice accretion on other components where ice amounts were measured, (4) frictional heating of the air drawn through the wind machine at low wind speeds caused erratic temperature fluctuations of up to 2°C.

B. The January-February 1978 Tests

The second round of tests were conducted in the main chamber at ADTC, which has floor dimensions of 61.3 x 76.8 m (201 x 252 ft). This enabled us to eliminate the problem of frictional heating of air through the wind machine at low speeds, since it could be moved further from the test stand rather than closing the intake vent to produce low speeds. Also, the wind speed could be kept more constant than in the smaller chamber.

In order to make sure that all components on the test stand were within the area of uniform icing, measurements of ice thickness and mass were made on only four horizontal cylinders, 3.2, 12.7, 25.4, and 50.8 mm (1/8, 1/2, 1, and 2 inches) in diameter. These were located approximately 30.5 cm (12 inches) behind and 15.2 cm (6 inches) above the sensors on the ice detectors. This arrangement also eliminated the turbulence caused by the clutter of collectors used in the first round of testing. Figure 4 shows the arrangement on the test stand.

A total of 42 1-hr tests were run, half with freezing rain and the other half with cloud/fog sized droplets. Linear least squares regression information for the mass of ice on the 25.4 mm (1-inch) cylinder versus the number of cycles for each of the 3 detectors are given in Table 1. Presented separately in the table are the regressions for the cloud/fog and the freezing rain tests. The information provided in Table 1 reveals the marked improvement in the correlations and standard errors by separating the cloud/fog and freezing rain data. This was also true for the 3.2, 12.7, and 50.8 mm cylinders.

Figure 5, which shows the regression lines from the information in Table 1, indicates that for a specific number of instrument cycles, a much greater mass of ice would accumulate on the cylinder during freezing rain than during freezing cloud/fog conditions. The most likely cause of this disparity is the change in collection efficiency resulting from the difference in drop size. This is the main distinction between the cloud/fog conditions and the freezing rain. For the cloud/fog test, droplet diameters were measured to be less than 0.2 mm, whereas the freezing raindrop diameters were measured to be from 0.2 to 1.5 mm, with an average diameter of 0.4 to 0.8 mm.

In order to determine how well the detectors worked under prolonged icing conditions, six tests were run for periods of 2 to 17 hours. In some of these tests, conditions, such as temperature, wind speed, and precipitation rate, were varied. As a result of these longer tests, two major problem areas were brought into focus. The foremost of these is an acceleration of instrument deicing cycles caused by melt water from the sensor accumulating on the flat surface area on the top of the strut. This can be most clearly visualized by referring to Figure 1. As the melt water builds up on the strut, it is held in place by the surface tension of the water and freezes. The sensor, which is partially submerged in the puddle, responds by returning to the deice mode. This particular problem apparently is a significant factor only at wind speeds of 15 kts or less. At higher wind velocities, the melt water is blown clear of the detectors.

The second problem area is ice buildup on the windward side of the detector strut. This occurs at wind speeds of 15 kts or more. Although the top 7.6 cm (3 inches) of the strut are heated, ice builds up from the unheated portion and is melted only at the surface of the strut. Under extreme conditions, this buildup extends slightly beyond the top of the strut and begins to obstruct the sensor. The effect on the instrument response time, though, seems to have been minimal.

Another important consideration was found to be the variance in output among the individual detectors. As can be seen in Table 1 and Figure 5, there is a significant difference in the response time of the two 872DC ice detectors. A representative of Rosemount stated that the difference in response time between detectors varies by 15 to 25%. He indicated that greater attention to calibration should reduce the variance to 10 to 15%.

Conclusions

At the time that this paper was written, much of the test data had not been analyzed. Based on these preliminary results, however, it can be concluded that the Rosemount Model 872DC ice detection system could be readily tailored to provide valid observations of ice accretion, mass and thickness, on cylinders. This will require modification of the detector, such as tapering the top of the strut, to facilitate drainage of melted ice from the sensor, and a method for reducing ice buildup on the strut during heavy icing.

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Figure 1. The Rosemount model 872DC ice detector. The sensing probe sits atop the 25.4 cm (10 inch) strut. During deicing, the sensor and the top 7.6 cm (3 inches) of the strut are heated.

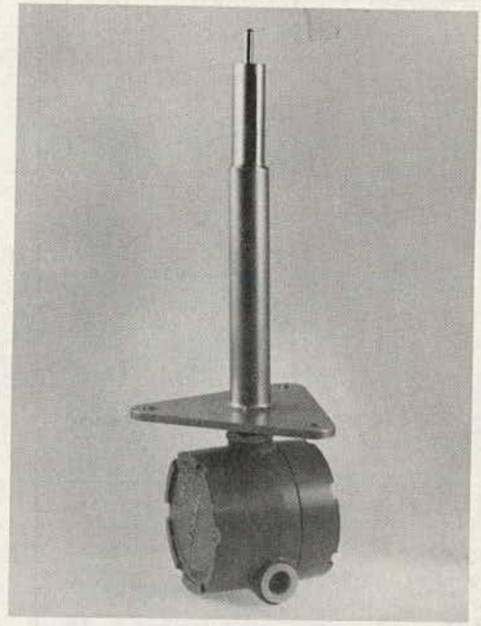


Figure 2. Arrangement of instruments and collectors for the April-May 1977 test period.

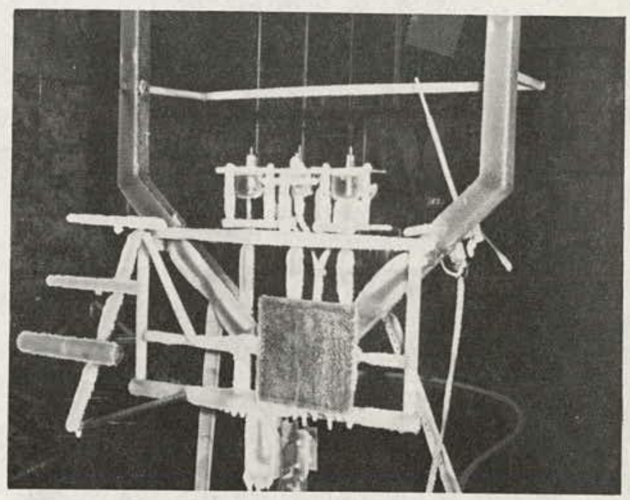


Table 1. Linear least squares regression information for the mass of ice on the 25.4 mm (1-inch) cylinder (Y) vs. the number of instrument cycles (X) for each detector. Results are given for all the test points and for the freezing rain and riming conditions separately.

Conditions	Detector No./Model	Number of Test Pts.	Slope	Y Intercept	Correlation	Standard Error (grams)
All	1/872DC	42	3.44	10.29	.80	29.2
All	2/871FA	41	3.66	7.42	.80	29.6
All	3/872DC	42	4.32	8.94	.79	29.8
Freezing Rain	1/872DC	21	1.89	9.52	.92	8.9
Freezing Rain	2/871FA	20	1.94	8.12	.93	8.3
Freezing Rain	3/872DC	21	2.38	8.99	.94	7.9
Cloud/Fog	1/872DC	21	5.33	11.43	.99	9.4
Cloud/Fog	2/871FA	21	5.75	5.11	.99	9.9
Cloud/Fog	3/872DC	21	6.97	6.61	.98	11.9

Figure 3. Linear least square regression of the ice thickness on the 25.4 cm cylinder vs. the number of deicing cycles. Data from the April-May 1977 test period.

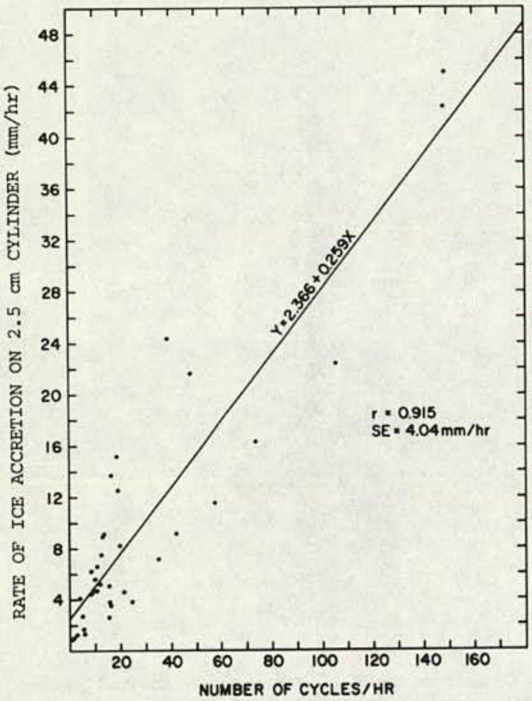


Figure 4. Arrangement of instruments and collectors for the January-February 1978 test period.

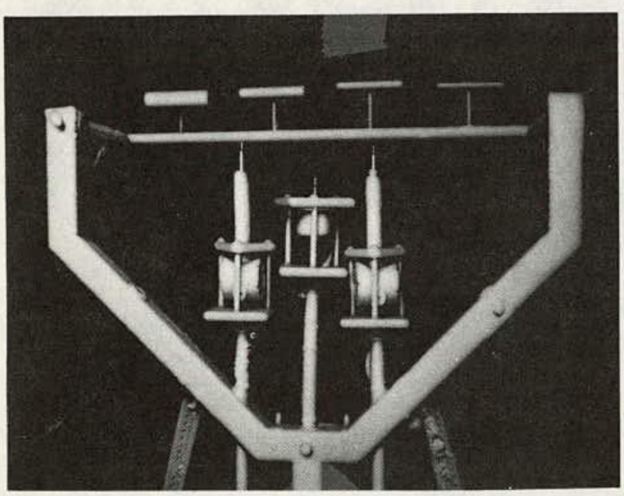
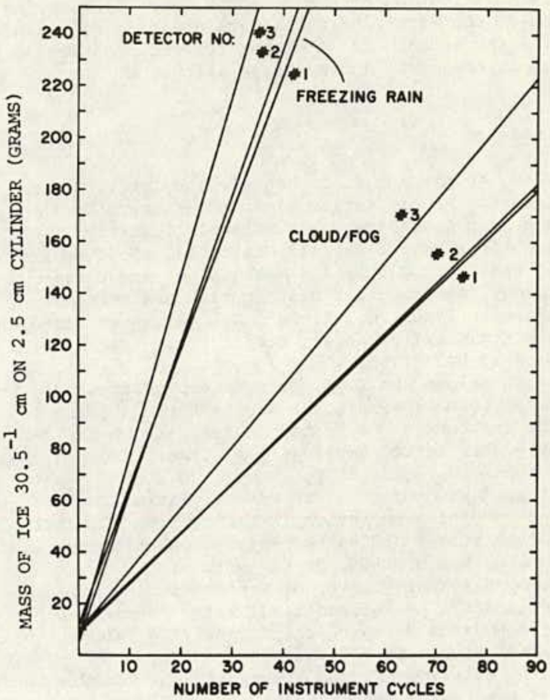


Figure 5. Regression lines from the information in Table 1.



A Model for Traffic Delay and its Convenience and Wage Costs

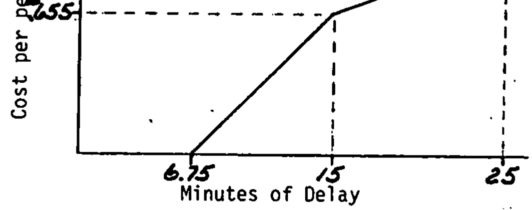
W. J. Kennedy and J. A. Austin, Jr., University of Utah

One of the large problems facing engineers in the economic analysis of public projects is the estimation of comfort and convenience costs and of lost wage costs. Comfort and convenience costs have generally been either ignored or treated as a linear function of the trip delay time; wages lost to tardiness have also generally been assumed to be linear when they have been considered at all. But personal experience argues against the idea of a linear comfort and convenience cost - except in unusual circumstances, short delays in the completion of a trip have negligible actual costs. Similarly the wage loss due to tardiness is recognized to have a zero value when the tardiness is below some threshold value, and this threshold value is recognized in most union contracts. This paper treats the problem of calculating comfort and convenience costs analytically and proposes a probability distribution that is easily used to estimate the value per person trip of both such costs. This technique is then applied to cost estimation where the delay is caused by snow and ice on a roadway.

In attempting to quantify the benefits from a proposed transportation system improvement, transportation engineers frequently are vexed with the problem of quantifying comfort and convenience benefits and benefits to industry because of reduced tardiness. It seems difficult to assign a dollar value to the comfort and convenience of travelling rapidly along a well-plowed road rather than one where the traffic does the plowing, yet some measure of this benefit is clearly necessary before an adequate benefit-cost analysis of roadway plowing can be performed. Complicating the problem is the observed fact that a small amount of delay is not regarded as significant. The problem of wages lost due to tardiness is another problem that is not as simple as it first appears. Most union contracts contain a clause on tardiness whereby a person is not docked in pay unless he or she is more than a specified number of minutes late. Due to many shop practices regarding tardiness, the average threshold is probably greater than that specified in the union contract, somewhat complicating the problem of assigning a dollar value to this component of delay. These two problems were addressed in two reports on snow and ice removal completed as part of a project funded by a twelve-state consortium and DOT (1,2) and are the subject of a Transportation Research Board report to be published in the summer of 1978 (3). Although the senior author was a consultant on that project and a co-author of all three reports referred to, the analytical material presented below is new and was not prepared as part of the consulting contract.

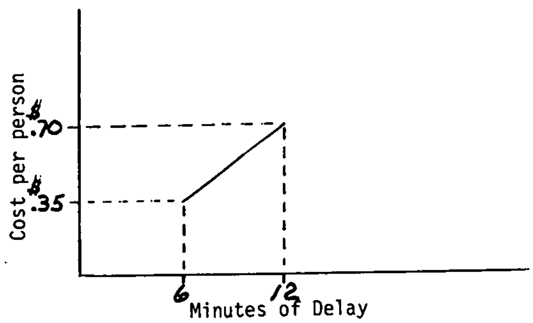
Consider again the problem of estimating comfort and convenience costs. A study performed by Stanford Research Institute (4) by examining the tolls people were paying in New Jersey to avoid delays of certain known time durations came up with a series of curves such as that shown in Figure 1. Eight different curves were found, for eight different income categories. Note that the concept illustrated by this curve is far more intuitively appealing than would be the concept of estimating a fixed amount per vehicle minute--being five minutes late may not cause any inconvenience, and the additional cost of being 25 minutes late rather than 20 minutes may not appear as significant as the difference between being seven minutes late rather than twelve.

Figure 1. Comfort and Convenience Cost



To estimate cost due to tardiness, it is necessary to know the threshold at which wages are actually docked and to know the actual wage. For any given industry segment, both of these numbers can usually be either obtained or estimated. The graphical representation of this cost component is shown in Figure 2, using an average wage of \$3.50 and a threshold of six minutes.

Figure 2. Tardiness Cost



Estimating the comfort and convenience costs and the lost wage costs is further complicated by the easily overlooked fact that the delay for a vehicle is a random variable. The magnitude of the delay for any one vehicle is given by

Delay = Trip Length x [1/snow speed - 1/normal speed]

The speed under snow conditions will vary from vehicle to vehicle, as will the speed under normal (dry-road) conditions. Thus, the delay will also vary and the way it varies depends upon the probability distributions of snow speeds and normal speeds. Trip-length also varies but will be assumed constant at this time. Dry road speeds have been observed to generally follow a normal distribution and it was assumed that speeds under snow conditions would follow this same distribution. Unfortunately, the probability distribution consisting of the difference between the reciprocals of two normally distributed random variables is not known. If it were known, however, it could be integrated to obtain the expected value of the comfort and convenience cost and the lost wage cost per person, using the functions shown in Figures 1 and 2. If $f_D(w)$ is the density function for delay, then the expected value of comfort and convenience cost is given by

$$\int_0^\infty C(w)\, f_D(w)\, dw \qquad (1)$$

Where C(w) is the equation of the function consisting of zero and the two joining line segments as shown in Figure 1. The corresponding value of the expected cost due to lost wages is given by

$$W \times [TH(K) \times (1 - F_D(TH[K])) + \int_{TH(K)}^\infty w\, f_D(w)\, dw] \qquad (2)$$

The first term in this equation is caused by the fact that the person is docked for the first part of the hour if he is late beyond the threshold time, e.g., if the threshold time is 10 minutes and the person is 11 minutes late, he is docked 11 minutes rather than 1 minute.

W = wage in dollars per hour
TH(K) = the threshold time in hours
$f_D(w)$ = density functions of delay D
$F_D(w)$ = cumulative distribution functions of delay D

The computations associated with calculating the density function described above and with performing the given integrations were treated in the original project, but the density function was very complex and was difficult to use in standard numerical integration routines. At the suggestion of Mr. David Minsk, of the U.S. Army Cold Regions Research and Engineering Laboratory, the authors undertook to find a more tractable solution technique for the computational part of the above problems.

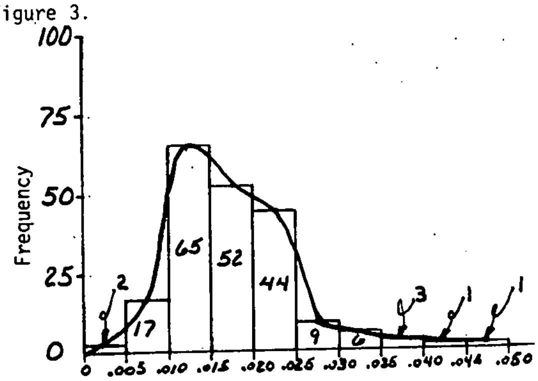
The fundamental problem is to ascertain the type of probability distribution associated with

$$Y = \frac{1}{S} - \frac{1}{N}$$

where S is the random variable snow speed assumed to be normal with mean μ_S and standard deviation σ_S and where N is the random variable of normal speed with mean and standard deviation of μ_N and σ_N respectively.

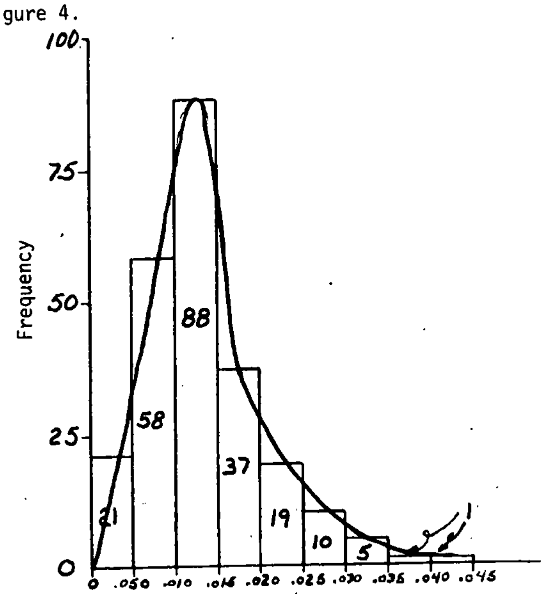
A small simulation program was written for the HP-97 calculator in order to get an idea about the shape of the distribution for various normal distributions associated with snow and normal speed. Four examples are shown in Figures 2, 4, 5, 6.

Figure 3.



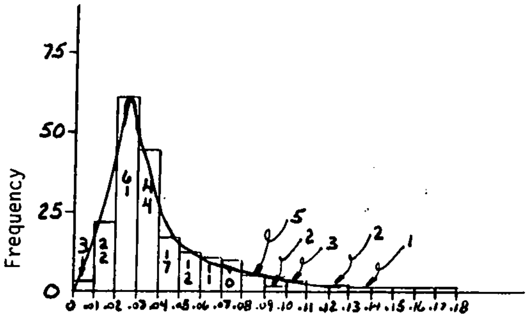
M_N = 57.5 $\quad$ M_S = 30.0
σ_N = 7.0 $\quad$ σ_S = 7.0 $\quad$ Based on 200 Points

Figure 4.



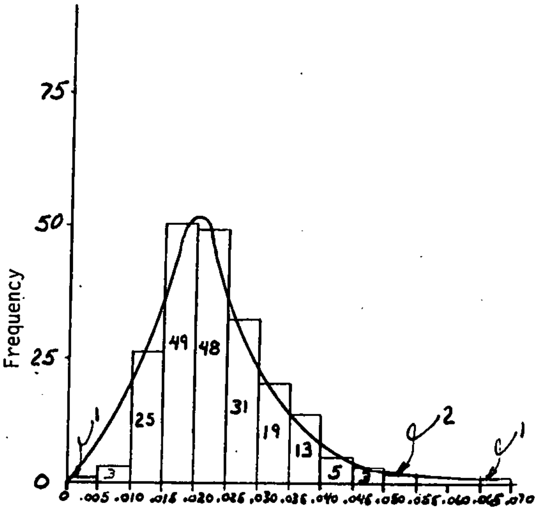
M_N = 57.5 $\quad$ M_S = 35.0 $\quad$ Based on 200 Points
$_N$ = 7.0 $\quad$ $_S$ = 7.0

Figure 5.



$M_N = 57.5$ $\quad M_S = 20.0$
$\sigma_N = 7.0$ $\quad \sigma_S = 7.0$ Based on 197 Points

Figure 6.



$M_N = 57.5$ $\quad M_S = 25.0$
$\sigma_N = 7.0$ $\quad \sigma_S = 5.0$ Based on 200 Points

Based on these histograms and because of the nature of Y, a log-normal distribution appeared to be the ideal type of distribution for the y variates. The general equation of the log-normal is given by the probability function

$$f_Y(y) = \begin{cases} \frac{1}{\sqrt{2\pi}\cdot\xi\cdot y} \exp\left[-\frac{1}{2}\left(\frac{\ell ny - \lambda}{\xi}\right)^2\right] & y \geq 0 \\ 0 \quad \text{elsewhere} & \end{cases} \tag{3}$$

$$\text{where } \xi^2 = \ell n\left[1 + \frac{\sigma^2}{\mu^2}\right] \tag{4}$$

$$\text{and} \quad \lambda = \ell n\, \mu - \frac{1}{2}\xi^2 \tag{5}$$

and μ and σ are the mean and standard deviation respectively of Y.

In order to see how good a fit the log-normal function choice was for the distribution, a Kolmogorow-Smirnov goodness of fit test was performed on the case μ_N=57.5, σ_N=7, μ_S=30, σ_S=5. In order to perform the goodness of fit test, one must calculate ξ and λ as given by Equations (4) and (5). Thus, the mean and standard deviation are needed. It was decided to expand Y=1/S-1/N into a Taylor series about the mean and use the series to estimate μ_Y and σ_y from the distributions of N and S.

Expanding Y in a Taylor Series about the means of N and S one gets

$$Y \equiv \left(\frac{1}{\mu_S} - \frac{1}{\mu_N}\right) + \left(\frac{-1}{\mu_S^2}\right)(S - \mu_S) + \left(\frac{1}{\mu_N^2}\right)(N - \mu_N) + \left(\frac{1}{\mu_S^3}\right)(S - \mu_S)^2 + \left(\frac{-1}{\mu_N^3}\right)(N - \mu_N)^2 + \ldots \tag{6}$$

To approximate μ_Y using up through second order terms

$$\mu_Y \sim \left(\frac{1}{\mu_S} - \frac{1}{\mu_N}\right) + \frac{1}{\mu_S^3}\sigma_S^2 + \left(\frac{-1}{\mu_N^3}\right)\sigma_N^2 \tag{7}$$

To approximate σ_y^2, using up through first order terms,

$$\sigma_y^2 \sim \frac{1}{\mu_S^4}\sigma_S^2 + \frac{1}{\mu_N^4}\sigma_N^2 \tag{8}$$

Now μ_Y and σ_Y will be used to calculate λ and ξ for use in testing the assumption of the log-normal distribution. These equations applied to the case being considered yield:

$$\mu_Y \sim \left(\frac{1}{30} - \frac{1}{57.5}\right) + \frac{1}{30^3}\cdot(25) - \frac{1}{(57.5)^3}\cdot(49)$$
$$= .0166102$$

$$\sigma_y^2 \sim \frac{1}{(30)^4}(25) + \frac{1}{(57.5)^4}(49)$$
$$= .0000353467$$

and

$$\xi^2 = \ell n\left(1 + \frac{\sigma^2}{\mu^2}\right)$$
$$= \ell n\left[1 + \frac{.0000353467}{(.0166102)^2}\right]$$
$$= .12054784$$

or ξ = .3472

and $\lambda = \ell n\, \mu - \frac{1}{2}(\xi^2)$

$$\lambda = \ell n(.0166102) - \frac{1}{2}(.3472)^2$$
$$\lambda = -\ 4.158$$

Now using the Kolomogorov-Smirnov Test to see if the data reasonably fit a log-normal distribution with λ=4.158 and ξ=.3472, we get the following table

Table 1.

Interval	Obs. Freq.	Obs. Cum.	Theor. Cum.	Obs.-Theor
<.010	19	0.095	0.099	.004
.010-.015	65	0.420	0.453	.033
.015-.020	52	0.68	0.76	.08
.020-.025	44	0.90	0.911	.011
.025-.030	9	0.945	0.969	.024
.030-.035	6	0.975	0.989	.014
>.035	5	1.000	0.9965	.0035
	200			

Based on the maximum deviation of .08, compared to the K-S value of .096 at the five percent level of significance we see that the assumption of the log-normal is not unreasonable.

Because of these results, the log-normal approximation has been used for the calculations of the integrals in Equations (1) and (2). The results compare favorable to those obtained as part of the earlier project, but there is a significant advantage to the new system--the procedure can be implemented on an HP-97 (or presumably other) programmable calculator. It is thus possible to estimate the costs per person under a wide set of differing conditions, with a minimum of inconvenience, without the necessity of obtaining access to a computer.

References

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(3) Welch, B. H., Steward, R. M., and Kennedy, W. J., "The Economic Impact of Snow and Ice Removal," Transportation Research Review #647, June 1978.

(4) Thomas, C. Thomas and Thompson, Gordon I., The Value of Time Saved by Trip Purpose, SRI Project MSU-7362, October 1970.

An Environmental Model for Predicting Impacts from Deicing Salts

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ABSTRACT

The intent of this study was to investigate the economic impact of snow and ice control and to develop a series of models to analyze the economics of various facets of winter maintenance. The environmental module is one part of this package.

The model was developed from information gathered from questionnaires sent to highway, environmental, and research personnel who were felt to have some experience in this area. Also a literature review and some assumptions based on observations about the nature of salt contamination were used.

Subroutines have been developed for predicting damage to plants, wells and lakes from either road applications of salt or its improper storage.

The environmental model has the potential to become a valuable tool applicable in a variety of situations. As the first effort of its kind, it is felt to be a substantial first step, while recognizing that much work still needs to be done.

INTRODUCTION

The original objective was to develop a model that would balance the social benefits and environmental costs resulting from snow and ice control on highways. These benefits and costs were to be expressed in monetary terms as they applied directly or indirectly to society or the highway department. However, as the study progressed, it became apparent that much of the environment does not lend itself to dollar estimates, and another approach had to be developed. An attempt was made to draw upon other research, past experiences of environmental damage, some understanding of nature and basic physics to devise a model that would provide the user with a practical tool to evaluate the impact of salting on his area. The intent of this model is not to serve as a final authority, but rather as a useful tool to identify potential environmental problems and provide some documentation as to the probability of any taking place.

The model is the first computerized attempt to grapple with the complex subject of salt use and the environment. As such, it admittedly does not include all of the factors influencing the problem.

This was part of a larger study to investigate the economic impact of snow and ice control and to develop a series of models to analyze the economics of various facets of winter maintenance.

MODEL DEVELOPMENT

The model was developed from information gathered from questionnaires sent to highway, environmental and research personnel who were felt to have some experience in this area. Also a literature review and some assumptions based on observations about the nature of salt contamination were used.

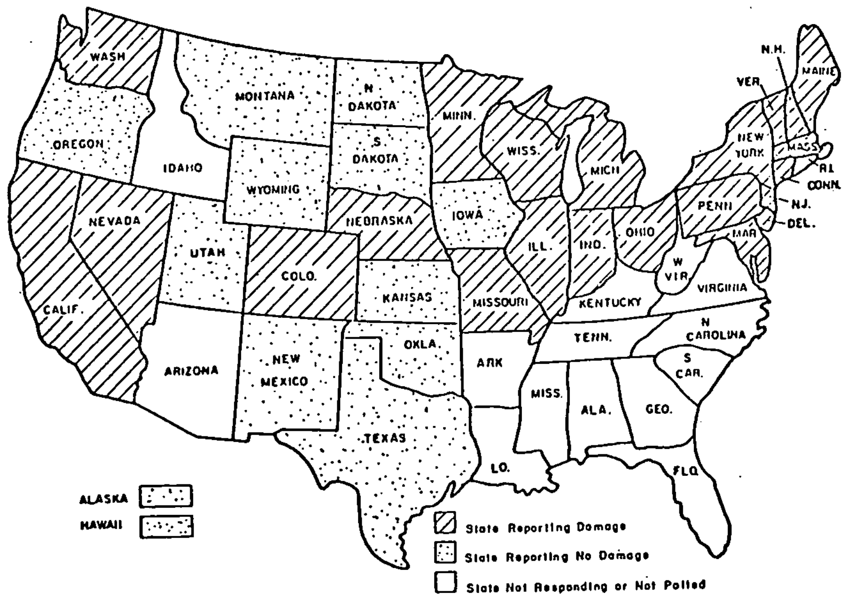
The questionnaires revealed that a large majority of the snowbelt states have experienced some environmental damage. (Figure 1).

However, the damage was considered minor in most cases. The majority of the damage reported was from salt applied to the road, but the most serious impacts came from improper storage. The questionnaires also seem to verify a relationship discussed in the literature concerning the distance of damage from the source of salt and the annual tons used (Table 1). The literature provided much of the theoretical framework and basis for many of the assumptions. Concepts of salt dispersion and accumulation were taken from the literature.

The module, as it is presently set up will only work for sodium chloride and it will only take into account environmental damage of a progressive nature. The model is designed for two sources of damage; road application, and storage. (Road application is defined as the amount of salt placed on the roadway to facilitate snow removal. Storage for this analysis is considered to be those areas where large quantities of salt are kept either in buildings or exposed.)

These sources of damage are applied as potential damage to wells, plants, and lakes. Subroutines have been developed for plants, wells, lakes and potential for lake stratification. Subroutines for roadside aesthetics and terrestrial animals were not developed because there is very little actual information available, and any impacts that were identified would be next to impossible to quantify.

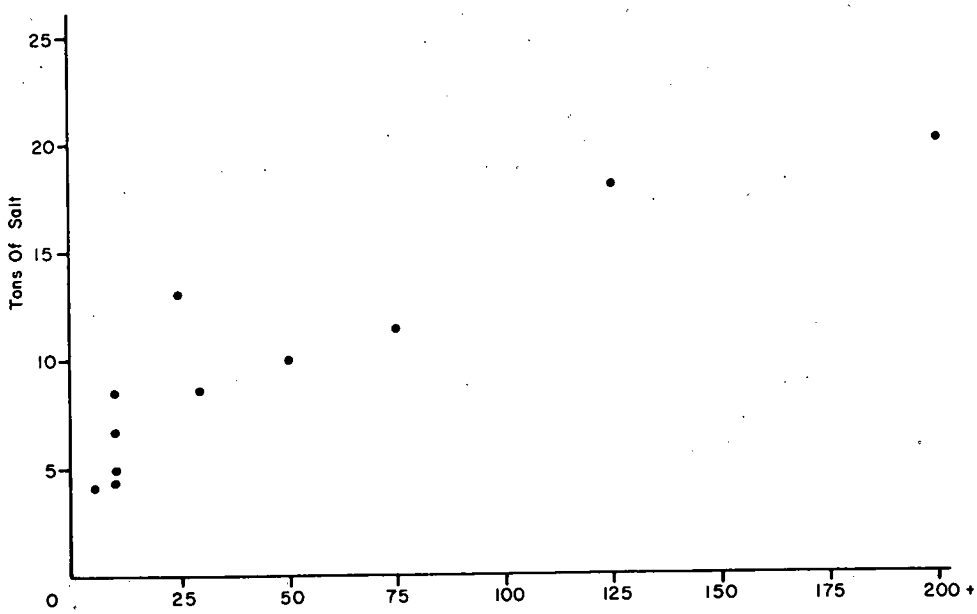
The model is designed to be used by someone who is familiar with the area under study, or could gather the information. It would



STATES REPORTING ENVIRONMENTAL DAMAGE FROM SALT

FIGURE 1

COMPARISON OF DISTANCE OF DAMAGE FROM ROADWAY AND ANNUAL TONS OF SALT PER LANE MILE APPLIED



Distance From Roadway, Feet

TABLE 1

have been possible to include inputs requiring detailed analysis of such things as soil composition, rate of flow and capactiy of the water table, but it was decided that the addition of more sophisticated variables would not have increased the models reliability appreciably and would have severely reduced the number of people willing to use it.

ROAD APPLICATION MODULE

The road application subroutine predicts contamination levels for wells and plants. The basic concept being, as salt is placed on the roadway, most of it will remain suspended in the snow bank along the side of the road. As the snow bank melts, the salt suspended in it will begin to migrate. The more moisture present, the further the salt will be carried. During this time, the ground is also thawing, allowing moisutre (and the salt) to penetrate into the soil. As subsequent rainfall and further thawing occur, the dispersed salt become further diluted and more molecules are forced deeper into the soil until they reach either the water table or get taken up the plant roots. The model accounts for this movement with two equations; one for the horizontal movement, the other for movement into the soil.

The inputs called for in this module are: The type of well or plant tolerance*, number of plants or wells in the area, the distance from the road, annual tons of salt used per lane mile, length of the road segment draining towards the well or plant, the percent of salt expected to remain in the area (the suggested value is 25%), winter precipitation, annual precipitation and the estimated distance from the surface to the water table or major roots.

The road application subroutine for plants uses the same basic principles and equations as the well section, but does vary somewhat in the printout. In this section, the tolerance of the plant is an input, when the (parts per million) reaching the roots are calculated, the computer matches the plant tolerance with the predicted uptake and prints the correct response.

SALT STORAGE MODULE

Improper salt storage has the potential to cause a number of severe problems, and is probably a greater threat to the environment than salt applied to the roads. (7) Improper storage is also an easier source of contamination to contain. A salt pile that is left unconvered will lose 0.25% of its contents for every 2.54 centimeter (inch) of rain that falls on it. (17) If the salt pile is large, with no catch basins, the amount of salt released into the environment can be substantial. This can lead to extensive vegetation and water table damage, in addition to being a direct financial loss in salt paid for, but not used.

The salt storage module, while similar to the road application module incorporates the above findings, and using some judgemental inputs estimates the amount of salt entering the area. The inputs used to determine this are: tons of salt contained in the pile, type of storage (open, enclosed or improved and the estimated effectiveness of the improvement) and months during the year the salt pile is present. These inputs, combined with many used in the road application module are used in an equation and an estimate of chlorides entering the environment is developed. The printout is also the same as used in the road application section.

LAKE CONTAMINATION MODULE

This module evaluates possible lake contamination in terms of lake stratification and the number of years to reach a predetermined salt content in the lake. This may be the Public Health limits of 250 ppm or whatever is felt appropriate by the model users.

In predicting the number of years for a lake to become contaminated, there are a number of variable that have an effect. These include: drainage to the lake, source and amount of salt, water flow in and out of the lake, the size of the lake, and lake characteristics including existing salt content, evaporation rates and lake bed composition.

The acceptable contamination level of a lake is dependent upon its use. For the purpose of this model, 250 ppm has been used as the tolerated value since the standard for drinking water is 250 ppm. There are, however, other standards for different uses, for instance, certain industrial uses require very few chlorides, while agricultural water can tolerate much more. It has been assumed that the conditions set forward in the initial model will remain constant, although it is possible that these conditions may not remain constant over several years. Based on the present state of knowledge this assumption must be made.

*A listing of the tolerances of most trees and shrubs can be found in the State-of-the-Art Report, Economic Impact of Snow and Ice Control. (7)

LAKE STRATIFICATION MODULE

The potential for lake stratification is dependent upon the lake size, surface area, the amount of salt presently in the lake, and the amount of salt reaching the lake. Lake stratification, although not a common problem has the potential to have far reaching economic consequences. Stratified lakes are a cause for the food chain to be broken resulting in death to the fish present. A considerable amount of information is required before this section of the model can be upgraded and considered complete.

It has been reported in the literature that as high concentrations of salt in solution enter a lake, it tends to flow directly to the bottom. As this builds up, it tends to interfer with the mixing of the lake in the spring and fall. This leads to anoxic condition in the lower lake strata, causing the hypolimnion to slowly lose its supply of oxygen, thus a break in the food chain by killing the organisms at the bottom of the lake.

The model format consists of a series of yes/no statements. If the answer to each question is yes, the progrm will print that there exists a potential for stratification. Any no answer will result in a prinout of low potential for stratification.

The inputs for this subsection are very subjective due to the limited data available. It is hoped that the use will understand these limitations and use their best judgement in answering such nebulous questions such as, are there any small deep lakes in the area? A trip to the field may be necessary, but the user could probably consult a detailed map for the required information.

It is recommended that this area be further investigated. The weaknesses in this area are possibly more severe than in any other. It should be kept in mind, however, that this is only meant to be a possible warning device to aid the decision maker and not a decision maker in itself.

EXAMPLE PROBLEMS

In using the model, the user may encounter a situation similar to the following. Smith, Jones and Thompson are neighbors, living on a road that leads to a popular ski area. Since this a quite a rural area, the only source of water is from wells. The Engineer, responding to a complaint decides to run the model.

Since this road is the route to a ski area, a lot of salt is used; approximately twenty-two tons per year. The road section in the area is fairly straight so an equivalent amount of salt will be draining toward each well. The amounts of precipitation are also equal, as is the depth of the water table. Smith's well is 30.5 meters (100 feet) away from the road, while the Thompson's well is 6.1 meters (20 feet) and the Jone's well is 9.1 meters (30 feet) away from the highway. While preparing the inputs, the Engineer remembers that the side of the road Thompson and Smith live on is almost perfectly flat while the Jones' land is on a bit of a slope. He assumes that more salt will be retained on the flat side and estimates a salt retention factor of 55% and assigns a 20% retention factor for the other side. When the data is run, the predicted ppm chlorides reaching the Jones' well is 30, Smith's 41 and poor old Thompson 208.

When the ppm's entering the water table are calculated, the computer* selects one of the follwoing responses and prints it out:

0-50	The well will probably be safe
51-100	The potential for damage is probably small
101-200	A potential damage exists, and monitoring should begin

*These equations can also easily be run by hand.

201-350 High potential for contamination exists, steps should be taken to reduce the salt reaching the well
351-up Well probably is now, or soon will be, contaminated

In this case, the model would predict that the Smith and Jones wells are probably safe, and that the Thompson well has a high potential for contamination. At this point the Engineer should investigate the situation more thoroughly and possibly begin corrective measures.

The road application subroutine for plants uses the same basic principals and equations as the well section, but does vary somewhat in the printout. In this section, the tolerance of the plant is an input, when the ppm's reaching the roots are calculated, the computer matches the plant tolerance with the predicted uptake and prints the correct response.

In the same area is a temporary stockpile that recently has been the subject of some critical editorials in the local paper. The pile is in the open, but is on an asphalt pad and is usually covered when it is not in use. He estimates the pile to contain an average of 100 tons during the winter season. Approximately fifty feet away is a stand of middle sized blue spruce.

He works the equation, using precipitation inputs of 12.7 cm (5 inches) during the winter and an additional 25.4 cm (10 inches) during the rest of the year. He estimates the major uptake level of the roots to be at 1.5 meters (5 feet) and applies a retention factor of 25%. He comes up with an estimate of 400 ppm's.

The blue spruce is considered to be very sensitive, and 400 ppm chloride are determined to have a moderate potential for damage. In facing this situation, he should insist that the loaders always cover the pile when loading operations are complete, and possibly consider reducing the size of the pile, or even relocating the pile.

Farther up the road is a lake that supplies much of the cities drinking water. A new road has been cut through that goes around the rim of the basin the lake is in. Since the lake is a source of drinking water, he decides to use the model to determine how much salt will be added to the lake from the road salting.

The lake contains 25,600 hectares (64,000 acre feet) of water (approximately 4.96 km x 4.96 km. [3.1 x 3.1 miles] average depth of 3 meters [10 feet]) and has an out flow of 3 cubic meters (100 cubic feet) of water per second. The lake has a present chloride content of 2 parts per million.

The 16.09 km (10 miles road around the lake receives approximately (1,500 pounds) of salt per lane kilometer (mile) (226.9 kg application rate 3 time) per storm for each of the 10 storms experienced. Making a total application of 68,000 kg (150,000 pound) during the year. Since the lake is in a basin, it is estimated that 100% of the salt applied will reach the lake. When these figures are run through the model, a predicted additional .634 parts per million are estimated to be reaching the lake, a low potential for stratification is also predicted.

IMPLEMENTATION

There are a number of uses for this model, among them are:
1. State inventory using present or proposed application rates to to identify any sensitive areas.
2. Assistance in doing Environmental Impact assessments.
3. Use in public meetings when facing citizens concerned about new or existing but controversial construction.
4. Examining the potential for environmental damage and related costs of salt loss versus construction costs of covering storage.
5. Basis for more sophisticated models in this area of study.

RECOMMENDED FUTURE STUDY

The environmental model has the potential to become a valuable tool applicable in a variety of situations. As the first effort of its kind it is felt to be a substantial first step, while recognizing that much work still needs to be done. Each module should be separately investigated and new modules added. One area of particular importance that needs a considerable amount of work is the impact of sodium contained in drinking water on people suffering from hypertension. This are could prove to contain the greatest economic impact and should be investigated.

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A Value Engineering Study of Snow and Ice Control

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Today I would like to share with you an approach we used in studying our Snow and Ice Control program. The purpose of this study was to identify ways of reducing direct and indirect costs. The ultimate results of this effort will be to reduce costs of our $10 million snow and ice control program by $3.3 million. The study method differs from what is generally considered "Value Engineering", in that the scope was much broader and strategies were employed throughout the study to make recommendations acceptable to those responsible for results. Also, because the study covered the entire Snow and Ice Control program, and the team members' time was limited, it was necessary to zero-in on high pay back areas that would have a high probability of being accepted and implemented.

What I would like to give you here is a description of that narrowing process, and hopefully it will be useful to you when looking at your own programs. Before beginning, I believe that it is necessary to provide some background on how this and other studies are initiated within our Maintenance operations.

BACKGROUND

After being appointed Chief of Maintenance (and then Operations) in 1973, I looked around at my staff and questioned the way that decisions were being made. Frankly, they were generally based on what had been done in the past. At the same time one could see that there was much that could be done to make improvements.

However, one of the problems that we have in bringing about change is the decentralized nature of our organization. Our Headquarters Office of Maintenance has functional responsibility for the maintenance activities of our eleven districts. Yet, the District Directors have line authority over the personnel. This is even more complicated with the maintenance function being further divided into over three hundred maintenance territories statewide. I am sure that this situation is not unique to Caltrans; however, it does make it difficult to standardize methods and procedures, and materiel and equipment selection and usage.

Within Headquarters, our maintenance responsibilities are divided into nineteen programs. The major responsibility for coordinating with the districts and overseeing their efforts rests with our four Headquarters Maintenance Reviewers. As an initial step in getting the reviewers and other maintenance staff members to view things differently, I asked that they identify areas for possible improvements. At the same time, I worked with others within the Department to find additional areas of concern. From these we developed and prioritized a list of issues to be addressed. Next, the Program Managers in their respective areas of responsibility were asked to develop proposals using an Issue Memo process. I will talk about that a little later.

By now you are asking, how does all of this relate to zeroing-in on high pay back areas. First of all, the decentralized nature of our organization presents special problems which necessitated having districts' involvement in proposed changes. Next, the process of bringing issues of concern forward, and having the Program Managers involved in developing proposals, has been successful in undertaking many studies within Maintenance. The "Snow and Ice Control Study" is an example of one of them.

Also, we have found that in many instances our studies are tied to other improvement efforts such as results of previous studies. For example, the Snow and Ice Control Study was the result of a previous effort completed in 1975. This was the "Bare Pavement Snow Removal Policy Study," which was concerned primarily with policy issues. During that effort it was recognized that significant savings could be realized through changes in our snow removal practices. Management concurred and this follow-up study was given tentative approval.

The steps taken to initiate and bring this evaluation to a successful conclusion were:

- First, the proposal was formalized by preparing an Issue Memo. In this, estimates of potential savings were spelled out; pertinent supporting data were given; the sensitivity of the project was discussed; and a general approach was proposed. *Attachment 1 is and example of that Issue Memo.)*
- After the Issue Memo was approved by me and other Managers who would be impacted, a study team was formed comprised of members who would contribute most to this effort. Their first step was to conduct a survey of the program to gain a greater understanding of what was involved.
- Following this a detailed study approach (or what we call a Work Plan) was developed. This was a planning effort that outlined what would be done, when, and what would be the final products. I have found that this is a very important part of any complex or major project. It increases the likelihood of getting a good product on time. You see, when this plan has been developed and improved by the client(s) and ultimate decision-maker(s), it does three things:

One, it limits the scope of what will be covered and thus saves time by not running up too many blind alleys.

Two, it provides a guide for conducting the study, and

Three, it becomes a quasi-contract between the study team and the client(s) as to what will be done, and what will be the product.

Attachment 2 is a copy of the Work Plan format that is generally used within Maintenance.

Finally, the study is conducted; a report is prepared with recommendations; and when approved, implementation begins.

However, in this project, because the entire program was being evaluated, an additional step was necessary. This was to zero-in on the high pay back areas to assure a greater return from the team members efforts.

In the remainder of this discussion, I will describe how this was done.

ZEROING-IN ON HIGH PAY BACK AREAS

Six steps were taken in this narrowing and prioritizing process; these were to:

1. Break down the program into major activities.
2. Rank them in order of importance.
3. Develop a specific detailed list of areas for investigation.
4. Develop criteria for determining which areas should be evaluated and in what order.
5. Zero-in on areas for evaluation using a Problem Investigation Evaluation Matrix.
6. Assign responsibilities to individual team members for evaluation of specific areas.

STEP 1 Break down the program into major activities:

Using budgets from 1964 through 1975, and information from our Maintenance Management System, overall direct costs were determined. When adjusted to 1974 dollars, they ranged from $8½ million to $14 million with an average of $10 million annually. These generally fell into two major categories; plowing -- $5.6 million, and sanding -- $3.4 million.

These costs, however, did not represent the total costs of the program. It was necessary to include indirect costs associated with snow and ice control as well, when considering specific areas for investigation. The following table shows that there are many areas that have an impact on the total costs of snow and ice control, but do not show up as budgeted expenses. For example: legal expenses; size, location and design of maintenance stations; and capactities of our multipurpose equipment.

TABLE 1

DIRECT & INDIRECT COSTS RELATED TO SNOW & ICE CONTROL

AREA	HOW RELATED	
	DIRECTLY	INDIRECTLY
1. Headquarters and district staff and facilities related to snow removal program but not directly involved in snow and ice control activities.		x
2. Excess equipment and personnel in Equipment Department because of snow removal and ice control.		x
3. Cost of purchasing activities for snow and ice control activities (not including cost of materials.)		x
4. Cost of materials.	x	
5. Delivery costs.	x	
6. Stockpiling costs		
• Manpower	x	
• Facilities and land		x
• Equipment usage	x	
• Costs associated with preventing pollution	x	x
7. Application of materiels and plowing		
• Manpower	x	
• Fuel		x
• Equipment rental	x	
• Equipment repair and cleanup	x	
• Equipment changeover for snow and ice control	x	
• Equipment changeover back to general use	x	
• Equipment damage		x
• Snow removal	x	
• Sand and abrasive cleanup	x	x
• Sign washing		x
• Equipment usage	x	x
• Special equipment required	x	x
8. Storage facilities for snow-related equipment		
• Size and type of facilities required to maintain snow equipment.		x
• Number of maintenance stations.		x
9. Location of maintenance facilities because of proximity to snow and ice control activities		
• Need for maintaining facility during portion of year other than snow season.		x
• Cost of maintenance stations that exist primarily for snow removal activities.	x	x
• Less than optimum location of maintenance stations (if not for snow removal where would it be located).		x
10. Legal expenses		
• Percentage of legal staff expenses caused by snow and ice related accidents.		x
• Accidents caused by damage to roadway, structures and signing resulting from snow and ice control activities.		x
• Costs associated with snow and ice control related environmental issues.		x
• Costs of judgments awarded against the Department, relating to snow and ice control activities.		x
11. Road condition information provided public by Department.		x
12. Environmental concerns		
• Cleanup costs, city streets, streams, etc.	x	x
• Costs of special environmental studies, EIR's, etc.		x
13. Damage to roads and structures.		x

STEP 2 Rank program activities in order of importance:

Again, using information from our Maintenance Management System, we identified thirteen major functions. These, in turn, were ranked in order of importance, considering the amount of effort expended on them. Table 2 shows that, within these, snow plowing ranked highest, and that snow fence installation and maintenance was lowest.

STEP 3 List specific areas of investigation:

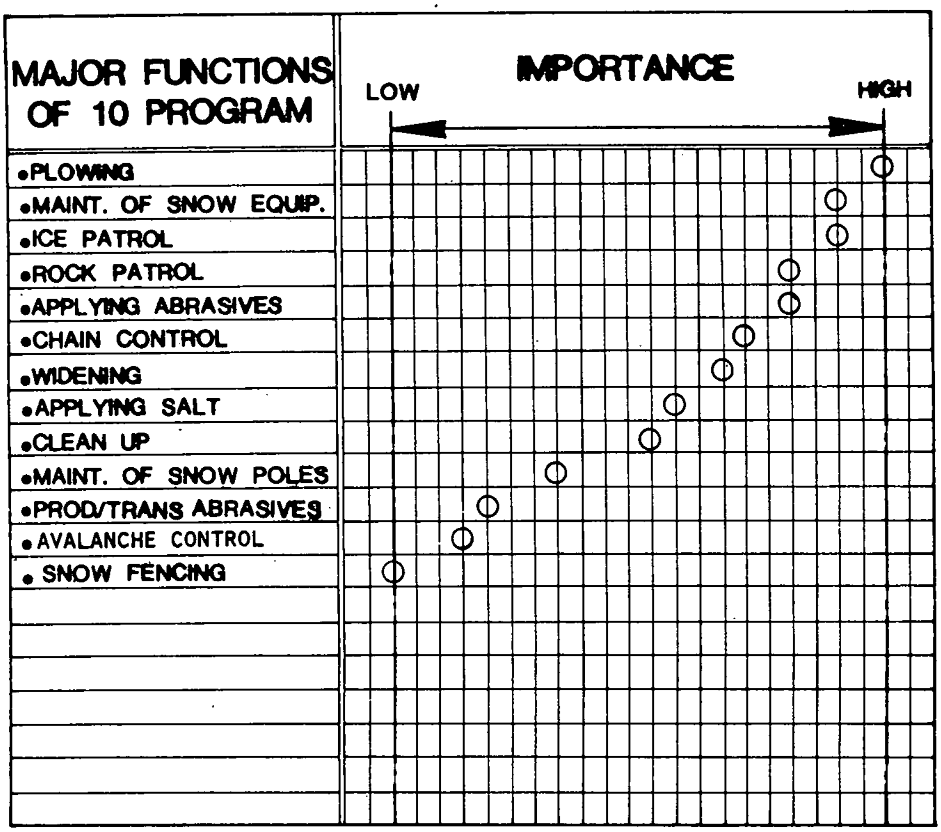
The activities necessary to carry out the thirteen major functions were identified. Using these, and the general areas covered in the work plan, specific questions and areas for evaluation were developed. The technique used here was primarily brainstorming. After completing this original list, the items were grouped under four major headings: Personnel, Equipment, Materiels and Other. At the same time these areas were further refined and clarified.

STEP 4 Develop criteria for prioritizing areas for investigation:

Determination of selection criteria logically followed what had been covered thus far and what we have learned from previous efforts. First, we wanted to reduce costs as much as possible without endangering the motorist. Second, it was necessary to put our effort where there was a high probability of successfully making changes. This in turn is closely tied to the acceptability of the recommendations. One helpful criterion that is usually considered, is "what are the potential consequences of making the change or not." Finally, it is necessary to consider how much of the team's effort will be required to evaluate a given area.

TABLE 2

RELATIVE IMPORTANCE OF MAJOR SNOW & ICE CONTROL FUNCTIONS



To summarize, the criteria are:

1. Estimated total saviangs ($'s involved x estimated % savings).
2. Probability of finding ways for improvements, and of getting them implemented.
3. Acceptability of recommendations (or proposed changes). These include:

- field personnel
- management
- public
- political.

4. Consequences:

- of error (making the wrong change)
- of not doing anything.

5. Team effort required.

STEP 5 Narrowing and prioritizing areas to be investigated:

Now that the tentative areas to be studied were identified and the criteria for prioritizing the investigation had been developed, the next step was to construct a "Problem Investigation Evaluation Matrix." This merely required placing the study areas on one axis and the evaluation criteria on the other. Next, we used a "modified delphi approach" in completing the zeroing-in process. Each team member independently made estimates and completed a copy of the matrix. Here they drew on their own backgrounds and expertise along with what they had found from the initial survey. After this was completed, the team made comparisons of their estimates. When there were extreme differences, the parties involved would give their reasoning. The objective was not merely to compromise, but to bring forward more information and come to an agreement on the estimates. From this exercise, some areas of the study were eliminated and one combined matrix emerged. Using these overall evaluations the study team prioritized the areas into first, second and third. Although weights were not given to the evaluation criteria, more importance was given to "estimated savings," "probability of success," and "consequences."

In some instances it was not possible to assign values and yet it was believed that an investigation was necessary. When this happened a statement was given in the "comment" column. Figure 1 is a copy of the completed Problem Investigation Evaluation Matrix. The number in the first column represents the priority given that area of investigation.

STEP 6 Assign team members areas to be studied:

Using the specific talents and background of the three team members, the areas of investigation were assigned. At the same time, in an effort to promote consistency throughout the evaluation, we developed another table that laid out the major contacts and responsibilities. As mentioned earlier, it was important that the districts be involved. In looking at Table 3 you will see that most of the major activities required input form the districts.

These steps represent the narrowing process. They may look complicated and time consuming, but are not. The study followed the assignments that were made and the team members completed evaluating all thirty-six areas that were proposed. Although this discussion does not cover the study itself, it is important to note that during this effort the team members worked independently. The team would meet periodically and discuss findings, conclusions and recommendations. Also, there were checkpoint meetings with the client(s) and decision-maker(s) resulting in many recommendations being approved and implemented during the course of the study.

Another important by-product of this planning and narrowing process prior to conducting the study was team building. I am sure that many of you have had projects that didn't turn out the way that you wanted, and if you were to look into the causes you might find that it was the result of team members not working well together. The time to correct this is before the study begins.

Before concluding this discussion I would like to give some examples of what we have accomplished thus far. As I said, the study took approximately six months of part-time effort of our three team members to complete. Out of the $10 million program, approximately $3.3 million will be saved annually when all recommendations are fully implemented. Some of the recommendations that have been implemented, or where implementation has begun, are:

Description	Savings
Standardized calibration and established maximum application rates for salts and abrasives. (Established monitoring and control system.)	$117,000
Lowered abrasive specifications to reduce procurement costs.	36,000
Increased purchases of bulk salt rather than bag salt.	35,000
Increased use of process salt rather than kiln dried salt.	70,000
Increased use of larger multi-purpose equipment.	58,000
Began use of wing plows in some places rather than using rotaries or doing tandem plowing.	129,000
Converted to carbide insert blades instead of carbon steel blades.	164,000
Specified use of diesel rather than gasoline trucks. (Annual fuel savings - 300,000 gal.)	322,000
Developed a new salt dispenser, giving capability to selectively apply salt where needed.	36,000
Calibrated all spreaders and installed ground-oriented controls.	176,000
Developed training program for equipment operators.	208,000

Although these recommendations have not been fully implemented, there has been a good start. Another by-product of this effort was the establishment of an ongoing system that was improved coordination between Headquarters and districts.

SUMMARY

Today I have described an approach that we have used within Maintenance to initiate projects. Also, the steps taken in the Snow and Ice Control Study were used to illustrate a process for zeroing-in on high pay back areas. Essentially, this narrowing process involves applying selected criteria to proposed areas of investigation, and this rules out looking at areas that have a small pay back of a low probability of making improvements.

As can be seen from the initial results, the process works. The team was successful in bringing about many real improvements.

Again, I believe these planning steps I've described are well worth the effort and, hopefully, they will be useful to you in looking at your own programs, primarily those that are large and complex.

FIGURE 1

PROBLEM INVESTIGATION EVALUATION MATRIX

Potential Problems or Areas for Investigation: Gen. Area	Specific Area Description	Magnitude ($ Involved)	Est. % Savings	Est. Total $ Savings	Probability of Success in Implementing	Acceptability: Field Support	Mgmt.	Public	Political	Consequence of Error	Consequense of Not Doing	Team Effort Required	Comments
PERSONNEL	TOTAL COST ANALYSIS OF VARIOUS STAFFING AND SHIFT ARRANGEMENTS	H①	5%	H	H	L	M	O	O	L	M	M	
	CONTRACTING WORK	H①	10%	H	M	L	L	H	H	L	L	L	
	TRAINING OF SNOW REMOVAL CREWS	H①	12%	H	H	H	H	O	O	L	H	L	
EQUIPMENT	ELIMINATE EXCESS EQUIPMENT	H①	10%	H	M	L	M	H	H	L	L	L	
	TRANSFER BETWEEN ENTITIES DURING YEAR	L②	5%	L	H	L	M	H	H	L	L	L	
	COST BENEFIT OF USING VARIOUS TYPES AND COMBINATIONS OF EQUIP.	H③	10%	H	L	L	M	O	O	L	L	L	
	SANDER CALIBRATION	H①	10%	H	H	M	M	H	H	L	M	M	
	AUTOMATIC SANDER CONTROLS	H①	20%	H	H	H	H	H	H	L	H	L	
	TYPES OF SANDERS	H②	5%	M	M	L	L	O	O	L	L	L	
	GASOLINE VS. DIESEL POWERD TRUCKS	H②	17%	H	H	H	H	M	M	L	H	L	
	TYPES OF TRANSMISSIONS	H③	2%	L	L	L	L	O	O	L	L	L	
	PLOW BLADES	H①	200%	H	H	H	H	O	O	L	M	L	
	TIRES	L③	2%	L	L	H	M	H	H	L	L	L	
	PLASTIC CHAINS	L③	5%	L	M	M	M	H	H	L	M	L	
MATERIALS	ABRASIVE TYPES AND SIZES	H②	25%	H	H	L	L	M	L	L	L	L	
	STOCKPILING	L③	3%	L	H	M	M	O	O	L	L	L	
	PURCHASING VS. PRODUCING	M③	5%	M	M	L	L	O	O	L	L	L	
	TRANSPORTATION COSTS	H③	2%	L	H	L	L	O	O	L	L	L	
	TIMING, PATTERNS AND RATES OF APPLICATIONS	H①	20%	H	H	L	L	O	O	L	L	H	
	DAMAGE CAUSED BY ABRASIVES	L③	1%	L	L	L	L	O	O	L	L	L	
	MELTING QUALITIES	L③	1%	L	L	L	L	O	O	L	L	L	
	HEATED	M②	2%	L	M	H	H	O	O	L	L	L	
	TRACTION QUALITIES	①											NEEDED AS PART OF DETERMINING ABRASIVE TYPE
	SALT IN BULK VS. PACKAGED	H①	20%	H	H	H	M	O	O	M	L	L	
	OR PROCESSED VS. KILN DRIED	H①	15%	H	H	L	L	O	O	L	L	L	
	PURCHASING AND SPECIFICATIONS-SIZES	H①											PROBABLY CAN'T MEASURE $ SAVING, BUT SHOULD BE LOOKED AT
	STOCKPILING	L③	2%	L	L	L	L	L	L	H	L	L	
	MIXTURE OF CALCIUM & SODIUM CHLORIDES	M③											
	MIXTURES & MIXING OF CHEMICALS & ABRASIVES	H①	7%	H	M	L	L	O	O	L	H	H	
	SNOW POLES	H②	25%	H	H	L	L	L	L	L	L	H	
OTHER	ONGOING IMPROVEMENT SYSTEM	H①	10%	H	H	L	L	H	H	L	H	L	THIS IS A MUST DO ITEM
	LEGAL RESPONSIBILITY FOR DRIVERS, ACTIONS	H①			L	M	H	L	L	L	H	L	CAN'T IDENTIFY SAVINGS BUT MUST BE DONE
	EVALUATION OF DIST. 02 SANDING POLICY	H①		H	H	H	H	H	H	L	H	L	COST AVOIDANCE TYPE AREA
	POSSIBILITY OF SHIFTING COST TO BENIFICIARY	H①			L	H	H	L	L	L	L	L	REVENUE GENERATING ACTIVITY
	MAJOR POLICY ISSUES TO BE RESOLVED REGARDING 10 PROGRAM	①											CAN'T IDENTIFY SAVINGS BUT MUST DO FOR OTHER IMPROVEMENT
	PLOWING & SANDING PROCEDURES & CHAIN CONTROL	H①	5%	H	H	L	L	L	L	M	H	H	THIS IS A MUST ITEM

Legend:

H = High

M = Medium

L = Low

O = Doesn't Apply

TABLE 3

ASSIGNMENT & PROPOSED CONTRACT SCHEDULE

	DISTRICTS	STATE PERSONNEL BOARD	CALIF. HWY. PATROL	HEADQUARTERS	LEGAL - PUC	TRANSPORTATION LAB.	HDQT. TRAFFIC	STATES, CITIES, CO.	VENDORS	OTHER AGENCIES FHWA	PUBLIC	PERSONNEL	OFFICE OF EQUIP.	RESPONSIBILITY
PERSONNEL														
Total cost analysis of various staffing and shift arrangements	X	X		X	X							X		D H
Training personnel	X			X				X	X			X	X	D S
Contracting out	X	X		X	X			X		X			X	D
EQUIPMENT														
Reduction in snow removal equipment	X			X									X	S
Transfer between entities during year	X			X				X		X				S
Eliminate excess equipment	X			X									X	S
Cost benefit of using various types and combinations of equipment	X			X									X	S
Sander calibration	X			X					X				X	D S
Automatic sanders	X			X					X				X	S
Sander type comparison	X							X	X	X			X	S
Gas vs. diesel trucks	X			X				X	X	X			X	S
Plow blades	X			X				X	X	X			X	D S
Plastic chains	X							X	X		X		X	S
Tires	X							X	X				X	S
MATERIALS														
Abrasives														
Type/size	X			X		X		X	X	X				D
Stockpiling	X			X				X		X				D
Purchase vs. produce	X			X				X	X	X				D
Application rates	X							X		X				D
Transportation costs	X				X									D
Melting qualities						X								D
Heated						X							X	D
Traction qualities						X								D
Damage potential						X								D
Wood chips						X								D
Salts														
Bulk vs. sack	X			X				X	X	X				D
Process vs. kiln dried	X							X	X	X				D
Heated	X					X								D
Storage	X			X				X		X				D
Specs/sizing	X			X				X	X	X				D
Calcium chloride vs. sodium chloride	X					X		X	X	X				D
Mixed calcium & sodium chloride	X					X		X	X	X				D
Application	X							X	X	X				D
Mix of salt and abrasives	X			X		X		X	X	X				S H
Patterns of application	X			X		X		X		X				D S
Snow poles	X							X	X					S
Gathering all FHWA data and slides	X							X	X					D
OTHER														
Ongoing improvement system	X			X				X						H
Legal responsibility for driver's actions				X	X			X						H
Evaluation of District sanding policy	X			X	X		X	X						H
Shift costs of snow removal to public	X			X						X	X			H
10 Program policy issues remaining to be solved	X			X	X					X				H
Plowing and sanding procedures	X			X				X			X			D H
Prepare final report	X			X	X					X				H

ATTACHMENT I

June 16, 1975

From: DEPARTMENT OF TRANSPORTATION
Division of Highways
Division of Maintenance & Operations

Subject: Issue Memo No. 26-75 System Operations

I. ISSUE

Improvement of snow removal methods and procedures, and equipment and materials selection and usage.

II. PROPOSAL

Undertake a procedural study of snow removal activities to reduce the cost by:

A. Improving methods and procedures for snow removal.

B. Improving equipment selection and usage.

C. Improving materials selection and usage.

D. Developing a system to assure that similar improvements are made on an ongoing basis.

III. BACKGROUND

Issue Memo N. 2-73 System Operations initiated the "Bare Pavement" study. As a result of this project, a clear snow removal policy was established with related levels of service. These will facilitate procedural improvements:

During this study the following were indicated:

A. Levels of service cannot be lowered significantly to reduce costs: however, potential savings will be realized through procedural improvements.

B. Savings realized in District 02 of $140,000 in the 1973-74 snow season were due to changes in salting and sanding methods.

C. Equipment used for snow removal is highly specialized (many districts require special adaptations that make equipment different between districts).

D. Our salting practices have resulted in significant bridge damage in the Central Valley.

E. Environmental concern over presumed salt damage in the Tahoe Basin will probably bring pressure for blanket changes on the use of snow removal chemicals.

F. Compared to some states, the Department appears to not be very sophisticated or cost conscious regarding snow removal procedures.

G. In the past, proposals have been made to buy more "off the shelf" equipment and this has been resisted.

This study will deal with these and similar type issues. Initially it is felt that an overall look at how snow removal activities are conducted is essential.

IV. POTENTIAL SAVINGS

During an average year snow removal costs are approximately $9 million (1973-74 dollars). Procedural improvements could result in at least a 10% savings. ($900,000). This seems reasonable if you consider that other than through the budgetary process there have been few efforts to reduce snow removal costs. Further, considering District 02 reduced their sanding and deicing expenses by $140,000 through a procedural change, it would seem that on a statewide basis larger savings are possible; especially when material and equipment selection and usage is evauluated.

V. SENSITIVITY

Public. In the Bare Pavement Study it was found that the public is very sensitive ot snow removal activities and that any lowering of levels of service will be met with resistance. However, as far as procedural changes are concerned, as long as the public is not detrimentally affected by these changes, they should not be sensitive. It becomes a case of how you approach it — some changes would be welcome.

Internally. Procedural changes will mean fewer hours spent and fewer jobs required, thus there will be resistance. Also there will be the natural tendency to resist any change. Furthermore, the snow removal "experts" in the Department will probably not like anyone suggesting improvements can be made. As far as equipment and materials selection and usage, there will be resistance internally, and if vendors are involved there will be resistance there also.

VI. SUGGESTED APPROACH

On approval of this Issue Memo:

A. Establish a core study team (suggest one member each from Management Analysis, Equipment, and Maintenance) to perform preliminary survey and to determine potential savings.

B. Following preliminary survey, the core team will prepare a work plan.

C. Conduct study utilizing team members identified as needed in work plan. Note: At this time the Management Analyst should become a consultant providing direction and objectivity on an as needed basis.

D. Preliminary indications are that major efforts will be on:

1. Improving methods and procedures.

2. Improving equipment, selection and usage.

3. Improving materials selection and usage.

E. Develop means of making continual improvements.

VII. ANTICIPATED PRODUCTS

A. Section 20 of the Maintenance Manual dealing with snow removal will be completely rewritten. It will include and supersede the snow removal policy contained in Policy & Procedure 75-24.

B. If necessary, additional Policy & Procedure directives will be issued for procedural improvements. However, if possible these should be contained in revised Section 20 of the Maintenance Manual.

C. A final report will be prepared documenting the proposed changes.

ATTACHMENT II

DATE __________

WORK PLAN FORMAT

(Descriptive Title of Project)

I. AUTHORITY:

Identify who requested the study, when: who are the original and ultimate client(s); who is (are) the decision-maker(s).

II. PROBLEM(S):

Where a preliminary survey report is not attached, clearly identify the problem(s) (or apparent problem(s)).

III. OBJECTIVES:

What is (are) the objective(s) of your project? What is it that you are trying to accomplish? You may wish to identify these as specific or secondary objectives. Use concrete rather than abstract terms. Your objectives will in turn dictate the design of your project.

IV. SCOPE:

What are the major areas of your study? What are the parameters?

V. LIMITATIONS:

This heading could logically be combined with Scope in that both define the limitations of your project. Include here manpower requirements or factors that will modify or restrict your project.

VI. DESIGN:

In designing your work plan, what are your assumptions and anticipated data collection processes?

A. Assumptions:

What are some of your initial beliefs that must be considered and clarified (these also may act to limit the scope of your project).

B. Study Order:

How do you propose to separate your projects into issues and subtopics? Considering these, what type of data do you need? How do you plan to collect and evaluate these data? The analyst should first think of what type of information he needs, how he will use it, what his sources of information are, and how he will collect the information.

1. Sources

What people, publications, documents, records, and other references pertain to your project? Which are available to you?

2. Data Collection

How do you intend to collect this information? Through reading, observation, interviews, questionnaires, telephone survey, other means? In what sequence do you expect to use the methods outlined for acquiring information?

3. Data Use

(This is probably the most important area for the analyst to consider when building a work plan.) What type of information do you need? And how are you going to use it? The analyst should have this clearly in mind before starting the data collection.

VII. EXPECTED PRODUCTS:

These fall into two classes, documentation and expected results (positive change).

A. Documentation:

What memos, reports, recommendations, action documents, and/or presentations will be produced?

B. Results:

What will be the expected results of this project—specific improvements.

VIII. RESPONSIBILITIES:

Identify person, task force members, decision-makers, and others who are responsible for specific actions.

IX. IMPLEMENTATION:

Identify the analyst's involvement in the implementation of recommendations. (Build in here feedback to interviewees and those providing information.)

X. SCHEDULE:

Include a schedule that is appropriate for the project. Keep the client in mind. Include checkpoints, decision points, and expected products. When studies are conducted in phases, provide sufficient information about the activities in these phases. The decision-maker can then evaluate the usefulness of the overall project. The type of schedule used should be appropriate for the project. KEEP IN MIND ITS USEFULNESS FOR THE CLIENT.

The Effects of Highway Design Standards on Snow and Ice Control Operations

Robert A. Hogan, New Hampshire Department of Public Works and Highways

Despite the many technological improvements of modern highways, there are new projects being designed and constructed with insufficient recognition of maintenance problems, especially those involving snow and ice control. The complications of urbanization, increased traffic, greater variation in vehicle size, initial cost restraints or considerations and ecological considerations have forced designers away from "the basics" thereby compromising highway safety. The hazards created by snow melt are explored and remedies suggested to either eliminate or substantially alleviate these and other problems to provide for greater safety and reduce maintenance costs. Methods are also offered on various techniques to obtain greater recognition by designers and constructors of the maintenance aspects of highway engineering thereby averting costly revision after maintenance becomes responsible for new highway sections.

There is no doubt in the minds of any highway engineer, regardless of the phase of specialization, that safety is a primary objective in providing modern highway facilities. However, many projects are still designed and constructed with insufficient recognition of the maintenance aspects, particularly in the area of snow and ice control, and have a direct bearing on safety.

Obviously, icing can least of all be tolerated on curves and interchanges, especially at ramp intersections with cross roads controlled by stop signs or traffic signals. The problem of snow melt which creates a wet pavement condition during the day can become treacherous glare ice at night. Maintenance personnel are cognizant of the potential hazard and take necessary precautions to alleviate these conditions. Such action takes a great amount of effort and is extremely costly in terms of manpower, equipment and materials year after year.

The additional cost of salting and/or sanding these trouble spots over a short period of time would more than pay for the increased construction cost of preventative measures, and most importantly, a much safer highway would be provided.

Maintenance engineers must impress upon designers to become more aware of this problem and implement designs to eliminate, or at least substantially alleviate, these hazardous situations. It will not be easy particularly in view of the fact that highway geometrics are now greatly influenced by environmental and political pressures more so than basic engineering decisions. Administrators are forcing designers to minimize costs thereby imposing another restraint, which in actuality is false economy.

The only solution is to begin a concentrated campaign calling these problems to the attention of administrators, as well as design and construction people.

First, let's take a brief look at some of these problems and suggested remedies.

Bridges

The design of bridge decks on banked curves for the most part have a cross section with a straight line grade from curb to curb with sidewalks sloped downward toward the pavement. (See Figure 1.) Snow plowing operations produce windrows of snow on the sidewalks or catwalks creating a snow melt problem until the snow is either physically removed or completely melts from the high side of bridges. Normally roadway cross sections are designed with a break in shoulder slope on the high side of banked curves such that snow melt runoff remains on the shoulder running along the snow windrow to suitable outlet. There appears to be no reason why screeds cannot be set to construct a similar cross section on bridge decks as on roadway sections. These screeds are set to establish a crown on bridges located on tangents and with relatively minor adaptations the proper cross section can be provided on superelevated bridges as shown in Figure 2. Bridge drains located so plows can easily keep them clear are necessary to capture the snow melt.

Many people feel that deicing chemicals are major contributors to the deterioration of bridge decks and support structures, and with the flexibility built into modern bridges, this is probably true. However, the suggested design criteria would reduce the number of saltings by as much as one half in many areas of the country.

Figure 1

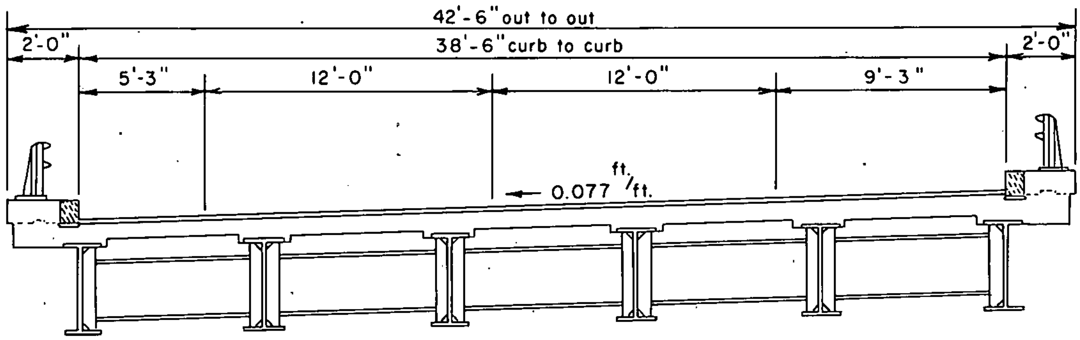
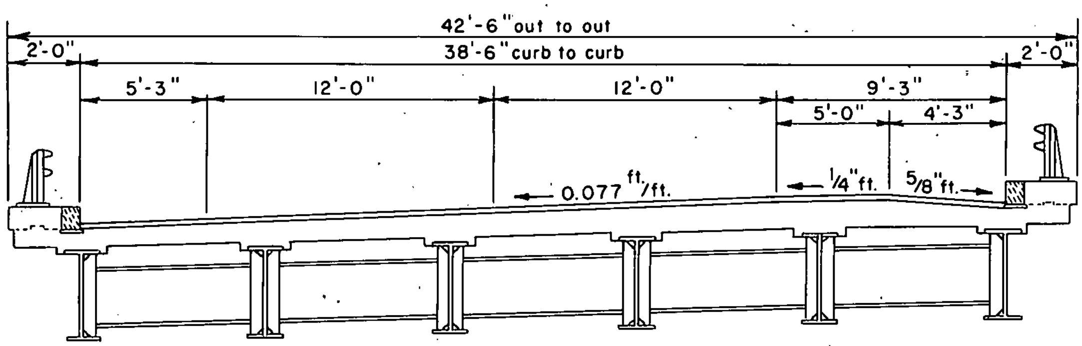


Figure 2



Although there is strong support for salt use to provide safe travel conditions following winter storms, heavy and needless seasoning with salt does not preserve bridges like it does many food products.

Several states have recently issued new design instructions adopting these basic recommendations and the Federal Highway Administration is becoming interested in this issue. All highway agencies in the nation's snow belt should implement these new design standards immediately.

A desirable remedy to many problems would be "getting back to basics" by keeping as many bridges on tangent sections as possible. In rural areas this can be more readily accomplished. High property values and other major control points in urban and suburban areas justify bridges on curves, but the ramifications must be considered.

Additional width of bridges would allow snow to be plowed onto the shoulder for temporary storage without the danger of pushing it onto pavements below. Such widening would also accommodate traffic more readily when deck replacement or other maintenance activity on bridges requiring lane closure is performed.

Channelized Intersections

Channelization creates many problems for maintenance forces during and following snow storms. Considerable non-productive dead heading occurs to return to clear slip ramps unless dangerous backing movements are attempted. Often plow operators are tempted to back up a hundred feet or so to avoid a trip of several miles to return. Unfortunately, the temptation is great and frequently plow units back into vehicles in the blind spot directly behind creating further delay and expense.

Many of the raised islands are definitely obstacles during a blizzard condition and periods of drifting, even if well marked with winter delineation.

These same barriers, whether directional, for lane separation or merely provided for placement of traffic control devices, contribute to sheet icing of adjacent pavements long after the storm is over unless proper grading and adequate drainage structures or systems are provided during the construction or subsequent improvement. All too often these improvements must be made by maintenance personnel at great expense for the highway organization, disruption to highway users, and criticism from the public.

Median Crossovers

Additional deadheading results from the lack of or improperly located median crossovers for use by snow removal equipment and emergency vehicles. In rural areas the use of crossovers can be used in a relatively safe manner, however, urban sections require special attention due to restrictions on right of way width, median barrier systems, the complexities of design, and safety considerations.

Medians and Gore Areas

Certainly in rural areas where wide median separation between opposing lanes is provided, drainage can be easily controlled with depressed medians and drainage systems. Likewise gore areas between mainline and ramps can be depressed and graded to facilitate drainage during periods of snow melt to prevent pavement icing on the mainline and ramps.

However, where narrow medians, with or without barriers, are required such as in urban areas and some mountainous terrain, the median is usually higher than the adjoining pavements (as shown in Figure 3) contributing significantly to the snow melt problem. The development of slotted culverts has offered a partial method in disposing of median snow melt, however, heavy frozen snow prevents capturing all run-off in the concept shown in Figure 4. Perhaps installation of slotted culverts along the pavement adjacent to the median barrier may provide a better solution although lack of cover and use of abrasives may involve expensive maintenance. By double crowning both pavements and installing ample drainage facilities as shown in Figure 5, a far safer highway can and should be provided with standard maintenance.

Interchanges

The complexities of directional type interchanges as well as interchanges of the non-standard variety (other than clover leaf, diamond, etc.) contribute to extra dead heading and extra equipment requirements. The complex elevated interchanges in urban and congested areas present especially difficult problems for winter maintenance operations as the result of narrow rights of way, superelevation, and transportation facilities and occupancy beneath them. (1)

Appurtenances

Guard rail, bridge rails, signing, delineation, and other elevated appurtenances can cause drifting and limit snow storage. Unfortunately, there are no simple solutions to many of these problems. The general discontinuance of cable guard rail by solid W-section beam rail has created many snow fences, although elevated highways with flatter slopes in recent years have been very helpful in reducing drifts and hopefully a high profile will continue to be used for this purpose. The opportunity for rectifying these problems offers a considerable challenge.

Despite many substantial improvements in recent years, even today many maintenance people will readily agree with a statement that appeared in one of the first maintenance studies back in the early sixties which stated: "From the beginning of highway maintenance, its heritage has included taking care of problems unknowingly and neglectfully perpetuated by design and construction engineers." (2)

In so agreeing, however, maintenance people are indicting themselves for failing to sound the alarm as well as design and construction people in perpetuating errors.

How can maintenance engineers impress upon designers to become aware of snow and ice control problems and implement designs to eliminate, or at least substantially alleviate, these problems? It's a difficult task, but not insurmountable. We cannot sit back and remain silent. Perseverance and imagination will be necessary. The establishment of an understanding must be instilled in the highway field and within our own organizations of the existence and magnitude of maintenance problems, and an atmosphere developed whereby our recommendations are given greater consideration.

Such an undertaking requires a diplomatic approach, but in the interest of safety and minimizing the cost of operations and costly premature reconstruction, the need to work toward such a goal is mandatory.

Although a thorough training program for young engineers exposing them to all major phases of highway engineering including maintenance would be most desirable, such a method would take considerable time and may not be attainable in many organizations. It is therefore suggested that maintenance input be brought into the pre-design stage by whatever methods will accomplish the objective. Post construction reviews with design and construction personnel can be used to point out deficiencies and problems which hopefully will be recognized and corrected in future designs. (3)

Invitations to designers to accompany plow operators from the initial call for a storm to the final clean up, seminars including training films, etc. can be used to produce desired results. Take the chief bridge and road design engineers for a ride on a beautiful early spring day and show them the melting snow windrows producing wet pavements and the salting and sanding crews treating the wet areas in the late afternoon to prevent sheet icing after the sun sets.

Figure 3

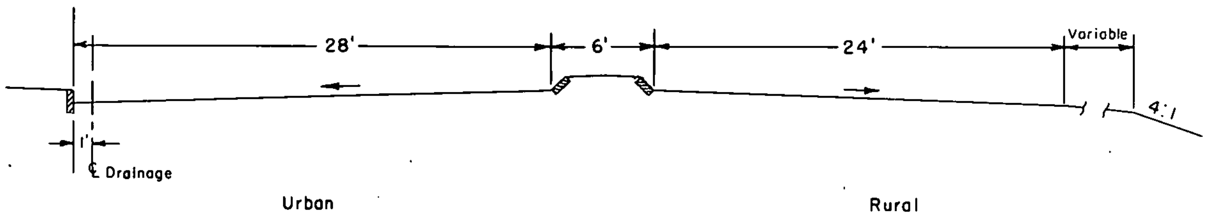


Figure 4

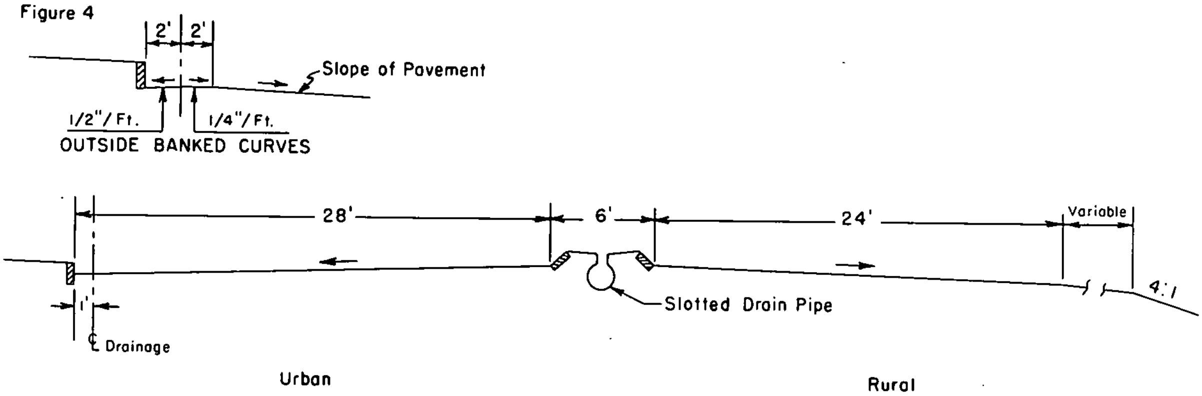
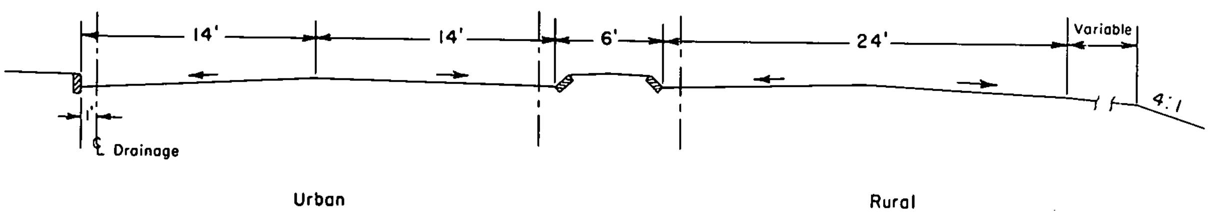


Figure 5



In any event a sincere and conserted attempt should be made to optimize the maintenance effort by initiating all highway personnel, administrators through laborers, and obtaining their assistance in achieving the safest highway systems that authorized funding will allow.

In any procedure adopted, what should be our objective as maintenance people? The first is obvious; the adoption of designs to provide safety and long life with a minimum of maintenance and of construction procedures that insure the attainment of design objective and preclude early failure of components. The second, and not so obvious and perhaps more difficult of attainment, is the inclusion of positive aids to maintenance. Some of the items that have been suggested previously include improving cross section on bridges, provision of crossovers on limited access sections for maintenance as well as police and emergency vehicles, the provision of access to all portions of interchanges to permit full utilization of equipment, the provision of parking spaces for maintenance equipment on long structures with movable spans to eliminate blocking lanes, the provision of adequate widths in medians with barriers requiring maintenance so equipment can be parked clear of traffic lanes and numerous others. In general urban projects require particular attention since it is in these areas where many of the special problems arise due to restrictions on right of way widths and complexities of design and it is here that maintenance is difficult and costly to perform due to high traffic volumes.

In summary, we need to establish positive channels with design and construction people so that the problems being encountered by maintenance can be brought to their attention in a climate of understanding that will insure consideration of these problems by the other divisions. Of the methods currently being used, post-construction review appears the most functional approach and it should work best when an adequate check list is used to insure consideration of all components of the completed facility.

Today the name of the game is to achieve high skid resistance. To achieve the highest possible skid resistance following a winter storm is to obtain a bare dry pavement as quickly as possible following cessation of each storm.

With sovereign immunity becoming a historic memory in many states, legal actions against governmental agencies rapidly are gaining in popularity and courts are awarding large settlements thereby further promoting perpetuation of this cycle, it behooves all highway officials to recognize the implications of the snow melt and other maintenance problems and take appropriate actions to rectify them in the planning, design and construction phases.

References

1. L. G. Byrd. Snow Removal and Ice Control Techniques at Interchanges. NHCRP, Report 127, 1971.

2. AASHO Committee on Maintenance and Equipment. Report by Subcommittee on the Practices of Design and Construction as to their Effects on Maintenance, 1966.

3. Robert W. Sweet. How Design Helps Maintenance. American Highway Magazine, April 1964, p. 7.

Snow Removal and Ice Control Standards at Canadian Airports

W.V. Levitsky, Transport Canada

Snow removal and ice control levels of service at Canadian airports are defined in terms of the maximum allowable snow accumulation and the maximum allowable snow clearance time. The influence of airport category, aircraft type and the relative importance of a surface area, on the level of service of snow removal, are explained.

Factors affecting the provision of resources for snow removal and ice control are outlined, such as the desired level of service, air traffic and equipment performance characteristics.

The standard methods of snow removal and ice control practised at Canadian airports are discussed, which are casting, hauling and compacting of snow and prevention, removal and sanding for ice.

Priority areas of an airport are defined in terms of the minimum operational requirements that must be satisfied during a defined maximum snowstorm.

The methodology for determining the type and number of equipment for snow removal for a given airport is developed which can be applied to a computer program. The computer input consists of: the maximum allowable snow accumulation, the size of the area to be maintained, the rate of snowfall, the average operational speed of equipment, the clearing width of the equipment, the average runway occupancy time and the average number of aircraft movements per active runway.

The approved materials for the prevention, removal and control of ice are described along with the required performance standards for chemicals and materials.

The procedures, equipment and responsibility for the measurement, reporting and dissemination of runway surface condition during winter operations are outlined.

Introduction

Objective and Scope

Snow removal and ice control is the major winter operational activity at Canadian airports.

The basic objective of snow removal and ice control is to ensure that safe and efficient aircraft and vehicle manoeuvring surfaces exist in accordance with stated level of service.

Levels of Service

The level of service of snow and ice control is expressed in terms of "how fast" and "how well" the service is provided. It refers to the maximum snow accumulation that will be permitted to occur on a maintained area during a storm, or the maximum time that will be allowed for the clearance of the storm's accumulation after the end of the storm.

The level of service of snow and ice control will vary for different areas, depending on the category of the airport, the type of aircraft and the relative importance or priority of the area.

Factors Affecting Provision of Resources

The factors which determine the provision of resources for snow removal and ice control (equipment, materials, manpower) at an airport are:

(a) the level of service;
(b) surface areas to be cleared;
(c) climatic conditions;
(d) aircraft traffic density;
(e) equipment performance characteristics.

Snow Removal Methods

The methods used to remove snow from airport operational areas are more varied in speed, capacity and type of equipment than those used in municipal or highway operations.

There are three basic methods to remove and/or control snow: casting, hauling and snow compaction.

(a) The casting method which is the fastest and most economical method is used on most areas on the airside such as runways, taxiways and portions of aprons.

(b) Hauling is normally employed to remove snow from portions of aprons and groundside areas.

(c) The object of snow compaction is to provide a sufficiently hard surface of snow on which aircraft or vehicles can safely operate. Snow compaction is generally practiced at arctic airports having gravel runways and is also employed on unpaved airside service roads and for snow control.

Snow Disposal

In cases where casting methods are used, snow disposal is not required. When hauling methods are used, means of disposal are necessary and normally consist of establishment of snow dumping areas.

Snow Removal Equipment

The mobile equipment generally employed at Canadian airports consists of truck-mounted plows, towed runway sweepers and self-propelled snow blowers.

Ice Control

Ice on aircraft manoeuvring surfaces creates an unsafe condition for aircraft operations and thus it requires removal or control. Ice is controlled by the use of sand and chemicals.

Operational Standards

Although Canadian winters range from extreme cold and heavy snow to moderate temperatures with little or no snow, the operational standard for active runways which we aim for is published in the IFR Supplement of Canada Air Pilot, "Insofar as practicable, snow removal and ice control are carried out to provide airport surfaces which will permit safe operational use at all times." The active runway, adjoining taxiways and access to the terminal apron and aircraft parking areas are maintained in a serviceable condition on a "priority one" basis. The remaining manoeuvring and movement areas are cleared on a lesser priority basis in accordance with operational requirements. Except for the extraordinary storm condition, the staff and equipment resources at international airports are such that a 75 foot wide centre area of the priority runway is continually cleared within 30 minutes.

Operational Requirements

(a) Priority Areas

The airside priority areas are:

(i) Priority I Area - This is the minimum area that must be cleared on a continuous basis throughout the storm to maintain the minimum airside operational capability of the airport.

This area is usually composed of the following surfaces:

(1) One runway
- the choice of runway is dictated by the prevailing wind direction;
- during severe storm conditions the runway shall be maintained to a minimum width of 23 metres (75 ft.);

(2) One taxiway
- maintained to its full width;

(3) Sufficient apron area to accommodate aircraft, passenger terminal and cargo requirements which accounts for at least 20% of total area.

(4) The entrance and exit access associated with the runway, taxiway and apron areas.

(5) Access roads from firehall to all of the above areas.

(ii) Priority II Area - This is the area that will be cleared throughout the storm so that in the event of a change in the prevailing weather conditions (e.g. wind direction) the other runway can be made operational on short notice.

This area will be composed of the following surfaces:

(1) Secondary Runway;
(2) Secondary Taxiway;
(3) The entrance and exit access associated with the above runway and taxiway;
(4) Associated apron access to taxiways if different from those previously cleared under Priority 1 clearance operations;
(5) Area of apron required to gain access to the minimum 20% previously cleared under Priority I clearance operations.

(iii) Priority III Area - This area is composed of surfaces which are cleared after a snow storm. Such areas are as follows:

(1) Airside service roads;
(2) Runway, taxiway shoulder areas;
(3) Pre-threshold areas;
(4) Glide path sites;
(5) Remaining airside areas required to permit full operational use of the airport.

Level of Maintenance - Aircraft Manoeuvring Areas

In order to reach realistic objectives in respect to effectiveness of snow removal the following assumptions are made:

(a) Sufficient equipment to keep the airport operational during a worst possible storm condition will not be provided.

(b) Sufficient equipment will be provided to keep an airport operational during 90% of all possible storm conditions. This 90% confidence level shall be considered "normal storm conditions" (weather conditions).

(c) Determination of equipment requirements will be based upon the calculation of requirements for runways, taxiways and aprons (equipment supply).

(d) All paved runways, taxiways and aprons shall be cleared to bare pavement surface using a combination of plowing, sweeping and/or blowing (degree of cleanliness).

(e) The maximum allowable accumulation depths of snow for the different priority areas, are set as follows:

- Priority I areas - 1.3 cm (1/2 inch)
- Priority II areas - 5 cm (2 inches)
- Priority III areas - storm accumulation

Provision of Equipment for Snow Removal

A method has been developed for determining snow removal equipment requirements at Canadian airports.

It consists of using a computer program, a formula and data which describes the pertinent conditions at a given airport site.

The formula determines the number of equipment types required as follows:

$$CPPP = \frac{AR}{1000\ V,S\ (1-t.M)} \quad \text{(Metric)}$$

$$CPPP = \frac{AR}{5280\ V,S\ (1-t.M)} \quad \text{(Imperial)}$$

where

CPPP is cleared path per pass, metres (feet)
S is maximum allowable snow accumulation, cm (in)
A is area to be cleared, m^2 (ft^2)
R is rate of snowfall at 90% confidence level, cm/hr (in/hr)
V is operating speed, km/h (mph)
t is average time per aircraft movement, hours
M is average number of aircraft movements per hour per active runway

It is intended that this technique become a rule of thumb in arriving at snow removal equipment requirements for a new airport or following expansion and air traffic growth at existing airport sites.

It is realized that certain factors such as prevailing winds, temperature fluctuation, efficiency of the snow removal operations and operational status of particular equipment at any given instant are not specifically being included; such variables will be considered at a later time.

The computer program itself is presently undergoing the debugging and refinement stage. Snowfall data for the various airports is being collected and reduced for computer storage. It is intended that the first full scale evaluations of the formula/computer program will begin by early fall.

The computer printouts will be compared with actual airport equipment inventories for compatibility. The need and extent of adjusting the program will then be evaluated.

Ice Control Standards

At the present time there are three approved solid chemicals that can be used for ice control on airport operational surfaces. These are described below.

In addition to identifying the chemicals that are acceptable for use on airports, criteria are needed by which chemicals shall be evaluated to determine their operational effectiveness.

Chemicals - Airside

Solid chemical Urea may be used both as an anti-icer and a de-icer on airside areas such as runways, taxiways and aprons.

Chemicals - Groundside

Solid chemicals sodium chloride (common salt) and calcium chloride may only be used on the groundside areas of an airport such as access roads, service roads, parking lots etc. The use of sodium chloride or calcium chloride is prohibited on any airside area due to their corrosive effect on aircraft components.

Performance Standards for Airside Chemicals

After a chemical has been found compatible with aircraft components, pavement materials and the environment, the criteria by which a chemical is considered to be effective is as follows:

(a) for anti-icing - the ice control chemical, when applied prior to or during a freezing rain, or a lowering of temperature, shall prevent the coefficient of friction from falling below half the value of the clean dry pavement; and will render possible the removal of ice/slush contaminant by mechanical means;

(b) for de-icing - the ice control chemical application shall raise the coefficient of friction of the ice covered surface to at least half the value of the clean dry pavement within one hour of application and will render possible the removal of ice/slush contaminant by mechanical means.

Winter Operational Reporting Program

(a) Transport Canada Policy

It is the policy of Transport Canada to measure the coefficient of friction of runways at designated airports during winter months and report the coefficient of friction value to pilots and airlines. The coefficient of friction is measured only when solid state conditions exist on a runway, that is when compacted snow and/or ice, but not water or slush, are present. This is an operational procedure and forms an integral part of winter maintenance of Canadian airports.

(b) General Procedures

Runway coefficient of friction is measured and reported on a routine basis using James Brake or Tapley Meter Decelerometers.

At all airports having ground-to-air communication, the Airport Manager or his designated authority provide periodic voice reports on runway surface conditions to the appropriate ATC unit, or if there is no ATC unit at the airport, to the aeradio station operator, in accordance with the criteria and terminology set forth.

(c) Follow-up Written Reports

Voice reports are confirmed by follow-up written reports at airports serving scheduled air carriers. Written confirmation is not to be carried out for every voice report, but only when a significant change in runway surface conditions takes place.

(d) Criteria and Terminology

The following criteria and terminology is used for reporting runway surface conditions:

(i) Runway Bare and Dry (give percentage);

(ii) Runway Bare and Wet (give percentage; also, if there are any pools of water, give location, extent, and depth; indicate "removal in progress" if applicable);

(iii) Runway Snow Covered (give percentage; also, give the depth, indicate drifting and depth of drifts if applicable; indicate "removal in progress" if applicable);

(iv) Runway has Ice Patches (give percentage; also, indicate "sanded and/or "Urea-treated" if applicable; indicate "removal in progress" if applicable);

(v) Runway Slush Covered (give percentage; also, give the depth; indicate "removal in progress" if applicable);

The James Brake Index (JBI) or Tapley Meter Index (TMI) is reported as an average for each runway. However, if one section of a runway has a friction value (JBI or TMI) that is 0.10 or more lower than the average for the whole runway, then that value and the affected area will be reported as well as the average value for the runway.

In addition, if one end of the runway happens to be water covered and the remainder of the runway is solid state (covered with ice or compacted snow), only the friction value (JBI or TMI) for the solid state portion should be reported. The wet condition should be reported as such together with the extent of coverage from the runway threshold.

NOTE: All condition report data refers to the entire width of the runway.

New Jersey Department of Transportation Model for Winter Equipment and Manpower Allocations

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The Equipment and Personnel Task Force of the New Jersey Department of Transporation met periodically over an eight-month period and during that time developed formulas applicable to spreading by State forces, plowing by both State and contractual forces, distributing manpower to spread on a shift basis and applying a distribution percentage to the assignment of new trucks whether they be replacements or new equipment.

The Chief Engineer, Construction & Maintenance, New Jersey Department of Transportation, directed that a Task Force be formed with the Chief of the Bureau of Maintenance to act as chairperson for the purpose of developing the required equipment and manpower allocation needed for snow removal and ice control operations.

The questions to be answered by the Task Force were the following:

What equipment and manpower is required for winter maintenance operations, snow removal and ice control to meet New Jersey's policy of "wet pavement as soon as ecomonically feasible after the storm?"

How can the department develop an equitable allocation of existing equipment to meet regional demands with reference to the number, type and age distribution of the truck fleet?

In response to these questions, formulas were developed for de-icing spreading, snow plowing, distributing manpower, and allocating new highway trucks.

Formula for Spreading

The basic concept of the following formula is to complete the initial statewide spreading application of chemical de-icers within one and one-half hours. Taken into account in this formula is the speed of the vehicle (spreading and not spreading), the presence of both long two-lane sections and short multi-lane sections, and the additional time consumed for spreading on ramps:

$$S = 0.4C + 0.9\,[L + 2.5R]$$

S = adjusted lane miles spread
C = center line miles
L = roadway lane miles
R = ramp lane miles.

The above formula is further modified to reflect the age of the existing fleet. The data supplied indicated an average 80% up time for our truck fleet. This formula is as follows:

$$(S') = (S) \times 1.25$$

Once (S') has been determined the following truck formulas can be used. The mix of trucks is adjusted to meet the requirements of each foreman's section:

$$T_{2.5} = \frac{S'}{22} = \text{Total of 2.5-ton trucks needed to spread } (S')$$

$$T_{6} = \frac{S'}{36} = \text{Total of 6-ton trucks needed to spread } (S')$$

$$T_{10} = \frac{S'}{62} = \text{Total of 10-ton trucks needed to spread } (S').$$

The criterion used for the number of loaders required for spreading operations is equal to the sum of mainline lane miles plus the ramp lane miles divided by 150:

$$\text{Number of loaders required} = \frac{L+R}{150}$$

Formula for Plowing

Similar to the spreading operations, a plowing formula was developed on the premise of completing one entire clearing of snow from the roadway within a two-hour time period. The formula is as follows:

$$P = \frac{L + E + 2.5R}{7.5t}$$

P = number of plow trucks required
L = lane miles
E = shoulder miles (over 5' in width)
R = ramp lane miles
t = 2 hours

Figure 1. NJDOT regional maintenance boundaries.

This formula allows for the increasing of plowing time which in effect decreases the number of plowing trucks required. This is of considerable importance because of the increasing difficulty of hiring private contractors to plow snow in certain areas of the State. This formula will allow the Department to formulate a policy as to the amount of time acceptable to clear the roadway of snow.

As a result of the application of this formula, it became evident that certain areas in Region 4 (see Fig. 1) cannot economically meet the two-hour plowing time criterion. There are no contractors available in this area and it is not economically feasible to purchase additional trucks to meet this need. A more realistic period of three or four hours should be established for this area.

Personnel Requirements for Snow Operations

Personnel requirements are based on one man to a truck on a twelve-hour rotational shift basis. Taken into account is benefit time and attrition, because turnover of employees is a way of life in Maintenance and should be recognized as such:

$$(M) = (A) + (B) + (W)$$

M = employees required
A = personnel required to man the spreading vehicles based on the adjusted spread (S) plus loader operators. (For a 24-hour coverage - multiply the personnel by 2)
B = the benefit time which is 20% x (A)
W = the attrition which is 8% x (A).

Truck Assignments

A distribution percentage was established for each region for 2 1/2-ton, 6-ton and 10-ton dump trucks. Taken into consideration was the use of 2 1/2-ton, 5-man cabs, needed in regular maintenance functions. Using this percentage, new trucks will now be assigned according to the set percentage. This will create an equitable fleet age distribution for each region.

Summary

The previous information is a valuable tool in budgeting, especially in the area where new highways are opening to traffic. By applying the above formulations, additional equipment and manpower required for winter operations can be determined when the project is in the design stage. To keep a program such as the one established, it will be necessary to perform periodic reviews to include additional mileage in the inventory, crew headquarter relocations, additional crews, and any physical or policy changes that would affect the data.

Conclusions

This study indicated that:

1. There exists a shortage in the total number of trucks and loaders available for snow emergency operations.

2. There were inequities in the existing distribution of trucks for snow and ice control operations. These inequities were both inter-Regional and intra-Regional.

3. While the average distribution by age appeared equitable, there exists some uneven distribution of vehicles for any one model year.

4. The problem of equipment "down-time" could be initiating a more realistic replacement cycle for dump trucks. We are currently on an eight-year replacement cycle.

5. The need for contract "snow plowing" to supplement our fleet is justified.

6. Due to the inability to obtain adequate contract plowing services to some areas of the state, a decision will have to be made either to: a) accept a longer period of time for the pavement to be cleared of snow, or b) "over-equip" those sections with state trucks in order that they may complete plowing operations within the specified time.

7. The need for hired loaders was verified.

8. Taking into consideration split shifts and employee benefit time, we are approximately 100 men short for statewide spreading operations.

Action Taken

1. Trucks will be reallocated based on spreading and plowing formulas developed by this committee subject to total available trucks.

2. The need for light graders and rollers, used to regrade unpaved shoulders and unpaved institutional roads, has decreased to a level that allows the cross-trading of 21 light graders and 2 rollers in the replacement program for trucks.

3. The age of the truck fleet will be adjusted so that in future years each Region will receive an allocation of new trucks based on the percentage of the total trucks of that class in each Region.

4. Some contractor plowing sections have been adjusted based on the data formulated in this report.

5. Funds were re-appropriated into equipment procurement accounts to purchase twenty additional six-ton dump trucks.

Further Recommendations

1. There should be periodic reviews as new inventory is added to the roadway system.

2. The data developed by this study should be used for budget purposes to document shortages that still exist.

3. A computer program based on this study should be established with inventory updating capabilities. The output documents should be made available semi-annually on a timely basis to coincide with the budget preparation and preparation for the snow season.

4. Top management should be advised that there are certain areas in the state where contract plowing services are not adequate. In these areas it will require a longer period of time for Department equipment to remove snow from the pavement.

5. An Equipment Review and Development Committee should be established. The purpose of this committee would be to provide field recommendations for new equipment purchases. Members of this committee would represent the Bureau of Maintenance, Bureau of Equipment and each of the Regions.

Laboratory Experiments on Icing of Rotating Blades

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Experiments have been conducted to provide a basis for a computer model that simulates atmospheric ice accretion on a rotating blade. A comparison of the computer model simulation and experimental results reveals that general agreement exists within the temperature range 0°C to -25°C and the velocity range 0 to 60 m/s. Beyond 60 m/s the computer simulation over-predicts the thickness of the ice accretion at the leading edge. Possible explanations for this observation are that beyond 60 m/s and in the wet growth regime the centrifugal forces experienced by the collected liquid water are a major contributing factor to water migration and shedding and therefore loss of liquid water and accreted ice. Also, there may be a significant loss in the collection efficiency at higher velocity due to turbulence developed by the proximity of the tip of the rotor. Below -25°C the simulation and experimental results disagree in that the simulation significantly overpredicts the thickness of the accretion at the leading edge. The possible explanation for the difference is that the effective liquid water content is suppressed due to increased ice particles in the air at these lower temperatures.

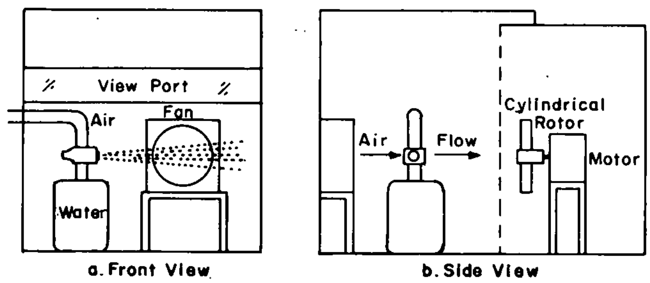
A preliminary model of the ice accretion phenomenon on an idealized helicopter rotor blade is being developed (1, 2, 3). Here we report some experimental data that can be used to test and improve the model and give further insight into the physical processes involved in icing. Six parameters, three of the ambient environment (air temperature, liquid water content and droplet size distribution) and three of the accreting object (velocity, cross section and shape), can specify the ice accretion process (3).

This paper discusses a series of experiments on a rotating icing system in which only the ambient air temperature and liquid water content were varied.

Experimental Apparatus

Figure 1 is a schematic of the experimental apparatus. The ice was built up on a hollow stainless steel cylinder 25.4 mm in outside diameter and 500 mm long with a 50-mm-diameter hub, centered at 250 mm from either tip so that the effective length of the leading edge was 225 mm. The rotor was driven by a 1.5 horsepower electric motor operating at approximately 373 radians per second (3600 rpm), resulting in a tip velocity of approximately 93.0 ± 3.1 meters/second.

Figure 1. Relative configuration of the water spray, fan, and ice-accreting rotor.

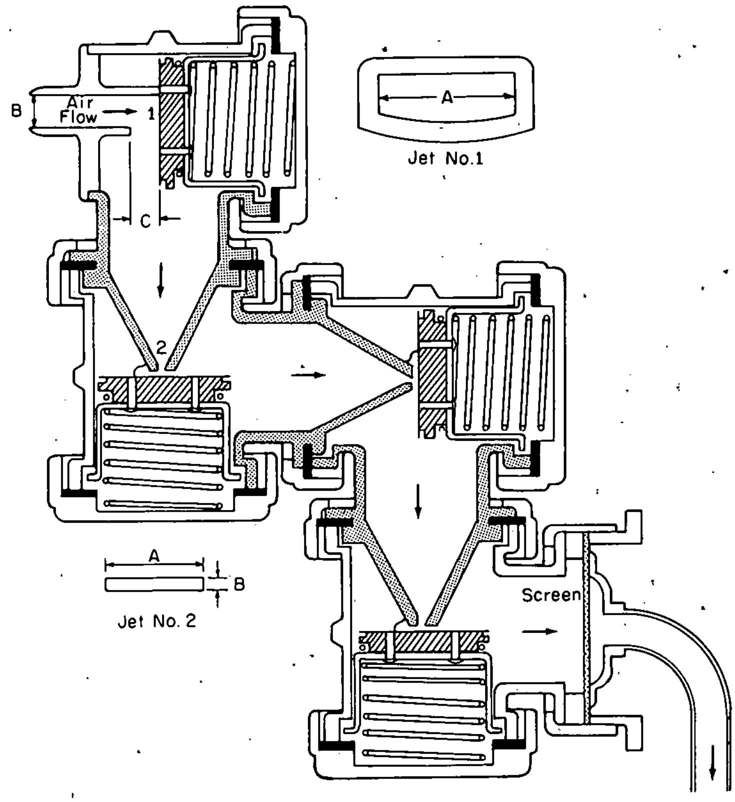


A simulated cloud environment was provided using an air atomizing spray nozzle and an electric fan (Figure 1a). The spray nozzle was operated in a variable head siphon configuration at 103 kP (15 psi). The electric fan delivered air moving perpendicular to the spray cone of water and carried a cloud of water droplets to the plane of the rotor (Figure 1b).

The droplet distribution of the simulated cloud was determined using a four stage cascade impactor as shown in Figure 2 (4). Glass slides covered with gelatin were mounted on each disc to record the droplets which impacted upon them. These glass slides were then examined under a microscope and by use of a semi-automated system the droplet size distribution was obtained. Figure 3 shows a histogram and average statistics of the droplet distribution.

Figure 2. Four-stage cascade impactor. Gelatin-covered glass slides were mounted on the disc and were held against the respective jets by the springs behind each disc. Jets 2-4 are rectangular slits whose dimensions are given below. Jets 1 and 2 are shown in cross section, detailing the dimensions. Jet 1 is 19 mm wide, 7 mm deep at the center, and 6 mm deep at the sides. All sides are straight except the bottom, which has a 45-mm radius of curvature.

Jet	Width (A)	Depth (B)	Clearance from disc (C)
2	1.4×10^{-2} m	1.45×10^{-3} m	2.00×10^{-3} m
3	1.4×10^{-2} m	7.50×10^{-4} m	3.60×10^{-4} m
4	$1.4 \quad 10^{-2}$ m	2.50×10^{-4} m	1.4×10^{-4} m



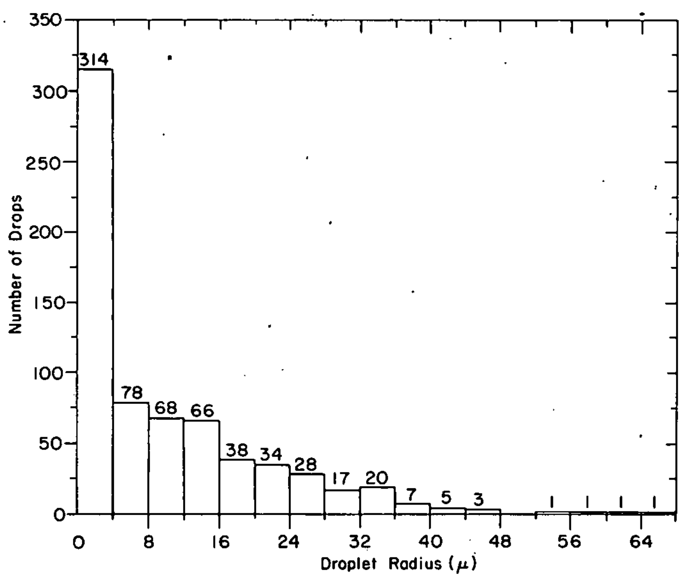


Figure 3. Histogram of water droplet distribution. The mean droplet radius was 9.56×10^{-6} m with a standard deviation of 11.09×10^{-6} m and a distribution skewness of +1.60. The mean volume radius was 1.87×10^{-5} m.

The liquid water content was obtained by measuring the rate of water usage by the spraying system in kg/s and dividing it by the total flux of air moved through the experimental setup by the fan.

The experiments were conducted in a coldroom held to within ± 0.5°C of each experimental temperature. The experiments were run for 240 ± 5 seconds total elapsed spraying time. Ambient air and water temperatures were taken just prior to and following each experiment. The accretion was photographed and weighed and its thickness measured on the rotor after each experiment was terminated. Thickness measurements were made along the leading edge at 10-mm increments. Ice accretion thickness measurements were also made at increments of six degrees of arc from the leading edge around the axis of the cylinder, up to 30 degrees of arc, on both sides of the leading edge. Maximum cross section widths were also measured at the corresponding 10 mm increments.

After these measurements were completed, the ice accretions were removed from the rotor and segmented into four 50-mm sections and one 25-mm section, beginning at the hub and proceeding to the tip. These segments were then weighed and used to obtain a density profile of the accretion. Thin sections for crystal structure analysis were then taken of the samples at the beginning and end of each section.

Results

Table 1 lists the experiments performed and the pertinent parameters for each experiment. The intent was to hold all variables constant with the exception of the ambient air temperature. As seen from Table 1, some variability was seen in the liquid water content between experiments. For the experiments, it was also assumed that the droplet size distribution remained the same as shown in Figure 3, where the values measured were taken at the usual experimental value of 1 g/m^3. It may be possible that the droplet size distributions also fluctuate with the variations in liquid water content.

Photographs of the accretions formed at -13, -17.5 and -29°C on the rotating cylinders (Figures 4, 5 and 6) illustrate three distinct regimes of ice formation. In the high temperature region from -13°C to the melting point, considerable amounts of unfrozen water were present, leading to the rough, irregular forms of the accretions shown in Figure 4. At lower temperatures (Figure 5) less unfrozen water was present, at least in the half of the rotor closest to the center of rotation (hub), and the ice accretion had a smoother appearance, more in conformity with the original rotor surface. The portions of the rotor nearest the hub began to show a more opaque appearance, indicating that the temperatures of formation on the rotor surface were somewhat below the freezing point (5).

At the lowest temperature (Figure 6) the ice accretion was smooth and regular in form, probably because the impacting droplets froze almost in place with relatively little movement of unfrozen water along the surface of the accretion prior to freezing. The ice also appeared milky and opaque, indicating that the surface temperature of the accretion was nominally below the freezing point, unlike the transparent ice formed at temperatures near the melting point (Figures 4,5).

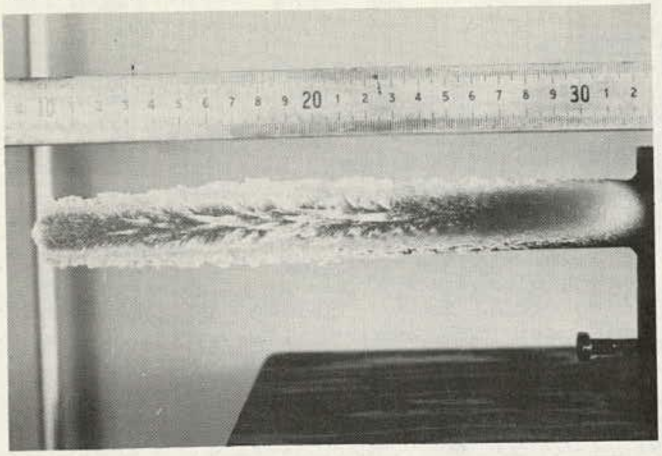
In Figures 7 - 9 we show the variation of the ice thickness along the leading edge, together with the results of a numerical simulation carried out by computer analysis using similar initial conditions as those of the experiments (2, 3). The thickness is plotted against the linear velocity of the position from the center:

$$v = R\omega \tag{1}$$

Table 1. Rotor test conditions and resulting maximum ice thickness.

Test	Temperature (°C)	lwc (g/m^3)	Maximum accretion (mm)	Velocity of max location (cm/s)
T-7-1	- 8.9	1.0851	9.3	61.51
T-13-1	-11.1	1.0851	10.19	68.97
T-9-2	-13.0	1.0851	10.64	68.97
T-11-2	-13.0	1.1109	10.32	68.97
T-10-2 (Fig 4)	-13.0	1.2662	11.08	68.97
T-15-1	-13.3	1.0330	9.05	61.51
T-17-1	-15.5	1.240	8.27	65.24
T-19-1	-17.5	1.0593	9.28	65.24
T-12-2 (Fig 5)	-17.5	1.2400	9.55	61.51
T-18-1	-17.6	1.0851	9.87	65.24
T-20-1	-19.5	0.9817	9.33	65.24
T-21-1	-20.0	1.0851	9.37	68.97
T-13-2	-21.5	1.4209	10.51	65.24
T-23-1	-21.9	1.0593	10.10	72.70
T-22-2	-22.2	1.0330	9.65	72.70
T-24-1	-24.0	1.1109	8.99	68.97
T-25-1	-24.2	1.1369	11.58	65.24
T-27-1	-24.9	1.0593	9.97	68.97
T-26-1	-25.0	1.1884	9.95	68.97
T-14-2	-25.0	1.3176	8.87	61.51
T-15-2 (Fig 6)	-29.0	1.2039	5.64	72.70

Figure 4. Ice accretion on rotor at -13°C
(a) Leading edge



(b) Cross section at tip of rotor

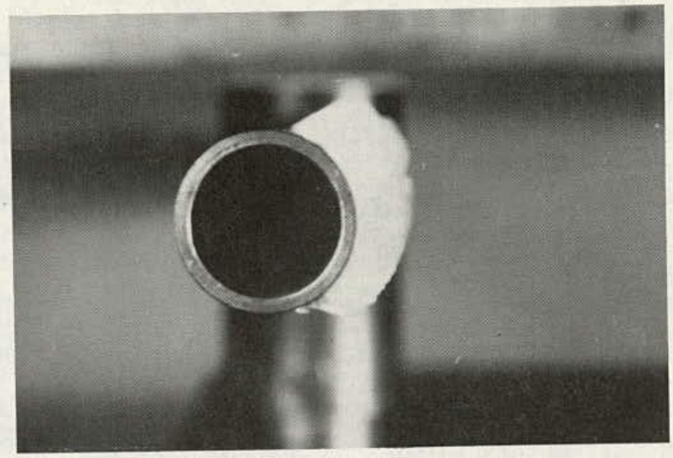
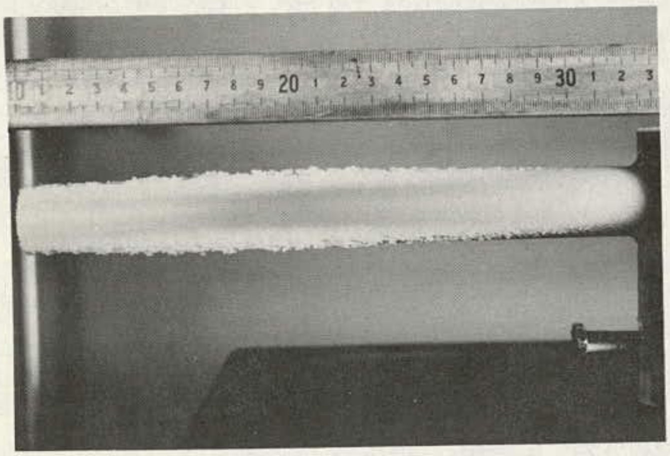


Figure 5. Ice accretion on rotor at -17.5°
(a) Leading edge



(b) Cross section at tip of rotor

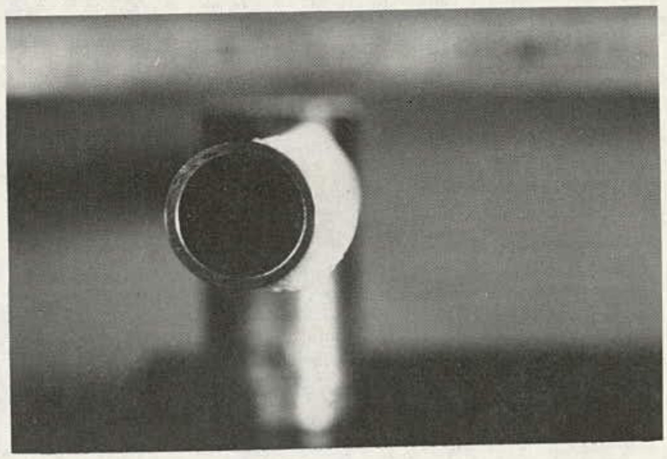
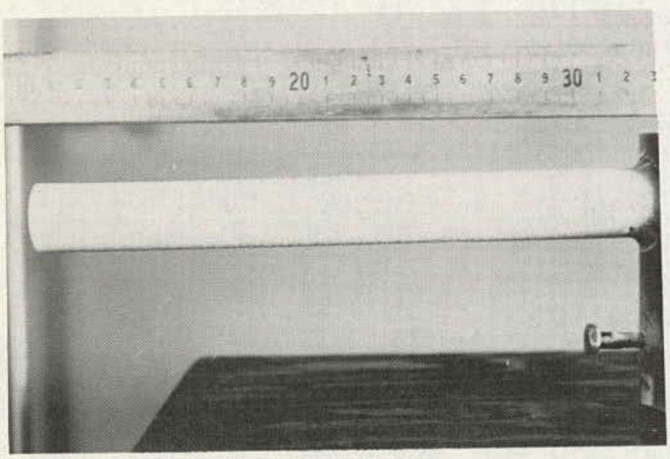


Figure 6. Ice accretion on rotor at -29°C
(a) Leading edge



(b) Cross section at tip of rotor

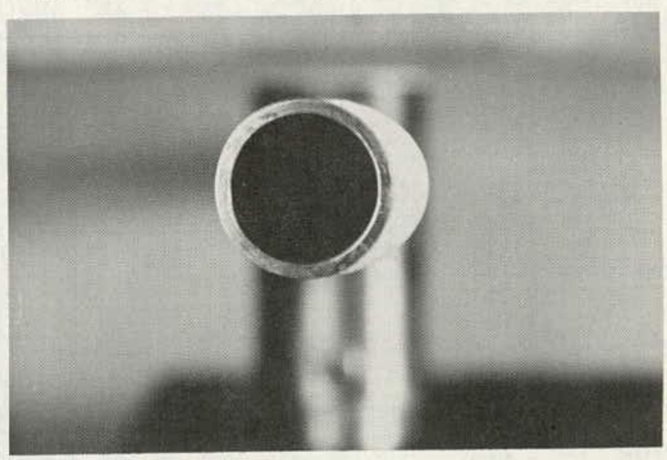


Figure 7. Experimental and computer simulation results for -13°C ambient air temperature. The Polynomial Fit represents the experimental ice accretion measurements. The scale at the top represents the grain size distribution versus velocity as measured on the thin sections.

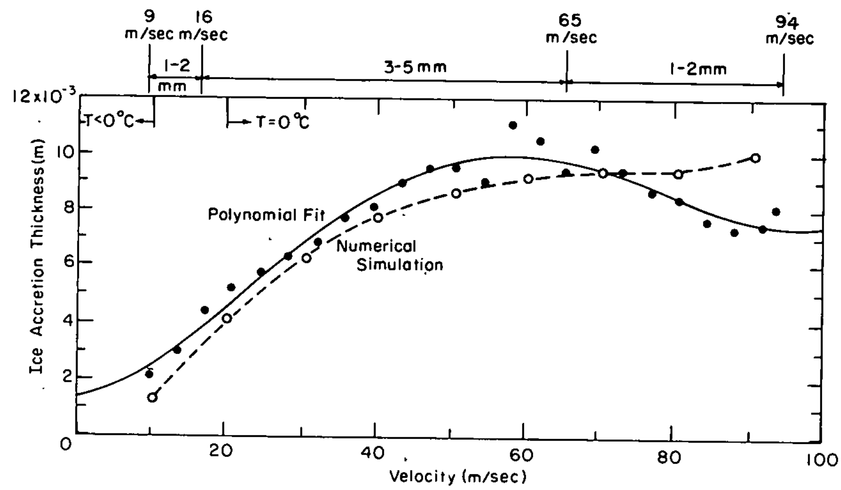
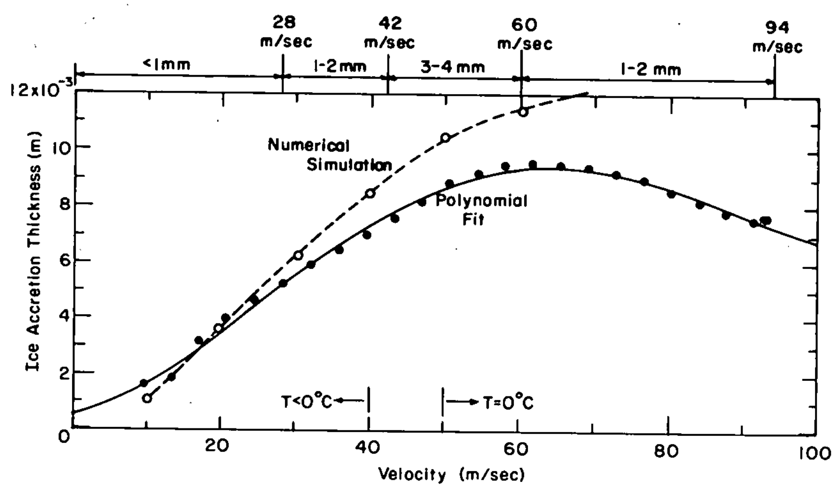


Figure 8. Experimental and computer simulation results for -17.5°C ambient air temperature. The Polynomial Fit represents the experimental ice accretion measurements. The scale at the top represents the grain size distribution versus velocity as measured on the thin sections.

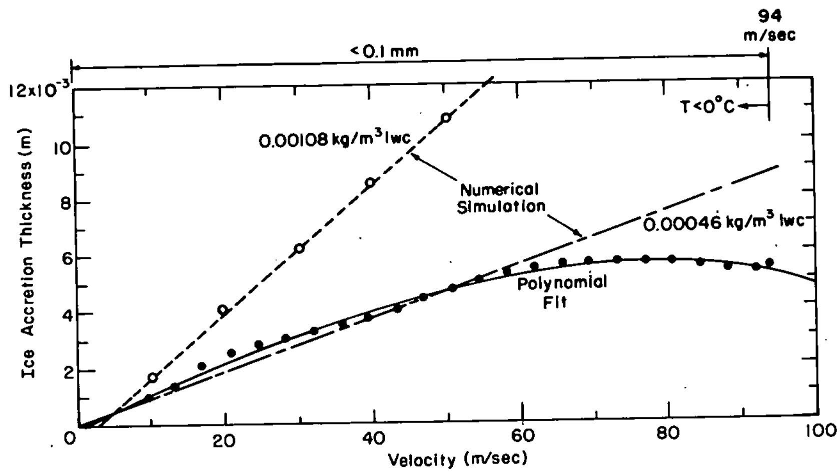


where v is the velocity, R the distance from the rotor center and ω the angular velocity of rotation. Some of the points of agreement and discrepancy between the experiments and numerical results are discussed more fully later. We note here a greater variability about the drawn curve (a fit of a 4th order polynomial to the experimental data) at the higher temperatures, as indicated by the rough appearance of the accretion in the photographs (Figure 4).

The accretions are characterized by a nearly straight line increase in thickness with velocity at lower velocities (up to 50 m/s), with a tendency for a longer straight line portion as the temperature is lowered. The accretion thickness reaches a maximum and falls off toward the tip of the rotor at higher velocities. The position of the maximum also shifts to higher velocity (for the smoothed fit) as the temperature is lowered: about 55 m/s at -13°C, 65 m/s at -17.5°C, and 70 m/s at -29°C.

Figure 10 shows the cross-sectional forms at velocity values that correspond to the position of the maximum leading edge thickness. As seen here, the maximum thickness occurs in the leading edge position with a tapering toward the outer positions of the rotor, the form changing slightly with the experimental conditions. For the -13°C temperature the cross-sectional thickness is nearly constant at the maximum value over a broad surface while at -17.5°C the form is strikingly like a linear translation of the initial circular rotor cross section. At the lowest temperature (-29°C) the form seems to drop back smoothly towards the edges

Figure 9. Experimental and computer simulation results for -29°C ambient air temperature. The Polynomial Fit represents the experimental ice accretion measurements. The second Numerical Simulation curve adjacent to the Polynomial Fit represents the adjusted computer simulation assuming an approximately 50% lower effective lwc. The scale at the top represents the grain size distribution versus velocity as measured on the thin sections.



so that the front section has an elliptical form rather than a circular shape as at -17.5°C.

An example of a thin section of the ice accretion is shown in Figure 11. This section was taken along the leading edge in the plane of rotation at a distance between 25 and 58 mm from the rotor center corresponding to velocities of 9.3 and 21.6 m/s. As shown here, the grain size changes from about 1 to 2 mm to 4 to 6 mm in the 15 m/s velocity region. Previous work on hailstone growth (6) has indicated that such a transition in grain size usually corresponds to a change in surface temperature from below 0°C to 0°C. These regimes are called the "dry" (T <0°C) and "wet" (T = 0°C) growth regimes, implying either the absence or presence of a liquid film at the surface during freezing. The figure also indicates a grain size change from the first layer formed at the rotor surface, shown at the top of the thin section, to those subsequently forming. This size change may possibly arise from a change in heat transfer conditions, where initially the latent heat of freezing escapes both into the rotor surface and also into the air flow, whereas later, because of the poor thermal conductivity of the initial ice layer, the heat transfer is dominated by transfer processes into the flow alone (2,3).

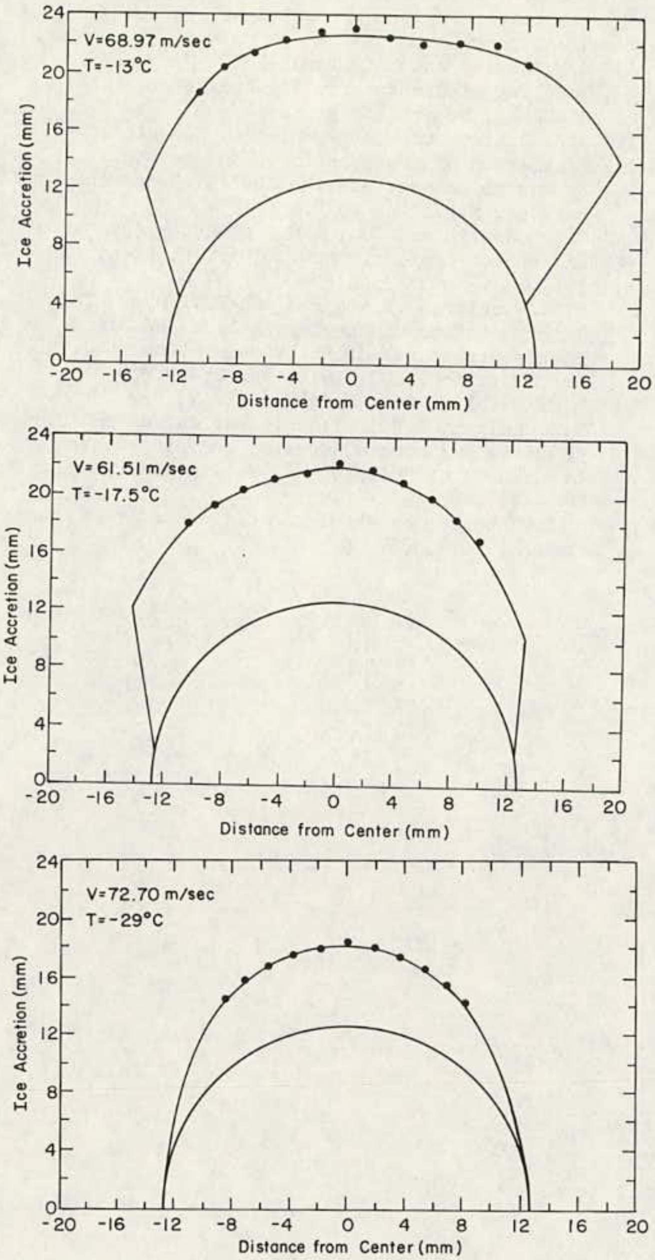
Discussion

In an accompanying paper (3) the methodology and assumptions of the numerical simulation are presented. Here we discuss the comparison of simulations with the experimental results shown earlier in Figures 7, 8 and 9. Figure 7 (-13°C) shows quite good agreement between the thickness predicted at the leading edge and that actually observed in the experiment. For velocities up to 70 m/s, it appears that the simulation consistently under-predicts the ice thickness, with the greatest discrepancy existing in the range from 40 to 60 m/s. This velocity range is also that just beyond the position where the predicted surface temperature goes to 0°C, in good agreement with the transition between small- and large-grained ice, which effectively delineates this temperature transition in the experimental ice accretion (Figure 11). Beyond 70 m/s, the experimental thickness drops off, while the numerical simulation predicts a continuing rise in ice accretion thickness at a reduced rate.

One possible source of the under-prediction in the 40 to 60 m/s range is the flow of unfrozen water from inboard positions, which subsequently refreezes in an irregular manner farther out. In the numerical simulation, the blade is broken down into individual velocity segments and the unfrozen water remaining after the heat balance is satisfied is assumed to be lost into the flow, i.e. no movement of unfrozen water is allowed along the blade. The outboard pointing icicles shown for the -13°C case in Figure 4 indicate this is not the case experimentally. Furthermore, the irregular surface protruding into the flow would allow a more efficient local heat transfer and possibly more freezing than the smoothly shaped surface assumed in the simulation. At positions beyond 70 m/s, the experimental ice thickness falls below that predicted by the simulation, possibly from two causes. One is the variation in the flow field near the tip of the rotor induced by the blunt end that probably causes turbulent effects for some distance inboard (e.g. as much as two diameters or ~5 cm). That effect would considerably modify the flow field in this region and break down the assumptions on how many droplets/ unit time are carried to the rotor. The second cause is the higher accelerations experienced nearer the tip as indicated by the lack of irregular forms (icicles) in this region. The migration of unfrozen water to the region beyond 70 m/s and later refreezing therefore may not occur as it apparently does at lower velocities.

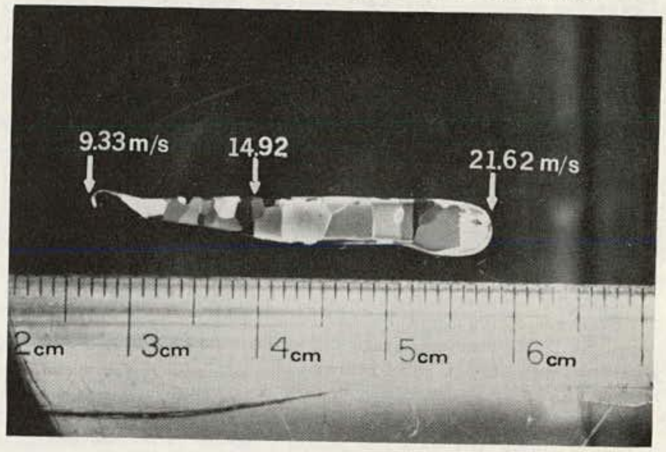
At -17.5°C (Fig. 8) the simulation is also in good agreement with the predicted thickness up to about 40 m/s, where the discrepancy between predicted and experimental conditions starts to become significant, with the slopes of the accretion curves changing at 60 m/s. As with the -13°C experiment, the simulated surface temperature rise to 0°C is in good agreement with the observed

Figure 10. Ice accretion thickness shown in cross section at the velocity of maximum thickness for experiments performed at -13°C, -17.5° and -29°C.



grain size transition that would indicate experimentally that this transition has occurred. The discrepancies between the simulated and observed thicknesses can again be broken into categories by velocity. In the range of 40 to 60 m/s, the simulation over-predicts the ice thickness. But if we also refer to the cross section in Figure 10b for this temperature, as noted earlier, the cross section resembles a translated circular section of the original rotor. In the simulation, however, we assume that the ice accretes in an elliptical manner with the maximum value at the leading edge, dropping smoothly to zero thickness at the 90° points. We can easily see that the total mass of ice for the simulated and experimental cases could then be very similar. But because of our assumption on the distribution as an ellipse, the centerline thickness would then appear greater

Figure 11. Thin section of ice accretion taken in the plane of the leading edge at -13°C. The thin section is from 25 mm to 58 mm from the center of the hub, in the velocity range 9.33 to 21.6 m/s.



in the simulation (elliptical cross section) than it would in the experimental case (circular cross section). Beyond 60 m/s, the differences become much greater and the effects may be as mentioned earlier, an end effect on the rotor and the high accelerations on the boundary layer at the larger distances from the center of rotation. The experiments also indicate a transition back to smaller grain sizes in the 60 m/s range for both the -13°C and -17.5°C experiments. Since the thermodynamic conditions differ between these two experiments, the only common feature is the mechanical forces on the droplets, and we therefore imply this as a further confirmation of end effects, high inertial forces or other mechanical processes dominating at the higher velocities.

Figure 9 shows the comparison between the simulated and predicted values for the given conditions at -29°C. Here the agreement between the simulated and experimental values is quite poor (solid line and circles). For temperatures below -25°C, the tendency was for decreasing amounts of ice accretion, even though the simulation would indicate that all the available water could be accounted for as accreted ice with the given heat balance. A simulation at an lwc less than half that of the measured value (0.00046 kg/m^3 compared to 0.00108 kg/m^3) gives a reasonable simulation of the accumulation seen up to the previously well-simulated velocity of 60 m/s.

A number of possibilities exist as to why less than the predicted amount of ice is accumulated at this temperature. These are only possibilities at this stage, without further evidence, but may provide some guidance for future experiments aimed at sorting out these possible effects. One of these is a drop in the effective liquid water content by the droplets nucleating to ice particles prior to striking the "dry" surface of the object and bouncing off rather than being captured. Hobbs (7) has indicated an exponential rise in ice nuclei (in the free atmosphere) at temperatures below -25°C compared to nearly constant values independent of temperature above -25°C. Presumably the chance for capture of an ice nucleus by a droplet and ice formation in the atmosphere might then be more likely at the lower temperature. A second factor might be a change in the properties of the droplets causing a tendency for increased rolling or bouncing off the object after striking it (still as supercooled water), thereby reducing the number that are directly captured at the lower temperatures. Unquestionably the effect is there, in that the amount of accreted ice is less than expected for the given conditions, but the explanation is open for future studies. The grain sizes of the accreted ice are less than 0.1 mm and are consistent with the droplets freezing nearly immediately on impact with little spreading.

Conclusions

In general, we find reasonable agreement between the simulated and experimental ice accretion thicknesses formed at the object's leading edge for temperatures down to ∿-25°C and in the velocity range from 0 to 60 m/s. The one major difference that can be adjusted to in this velocity range is the possibility of unfrozen water migrating along the object surface and refreezing irregularly at a different location. The cross-sectional shape in the wet growth regime (generally the higher temperatures but equivalently higher liquid water content at lower temperatures) appears to be flatter and more uniform across the cross section (Figure 10a) than the elliptical shape assumed in the numerical simulation. Good agreement is found between the predicted surface temperature rise to 0°C in the simulation and the structural evidence for this change given by the small- to large-grained transition in the ice accretions. This agreement indicates the thermodynamic formulation used in the numerical simulation (2) is reasonably good. Within this framework some adjustments can be introduced into the current numerics to account for these variations which seem to be both general and currently explainable.

Less explainable are the deviation between the numerical results and the experiments at velocities greater than 60 m/s. Two possibilities appear at this time; one is the high radial accelerations at these velocities and the other is end effects because of the blunt end of the rotor. More experiments are necessary at different rotation rates and with longer rotors at the same rotation rate to further clarify the effects seen here at velocities greater than 60 m/s.

Similarly, the less-than-predicted accretions seen at -29°C have a few possible causes at this time and it has not been decided whether the effects arise from processes in the droplet's path to the rotor (e.g. greater numbers of ice nuclei) or from processes at the rotor surface such as a greater propensity for droplets to roll or bounce off without accreting at these temperatures. Experiments to examine the structure of the droplets prior to accreting are planned and may assist in clarifying this problem. In addition, analysis of data obtained this past season at Mt. Washington may also assist in resolving these issues. This analysis will be proceeding and will be the subject of future reports.

The problems reported here for the rotating case should be viewed in that context, however, and we are strongly encouraged by the good agreement up to the 60 m/s velocities. Since this velocity range encompasses most of the naturally occurring wind velocities on the earth's surface, we conclude that the numerical ice accretion simulation will probably give quite reasonable results for many structural applications that do not have the complex velocity fields reported here. These include power lines, tall towers, and ship icing conditions.

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Crystalline Structure of Ice Developing by Accretion of Supercooled Water Droplets on a Single Wire and Growth Process of Rime on a Square Board Placed in the Air Flow Containing Supercooled Droplets and Snow Flakes

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Ice fabrics or crystalline structures of ice formed by accretion of supercooled water droplets have been observed by many authors, by making a thin section of ice which allows examination of crystal structure between crossed polaroids. It has been shown that ice crystals formed by accretion of supercooled droplets consisted of many columnar grains developed in the growth direction. Therefore, it is interesting to observe crystalline structure of ice growing on a single wire by accretion of supercooled water droplets. A rigid frame stretched with a fine metallic wire (0.001 m in diameter) was place on a microscope stage in such a way that the surface of stretched wire was brought into the focus of an objective lense of the microscope. The microscope was placed in a wind tunnel where cold air containing supercooled water droplets was flowing continuously. The riming process on the stretched wire was recorded cinematographically through microscope.

The time lapse movies of icing process taken in a cold room of the Institute of Low Temperature Science indicated that supercooled water droplets captured on a metallic wire increased their size by the successive impingement without being subjected to any freezing even at -10°C, and that when the size of droplets attained 0.003∿0.005 m in diameter, freezing occurred spontaneously on a particular droplet, neucreating successively adjacent droplets. According to our observation, if wind speed differs, the appearance of ice formed by accretion of water drop-

Figure 1. Photomicrograph of growing front of ice. 10m/sec : -10°C

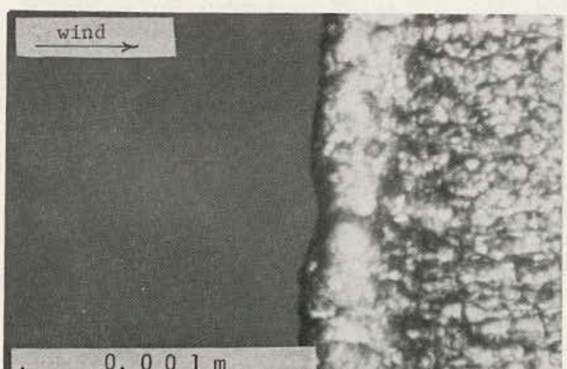


Figure 2. Photomicrograph of growing front of ice. 3.5m/sec : -10°C

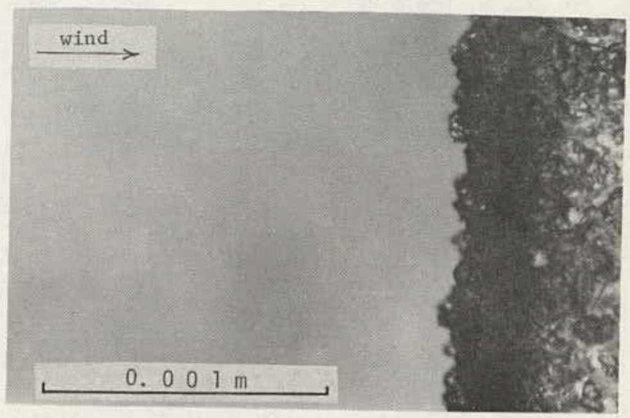
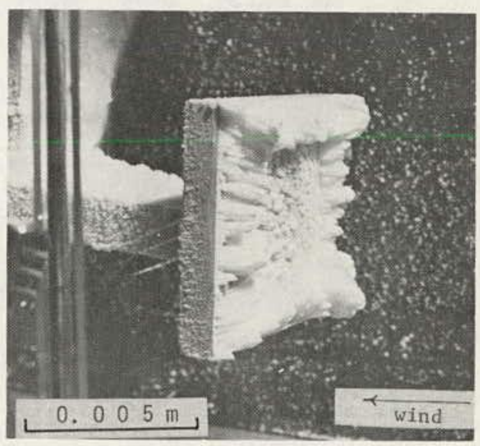


Figure 3. Rime deposits on a square board.



lets was different even at the same degree of supercooling. Figure 1 and 2 show photomicrographs of growing fronts of ice taken at 10m/sec and 3.5m/sec respectively.

On the summit of mountain covered with snow, icing on structures is created by not only accretion of supercooled water droplets but also by adhering of snow flakes. Icing process on a wooden square board placed in the air flow containing supercooled water droplets and snow flakes was observed at the summit of Mt.Zao (1660 m in altitute). A time lapse movie indicated that no snow flakes adhered on the surface of the board until long rimes developed along the circumference of the board as shown in Figure 3. Snow flakes impinging on the board began to deposit in a hollow space being surrounded by long deposits of rimes developed at the edge of the board.

Experimental Studies of Snow Accretion on Power Lines

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Experimental studies were carried out of the snow accretion on a power line using wind tunnel. Observations were made of the growth processes, especially their initial stage, together with measurements of wind speed around the snow accreted on the line. From the results obtained, the growth mechanism have been confirmed as follows: The coefficient of collision of snow particles against the trajectory of the line was nearly 100%, but the snow particles which collided against the line, rebounded from it, reducing the coefficient of collection to less than 10%. Snow particles which stayed at around the stagnant point of the front, formed an equilibrium triangular prism wherein the prism was defined by the repose angle of snow particles, which is the function of the adhesive force and the shear stress of a wind, as well as the trajectory of the accretion. When the mass of the prism exceeded a critical weight, which was defined by the adhesive force, the prism began to rotate around the line by its own weight. Then, the distribution of wind speed around the accretion changed as a result of the drag effect of the rotating prism. This change of the wind suggests that the shear stress of the wind around the upper side of the prism decreased; then the snow particles could deposit more easily on this effective stagnant region. By this continuous deposition on the upper side of the prism, the whole snow accretion rotated. Finally, the snow accretion grew to a cylindrical snow mass which had a spiral face of growth.

Results obtained confirmed qualitatively processes of the initial growth and the spiral growth of snow accretion on the power line.

Accretion of snow accompanied by a warm strong cyclone in winter usually brings about serious damage on the power line system.

Clarifying of mechanisms of formation and growth of this type of snow accretion has been urgently called for by various fields concerned so that disasterous damage can be prevented.

Experimental studies based on an artificial snow accretion by use of wind tunnel were carried out as one of a series of researches (1, 2) to meet such a demand with an aim to clarify such fundamental mechanisms as wind and turbulence distributions around a power line, collision and collection rates of snow particles against the power line, etc.

Experiment

Experiments of an artificial snow accretion were carried out using a Götingen type wind tunnel, which has a wind outlet of 50 × 50cm installed in the cold room at the temperature range of +4∿5°C at the wind speeds of 10 and 20m/sec.

Snow particles, which were collected from a snow pack, were fed at nearly the same supply rate of 1.2∿1.6g cm^{-2} min^{-1} by electric sieves from the upper part of the outlet into the wind tunnel, after only those snow particles which had the same size of about 0.5∿1.0mm in diameter were selected. At the same time, water of 0°C was sprayed at the rate of 0∿0.05g cm^2 min^{-1} into the wind tunnel.

An aluminum cylinder of 4cm in diameter was set at 4m leeward from the outlet in a horizontal position at a right angle to the wind axis. Supplied snow particles and water droplets collided against the cylinder.

The formation and growth processes of accretion on the cylinder were observed and recorded by a video camera.

A model, which was composed of the cylinder and such prisms as approximate to a snow accretion, was used to measure wind and turbulence distributions around the accreted snow mass at each of growth stages.

Namely, for the initial stage of an accreted snow mass, a triangular prism made of plastic clay which had a dimension of the same length as the cylinder and the cross section of 4cm in base and 0.6cm in height was affixed along the surface, parallel to the center line of cylinder and with its apex parallel to the wind axis, as shown in Fig.1 (1). For the next stage of growth in which the apex of the first prism was rotated downwards by 30°, another plastic clay prism with the same dimension was laminated on the cylinder, with its apex parallel to the wind axis, as shown in Fig.1 (3). This procedure was repeated for each stage of growth.

Finally, the laminated prisms covered and enveloped the entire surface of the cylinder, as shown in Fig.1 (11).

Using a hot wire anemometer, measurements were made of wind speed and turbulence continuously along the vertical line to the wind axis at 0.5cm windward from the apex of the prism, at the upper side above the center line of the cylinder and at 2.5cm leeward from the surface of the cylinder.

Experimental Results

Observation of A Growth Process of A Snow Accretion

Almost 100% of the snow particles, which were blown from windward and passed through the trajectory of the cylinder, collided against the front surface of the cylinder. The colliding snow particles rebounded elastically from the cylinder and accreted only around the stagnant point at the front of the cylinder and formed a triangular prism around it (Fig.2). Once snow particles accreted on the surface, the accretion grew rapidly, keeping a similar shape, namely a triangular prism. When the prism grew up to some extent, it started rotating downwards along the surface of the cylinder. Thus, the apex of the prism moved downwards by the rotation (Fig.3). Blowing snow particles continued to accrete only around the stagnant point, giving rise to the accretion of snow only on the upper side of the prism that just moved downwards, which resulted in formation of an unsymmetrical accretion, whereby the shape of the combined prism changed to a somewhat distorted prism; that is, the upper side kept the initial form of a prism but the lower side changed to an elongated prism along the surface of the cylinder (Fig.4).

By the continuous deposition of blowing snow particles, an accreted snow mass grew, rotating around the axis of the cylinder, and thus enveloping the entire surface of the cylinder (Fig.5). Finally, it grew to a cylindrical snow accretion, which had a spiral face of growth.

Throughout this growth process, blowing snow particles accreted only around the stagnant point, which caused the accretion of snow only on the upper side of the combined prism, accreting neither on its lower side nor on other place than the stagnant around the cylinder.

Distributions of Wind Speed and Turbulence

Typical examples of distributions of wind speed and turbulence around a cylinder which had laminated prism layers are shown in Fig.6.

The distributions showed the same tendency depending on either the change of wind speed or the number of laminated layers, though the influence of the laminated layers was remarkable as to the distributions around the stagnant point and the lower side of the cylinder which was covered by the laminated layers.

Vertical distributions of wind speed at various distances from the front on the wind axis for each model are shown in Fig.7.

It is clear for every model that wind speed decreases as a measuring point approaches the stagnant point, either horizontally or vertically to the wind axis, at which it has the minimum value. As for a cylinder without a prism and a cylinder with a prism whose apex is parallel to the streamline, a decrease of wind speed is symmetric with respect to the wind axis, but as for the latter, the decreasing rate of wind speed is larger and the region in which wind speed is affected is narrower than that of the former. On the other hand, as for a cylinder with a prism whose apex is inclined at 30° leeward against the wind axis, the distribution of wind speed is remarkably different from those of others. That is, as the apex of the prism moves leeward with the stagnant point, a remarkable decrease of wind speed and an enlargement of the af-

Figure 1. Schematic pictures of models which were used to measure wind and turbulence distributions at each growth stage.

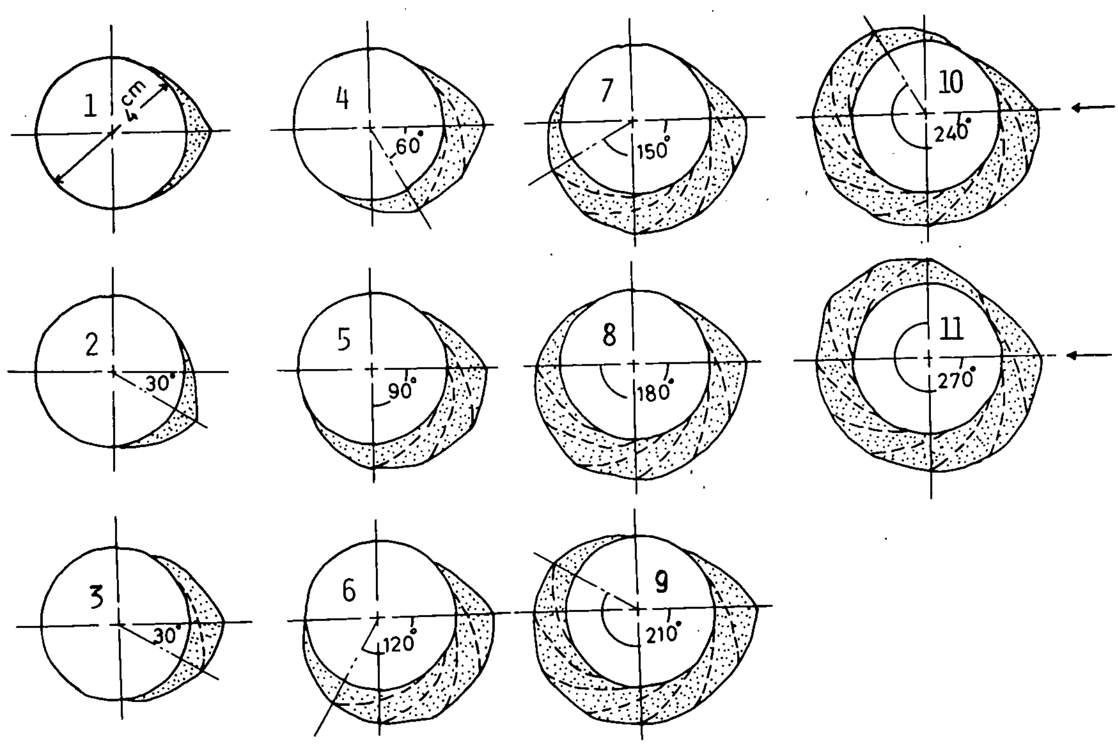


Figure 2. Initial stage of snow accretion. A triangular prism of accreted snow formed around the stagnant point.

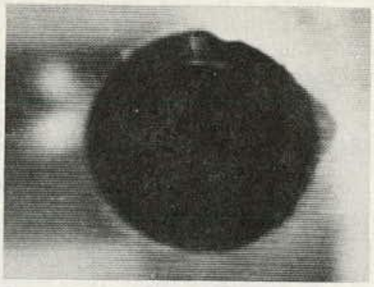


Figure 3. An accreted snow whose apex of the prism moved downwards by the rotation.

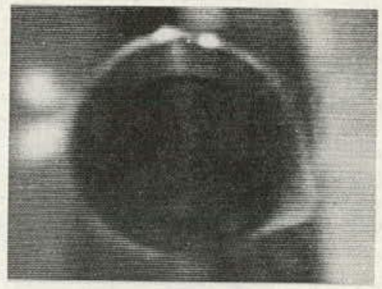


Figure 4. A distorted prism of accreted snow mass by the rotation.

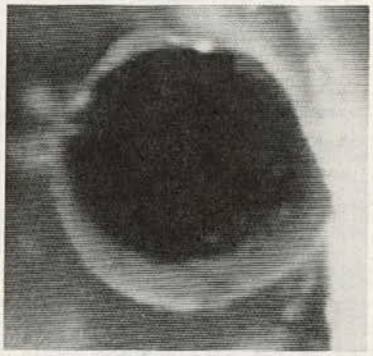


Figure 5. An accreted snow mass enveloping the entire surface of the cylinder.

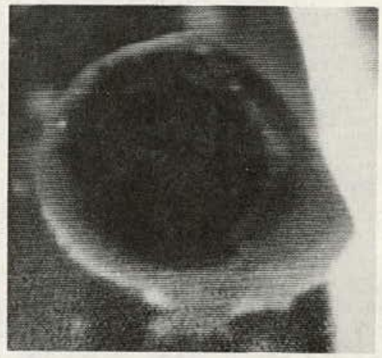
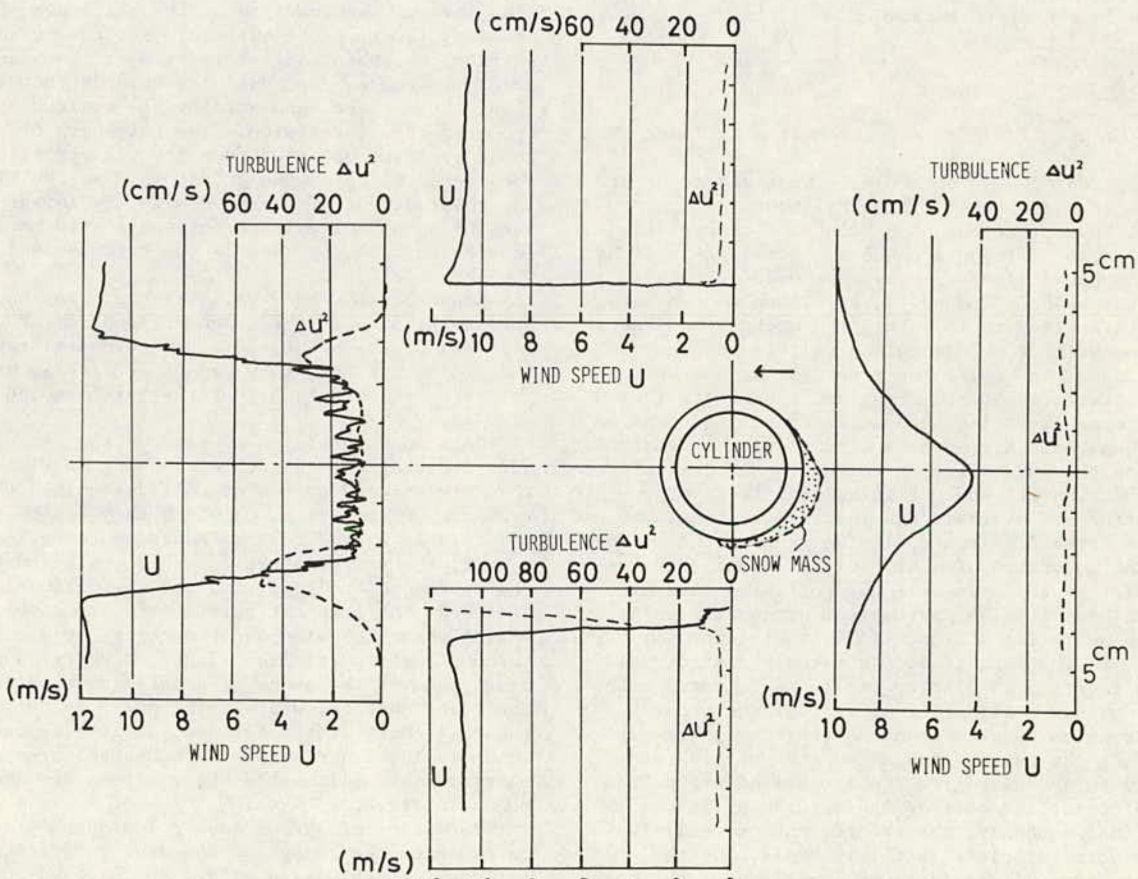


Figure 6. Distributions of wind speed and turbulence around a snow accretion.



fected region at the windward side of the prism are observed, while those are kept nearly the same at the leeward, as are in the case of the cylinder with a prism whose apex is parallel to the wind axis. Thus, it is shown in this figure that the distribution of wind speed is distorted, becoming unsymmetric with respect to the wind axis.

With increase of the number of laminated prism layers, the same tendency was observed. But, when the laminated layers enveloped the entire cylinder, the distribution of wind speed recovered nearly the same as that of the cylinder without a prism. The distribution of turbulence at the front was not so much changed with the number of prisms, that it was negligibly small.

Figure 6 also shows the distributions of wind speed and turbulence at the upper and the lower side of the cylinder. Wind speed increases gradually, as a measuring point approaches the surface, reaches the maximum value at 0.7∿0.8cm from the surface, thereafter decreases rapidly and reduces to zero at the surface. Turbulence is negligibly small in the region where wind speed increases, but it increases rapidly with decreasing wind speed. Concerning such a distribution, nearly the same tendency is observed both at the upper and the lower side. However, in proportion to the number of layers, a slight increase is observed in the thickness of a turbulent layer on the side where laminated layers cover the cylinder.

At the lee side of the cylinder, as also seen from Fig.6, wind speed and turbulence gradually increase as a measuring point approaches the tangent of the upper and the lower side of the cylinder, have the maximum value there, and then decrease rapidly. Their distributions are nearly symmetric with respect to the wind axis, but on the side where laminated layers cover, a slight disturbance is observed in the distributions.

Discussion

Initial Growth of A Snow Accretion on A Cylinder

Accretion of snow particles always starts at or near the stagnant point of the cylinder.

Many investigations have been made to explain the mechanism of icing around an obstacle as well as that of a power line, whereby many aerodynamical models have been proposed.(3, 4) These models have also been applied to look into the mechanism of snow accretion without examining the validity of the application. The following constitutes, however, a basic difference between icing and snow accretion. That is, the particles such as water droplets and snowflakes, are carried by a wind along a streamline; even when the streamline is curved by the drag effect due to a cylinder, the particles tend to move straightforward by their own inertia, turning away from the streamline and colliding against the cylinder. The curvature of a streamline around the stagnant point is so large that the collision rate of the particles attains the maximum around the point, at which accretion starts. In case of icing, however, as the mass of a water droplet is so small and its inertia is also so small, as compared with that of a snow particle, that most of the water droplets which pass through the trajectory are carried along the curved streamline and very few of them are turned away from the streamline around the stagnant point and collide against the cylinder there. Consequently, the coefficient of collision of such water droplets is fairly small. On the contrary, as is clear from our experiments, the coefficient of collision for snow particles is almost 100%, and snow particles passing through the trajectory of the cylinder collide against the cylinder not only around the stagnant point but also at the whole windward surface of the cylinder. When water droplets collide against the surface, they collided plastically and adhere on it, making the collection rate of the collided droplets almost 100%. As a result, the coefficients of collision and collection are nearly equal. On the other hand, snow particles collide against the surface elastically and rebound away from the surface, as is confirmed from our observations. Hence, as for snow particles, though the coefficient of collision is almost 100%, that of collection is fairly small, that is, less than 10% of colliding particles. This is one of the characteristic differences between icing and snow accretion.

Snow particles, which collide against the surface, lose their kinetic energy and stay on the surface, are adhered there by the surface tension of water films which exist on the surfaces of snow particles and the cylinder. As has already been known an adhesive force between a particle and a surface varies, depending on the material of the surface. Although it is important for the investigation of snow accretion, there are few experimental reports concerning an adhesive force between a snow particle and the surface of various materials. (5) It is considered from our experiments that an adhesive force between a snow particle and an aluminum surface is in the order of a few dyne/cm^2 and that an adhesive force between two snow particles is larger than that between a snow particle and another material.

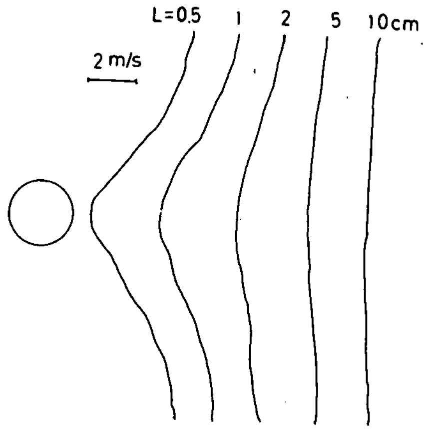
As for snow particles, which stay on the surface of a cylinder after losing their kinetic energy as a result of their elastic or plastic collision against the surface, an adhesive force between them and the surface must be equal to or slightly larger than the shear stress of the wind which acts on them. The wind shear is the function of the thickness of a boundary layer of the surface. For the cylindrical surface, the shear stress is zero at the stagnant point, increases exponentially towards the sides along the surface, and attains the maximum at the upper and the lower side. The thickness of the boundary layer obtained from the wind profiles is considered to be in the order of mm at the sides, to the shear stress of the wind might be larger than that of an adhesive force between a snow particle and the surface, but nearly the same as that between two snow particles.

Consequently, snow particles can stay on the surface at or near the stagnant point after colliding against the point, but, as they part from around the stagnant point, they cannot accrete so stably at points apart therefrom that they are removed by the wind shear.

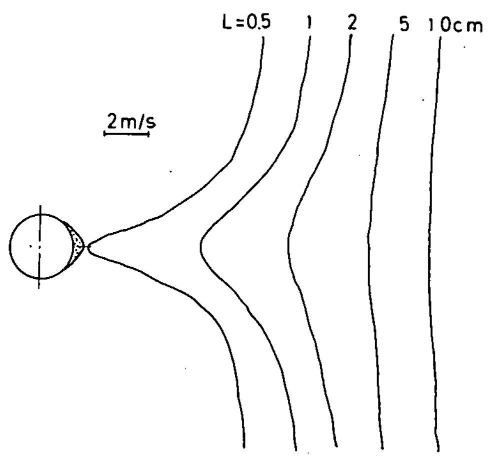
Once snow particles accrete on the surface at or near the stagnant point, late-coming snow particles that are carried by a wind collide against the accreted snow particles, on which they can be deposited more stably by their large adhesive force. As a result, the accreted region can be extended towards the upper and the lower side of the cylindrical surface from the stagnant point until it reaches the region where the wind shear exceeds the adhesive force of snow particles. Thus, an accreted snow mass grows in the shape of a triangular prism around the front surface, wherein the prism is defined by the trajectory of the cylinder and the repose angle which is the function of the adhesive force of snow particles as well as the shear stress of wind as shown in Fig.2.

Formation of such a snow prism on the front surface causes the change of the drug coefficient of the cylinder, which has an effect on the wind shear around there.

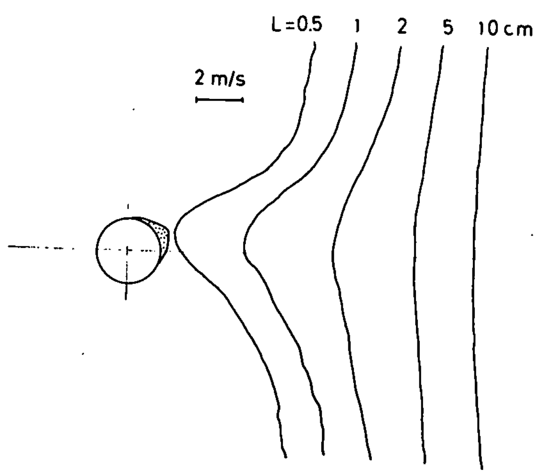
Figure 7. Vertical distributions of wind speed at various distances from the front on the wind axis for each model.
a) cylinder without model



b) cylinder with the model of fig.1-1.



c) cylinder with the model of fig.1-2.



From a comparison of the wind profile between the cylinders without and with a prism on the front, it is clear that the effective region of the latter becomes sharper and narrower than that of the former, and that consequently, the wind shear around the surface of the prism might be larger than that of the cylinder itself. As the coefficient of collision is 100%, the number of the snow particles which collide against the surface does not depend on the curvature of the streamline but on the trajectory of the cylinder, so the number is equal between the two cylinders. Also, the adhesive force of the snow particles is equal between the two cylinders. Then, the latter has a larger wind shear around the front because of a smaller drag coefficient, so the collection rate of the snow particles of the latter is smaller than that of the former.

Hence, it might be considered that, as the snow accretion continues to grow, the shape of the front of the cylinder changes to that of the model, which has a prism on the front, then, the growth rate of the snow accretion decreases and, finally, the shape of the front reaches an equilibrium triangular prism which is defined by the repose angle and trajectory mentioned above, should the rotation of the accreted snow mass due to gravity be not allowed.

Spiral Growth Mechanism of A Snow Accretion

At the initial stage of the growth of a snow accretion, the gravitational force which acts on the mass of the accreted snow is almost negligible compared with the adhesive force and the wind shear. However, as the accreted snow grows to a fairly large mass, the gravitational force becomes no longer negligible, starting to play an important rôle to the growth process of the snow accretion.

With the growth of the mass of the accreted snow, the center of gravity moves from its original point and the moment of rotation acts around the center of the cylinder. When the adhesive force between them is larger enough, the cylinder itself rotates by that moment, as seen in icing and snow accretion on the strand cable. But, in our experiments, the snow mass slided along the surface, rotated downwards, and then kept its balance when the moment of rotation exceeded the adhesive force between the accreted snow mass and the surface, thus the snow mass moved from the initial position downwards to keep its balance, as shown in Fig.3.

By the rotation of the accreted snow mass, the wind profile of the front changes, as shown in Fig.7. That is, with the rotation of the prism leeward, the stagnant point also moves leeward and the wind profile becomes unsymmetric with respect to the wind axis.

At the windward side of the rotated prism, the wind speed decreases and the affected region becomes broad, compared with that of the unrotated prism; then, the wind shear at this side decreases with the rotation. As a result, with the rotation of the prism, the collection of the snow particles on the windward side increases, whereby the more snow particles accrete on this side, the more the snow mass rotates to keep its balance with the moment of rotation; then the growth of the snow accretion occurs around the stagnant point and windward side. On the contrary, on the lee side of the prism, the wind shear is not so much changed from the initial one that the growth of the snow accretion hardly occurs with the rotation.

Consequently, by this unsymmetrical growth due to the rotation, the accreted snow prism grows continuously and deforms its initial prism to a distorted shape and gradually envelopes the entire cylinder and finally grows to a cylindrical snow mass, which has a spiral growth face.

In this growth mechanism, once the accreted snow mass starts rotating, the growth of the accreted snow might never reach the equilibrium which is seen at the initial growth stage. Before the accreted snow envelopes the entire cylinder, if the weight of the accreted snow mass exceeds the adhesive force between the snow mass and the surface, then the snow mass falls down from the cylinder and the same process repeats from the initial stage. When the accreted snow envelopes the entire cylinder, the accreted snow might grow by a continuous rotation until the weight of the snow mass exceeds the fracture strength of the accreted snow at the upper side of the cylinder.

Conclusion

Experimental studies were carried out of a snow accretion on a power line using a wind tunnel in the cold room.

Observations were made precisely of the growth processes, especially in their initial stage, together with measurements of wind speed and turbulence around the snow mass accreted on the line, as shown in Fig.6.

From the results obtained for the snow accretion, an equilibrium prism and a spiral growth mechanism have been confirmed as follows: The coefficient of collision of snow particles against the trajectory of the cylinder was nearly 100%, but the snow particles which collided against the surface of the cylinder rebounded elastically from it, reducing the coefficient of collection to less than 10%.

Snow particles which collided against and stayed around the stagnant point of the front formed an equilibrium triangular prism of snow, wherein the prism was defined by the repose angle of snow particles which is the function of the adhesive force and the shear stress of a wind, as well as the trajectory of the cylinder, as shown in Fig.2.

When the mass of the triangular prism exceeded a critical weight, which was defined by the adhesive force of the surface, the prism began to rotate around the cylinder by its own weight as shown in Figs.3 and 4. Then, the distribution of wind speed around the accretion changed as a result of the drag effect of the rotating prism, as shown in Fig.7.

This change of the wind speed suggests that, as the shear stress of the wind around the upper side of the prism decreases, snow particles could deposit more stably on this effective stagnant region.

By this continuous deposition of snow particles on the upper side of the prism, the whole snow accretion also rotated continuously and repeated this process, as shown in Fig.1.

Finally, by this rotation, the snow accretion grew to a cylindrical snow mass which had a sprial face of growth and enveloped the entire cylinder, as shown in Fig.5.

Acknowledgments

The authors wish to express their deep appreciation to the members of the Snow and Ice Accretion Study Group in the Institute of Low Temperature Science, Hokkaido University, for their kind cooperation and stimulating discussions throughout the work. This study was partially supported by the Ministry of Education of JAPAN.

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Snow Accretion on Traffic-Control Sign Boards and its Prevention

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Visual observations of snow accretion on the sign board and continuous measurments of the wind velocity and the air temperature have been made in blowing snow. The flow and velocity distribution of wind around and on the surface of the board, respectively, was measured. The set of results show that snow accretion develops around the wind stagnation point of the board, that at a wind velocity exceeding 4 to 5 m/sec the board is covered even with dry snow which does not contain liquid water and that this dry snow accretion can occur more easily with increasing wind velocity with ascending air temperature and with decreasing area of the sign board. The dry snow accretion can be classified into three types. One of the most frequently observed among them is caused by strong collision of snow against the board. The snow accretion of this type can be explained in terms of snow melting at the contact points of snow and the board by the collision which transforms the kinetic energy of snow into internal energy of it and melted snow adheres to the board. Experiments for preventing snow accretion were carried out by three methods. Among them, the method of altering the wind flow is a comprehensive application of making shift the wind stagnation point, making snow collide against the board at an acute angle so that the snow accretion becomes more difficult. It is the most effective among the three methods and can be expected from the practical point of view.

Snow accretion on sign board, that is, covering it with snow, prevents the drivers from being furnished with traffic information to spoil the traffic safety. On a road covered with snow, the traffic sign boards also play the part of optical guidance besides the snow poles. If these are covered with snow, it will become impossible to discriminate them from the surrounding snow under the poor visibility and, in extreme cases, to recognize even its existence. Snow accretion on sign board increases the poor visibility and often becomes a cause of traffic accident and jam.

Until quite recently, however, it has been almost left out of consideration, because there is no such direct damage as breaking sign board and the covered snow gradually falls off spontaneously. The field observations of snow accretion on sign board and the experiments on its prevention have been made from 1974 in the Ishikari plain Hokkaido

Observational Methods

The circular sign board of 60 cm in diameter, the square of 45 cm in the length of side, the inverted equilateral triangle of 74 cm and pentagon 68 cm high were used for the observation. These sign boards are most frequently applied on highways in Japan.

Glass plates and five polywoods boards of various sizes, which have areas, from 22.5 x 45 cm to 90 x 180 cm, growing in geometrical progression of common ratio 2, were also used. Snow accretion on sign boards were visually observed. The following quantities of the test boards covered with snow were measured: Wind direction and velocity, air temperature and surface temperature of the board with copper-constantan thermocouple.

As indoor experiment, wind flow around and wind velocity distribution on the surface of the model boards were measured in wind tunnel.

The Mechanism of Snow Accretion

The mechanism and aspect of snow accretion on sign board depend on the meteorological conditions such as wind direction and velocity with regard to the board, air temperature and characteristics of snow.

As for characteristics of snow, in particular, there are differences in snow adhesion mechanism between wet and dry snows. For this reason, the snow accretion mechanisms of wet and dry snows will be discussed separately.

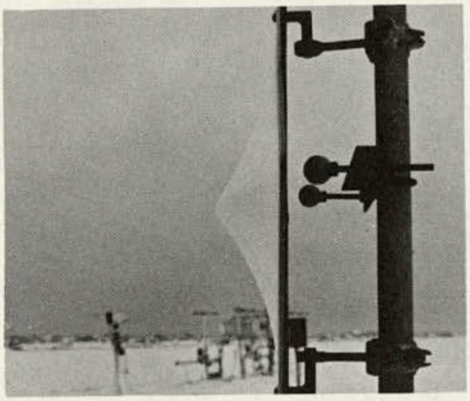
Wet Snow

Wet snow accretion occurs through the surface tension of water contained in the snow. Since the surface tension of water is larger enough compare with the spesific weight of snowflake, snow accretion occurs more easily than dry one: The latter appears only in strong wind, whereas the former can be seen even under windless condition. When it is calm or weak wind blows, covered snow is approximately uniform in thickness all over the surface of sign boards.

In the condition of strong wind the sign board perpendicular to wind is covered with snow around a stagnation point in its center and snow accretion finally becomes conical, the cone standing up from the center.

Photo. 1 shows the side view of the snow accretion and it takes such a form as this, because the probability of snow accretion is the highest at a wind stagnation point of sign board and decreases towards the circumference.

Figure 1. Side-view of snow accretion on sign board faced to blowing snow.



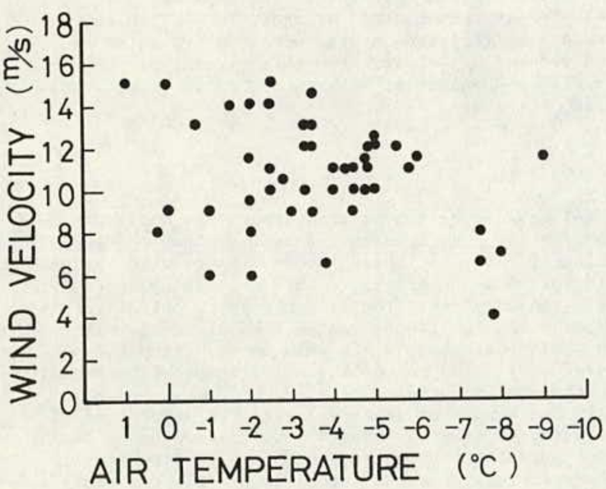
Dry Snow

Also in the case of dry snow which does not contain liquid water, the snow accretion occurs.

The dry snow accretion on sign board occurs only when strong wind blows such as when snow storm prevails and according to its mechanism it can be classified into the following three types.

Dry snow accretion on sign board when wind blows perpendicularly to the board. In the same way as the case of wet snow, the snow accretion of dry snow on sign board, to which strong wind blows perpendicularly, forms a conical form which stagnation point of the wind corresponding to a vertex of the cone.

Figure 2. The meteorological condition for snow accretion of dry snow is shown the relation between wind velocity and air temperature.



Differently from wet snow, dry snow of lowere adhesion has a lower growing rate of snow accretion, because dry snow particle can be more easily repelled even when it collides against the board.

Fig. 2 shows, in a form of dependence on wind velocity and air temperature, the meteorological condition for snow accretion of dry snow.

From Fig. 2 it can be seen that snow accretion occurs when wind velocity exceeds 4 to 5 m/sec in falling snow and does not occur when the velocity is lower.

To give an explanation snow accretion occurrence only at a higher wind velocity, the authors assume that when snowflakes carried by wind collide against a sign board, the kinetic energy of them is coverted into the inner energy of snow, which in consequence of the collision is partially melted, adheres to the board and freezes again there. Let us make sure of the assumption by means of a simple calculation as follows:

The kinetic energy of a snowflake, which is carried at a velocity V cm/sec and has a mass mg, is given by the following equation (1).

$$q = 1/2\ m\ v^2$$

Now, suppose that a snowflake of temperature -10° c, mass 15 mg and diameter 1 cm collides against a sign board at a velocity of 500 cm/sec.

On the assumption that all the kinetic energy of the snowflake is converted into thermal, heat of 4.5×10^{-5} cal will be generated. If this quantity of heat is divided by the value of contact area between the board and the snowflake, calculated on the basis of the latter considered to be a disc of 1 cm in diameter. Then it is possible to determine the thickness of the melted snow, which is 7.3×10^{-7} cm. As being known from the researches on friction, however, the true contact area between both in real contact point with each other is only one several hundredth to one several millionth of apparent contact area.

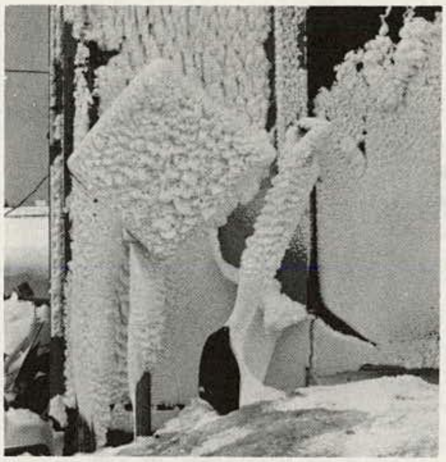
If it is assumed for this reason that the true contact area in the case of snow accretion is equal to one thousandth of apparent area, the thickness of melted snow will be equal to 0.73×10^{-5} cm at the contact point.

While in this calculation, difference in temperature does not so remarkably affect its results as that in wind velocity, heat is emitted in fact to the sign board, the air and the snow and its amount increases with descending temperature. If all of these factors are taken into consideration the thickness will exceed 3000 A even when only several percent of the kinetic energy of a snowflake is consumed. It can be thus supposed that dry snow accretion on sign board is caused by dry snow, whech collides against the board to be melted and then freezes again. Even if the true contact area is only one thousandth of the apparent, the coherence between board and ice is so large as to be able to support a sufficiently grown snow accretion.

Snow accretion due to wake. When wind velocity exceeds 12 to 13 m/sec, snow accretion appears also on another surface of the sign board opposite to the wind direction. This snow accretion is a result of violent collision to the board, of snow which has been swallowed up in eddy wake, formed on the leeward of the sign board by strong wind, and it has approximately a uniform thickness.

Snow accretion occuring in wind shadow. When snow is suspeded by the wind, snow accretion can also appear on sign boards installed in the turbulent eddy, which is formed in urban area and on the leeward of buildings, trees etc. Fig. 3 shows a view of snow accretion on sign board which occurred on the leeward of the observatory.

Figure 3. Snow accretion formed in leeside vortex of the observatory.



The snowaaccretion of this type is first thin, then grows to form an uneven surface of snow resembling to cirrocumulus and finally the depressions are filled with snow to produce a uniformaly thick snow layer.

Since in an eddy air-born snow is suspended and its has a falling velocity equal to almost zero, its apparent weight is slight so that snow accretion occur even with very small adhesion.

This is similar to a phenomenon that minute powder and dust adhere to a body. It appears that after snow adheres the adhesion increases with the lapse of time even if it is first slight. For this reason, a fully-grown thick snow can be supported.

Experiments on Snow Accretion Prevention

The authors carried out experiments in order to prevent snow accretion on sign board perpendicular to the wind.

The snow accretion frequency of this type is the highest in Hokkaido Japan and the traffic is also remarkably affected. The results are described in the following.

From the practical stand point, it was decided in these experiments of snow accretion prevention that the sign boards for text themselves would not be changed at all and not heated as far as possible and the experimental methods were fundamentally the following three. Among them the method of altering the wind flow around a sign board will be mainly described.

Method of Utilizing Wind Force

An anemovane is violently swung with in an angle range from 20 to 30 in strong wind. The wind velocity is also variable. The authors hit upon an idea that these are utilized to swing the sign board, which will strike a hammer behind it, and force of the shock at that time may make the snow fall.

Since snow is light enough in comparison with its adhesion and such a force of shock as this scarcely transmitted by it, however, the authors succeeded by this method in obtaining only an effect of quickening falling off of the adhering snow.

Method of Surface Treatment

If there are some materials or transparent paints to which snow does not adhere, it is valuable from the practical point of view.

Since the adhesion of wet snow is owed to the surface tension of water, it adheres only slightly to hydrophobic substances which repel water well.

The authors investigated the possible snow accretion prevention effect of sign board made of teflon and painted with ski wax, which are both known as hydrophobic substance. In comparison with untreated, as a result, such effects as low growing rate of snow accretion were obstained but it is impossible by this method only to prevent snow accretion in such a digree that the sign board can be recognized without hindrance.

Method of Altering The Wind Flow Around a Sign Board

In a strong wind snow accretion is the most remarkable on a sign board perpendicular to the wind.

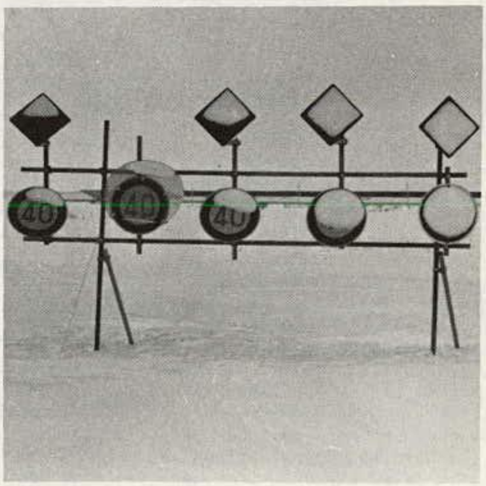
Snow accretion decreases on the board, which approaches more the direction parallel to the wind.

Finally not any snow accretion exists at all on the board parallel to the wind.

This is caused by the facts that snow accretion grows around a stagnation point of wind on the sign board and that a snowflake collides against the board with difficult in a wind blowing along its surface and even if the snow does it is repelled. Baced on these facts, the method consists in removal, if possible, of the wind stagnation point from the sign board or in displacement of the point's position so that even if snow accretion occurs on the board the whole board can be recognized without hindrance.

Providing sign board with a negative angle of depression. The quantity of snow accretion on a downward-inclined sign board decreases with increasing angle of its inclination. Fig. 4 shows a dependence of snow accretion on the angle of inclination. According to the angle increases from 15° to 25°, then 30°, the quantity of snow accretion decreases and snow accretion occurs only on the upper corner of the board.

Figure 4. The dependence of snow accretion on the angle of inclination of sign board.



To know possible cause of this phenomenon, the authors measured the flow and velocity distribution of wind around a sign board model placed in a wind tunnel. Fig. 5 shows such flows of wind in the wind tunnel. This wind tunnel experiment revealed that inclination of the board makes the wind stagnation point shift upward.

Fig. 6 schematically shows a relation between the snow accretion inclined boards and the corresponding wind flow and shift of stagnation point.

Figure 5. Flow around the sign board in wind tunnel.

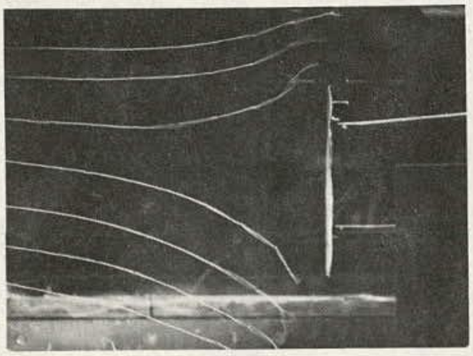
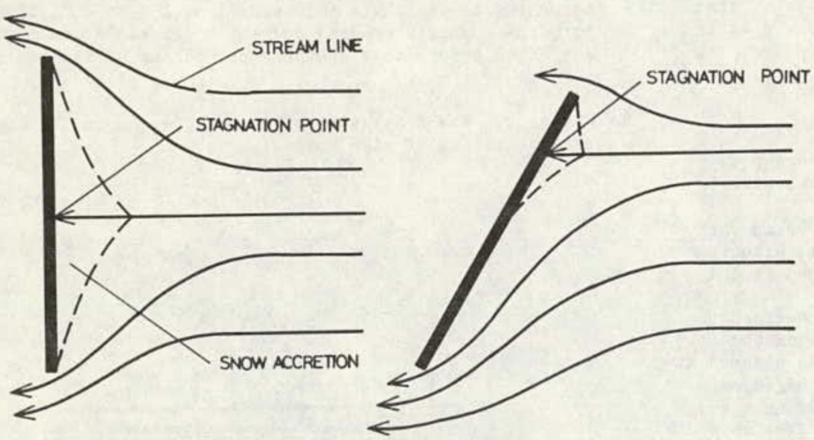


Figure 6. Schematic drawing of relation between snow accretion on inclined sign boards and the corresponding wind flow and shift of stagnation point.



Shielding sign board with a transparent cover having a negative angle of depression of its front. Though based on the same principle, a sign board is not inclined but shielded by a transparent cover having an angle of inclination: The fourth sign board from the right in Fig. 4 is fitted with a transparent acrylic cover as this contributes to shift of the stagnation point to a part of the cover, protruding above the sign board and although snow accretion occurs on this part the sign can be recognized without any hindrance at all. This method can be also applied to reflector.

Dimension of Sign Board and Quantity of Snow Accretion

The stream of snowflake is bent on the circumferential zone of a larger sign board in the direction of wind streamline and collides against the board at an acute angle, so that the snowflakes are repelled. For this reason, snow accretion becomes more dificult with increasing dimension of the board. The authors investigated the dependence of snow accretion omount on the dimension of the sign board. For this purpose, the authors used five painted poly wood venner boards, which are of rectangle with a ratio of the larger to shorter sides 2 : 1 and have areas from 22.5 x 45 to 90 x 180 cm in geometrical progression with a common ratio 2. Fig. 7 shows the views of snow accretion on the boards of various dimensions.

Figure 7. The amount of snow accretion depends on the dimension of the sign board.

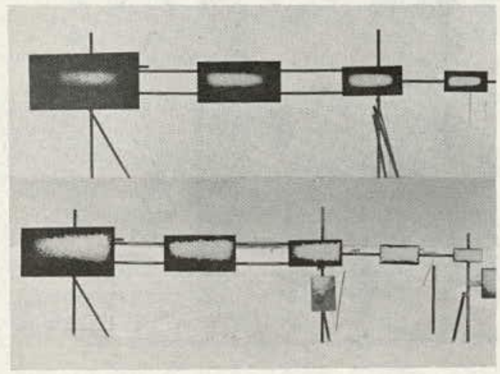


Fig. 8 is a diagrammatic representation of the relation between the shorter side of board and corresponding snow accretion ratio which is defined as a ratio of the area of its part covered with snow to that of its whole. It can be seen from Fig. 8 that the snow accretion ratio decreases linearly with increasing dimension of the board up to 64 cm of its shorter side and beyond it the ratio does similarly but with gradually decreasing rates. Fig. 9 reveals a tendancy that the rate of decrease in snow accretion ratio with increasing dimension of the board is lowered with increasing wind velocity and air temperature. Fig. 9 shows the snow accretion rate on the test board of 90 x 180 cm as a function of wind velocity and air temperature.

Since the larger value of snow accretion ratio means the occurrence and growth of snow accretion being easier, it can be said in general that snow accretion occurs more frequently with increasing wind velocity and air temperature.

Figure 8. The relation between the shorter side of board and corresponding snow accretion ratio shows that the snow accretion ratio decreases linearly with increasing dimension of the board up to 64 cm of its shorter side.

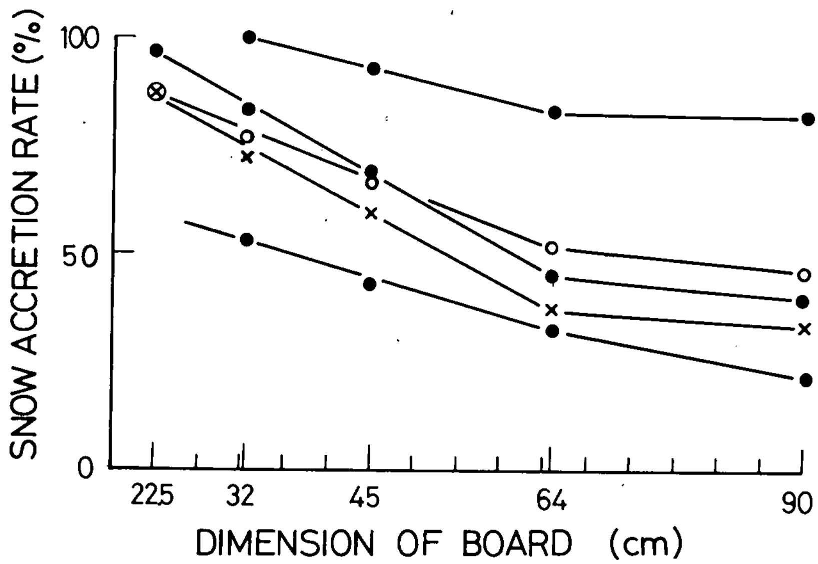
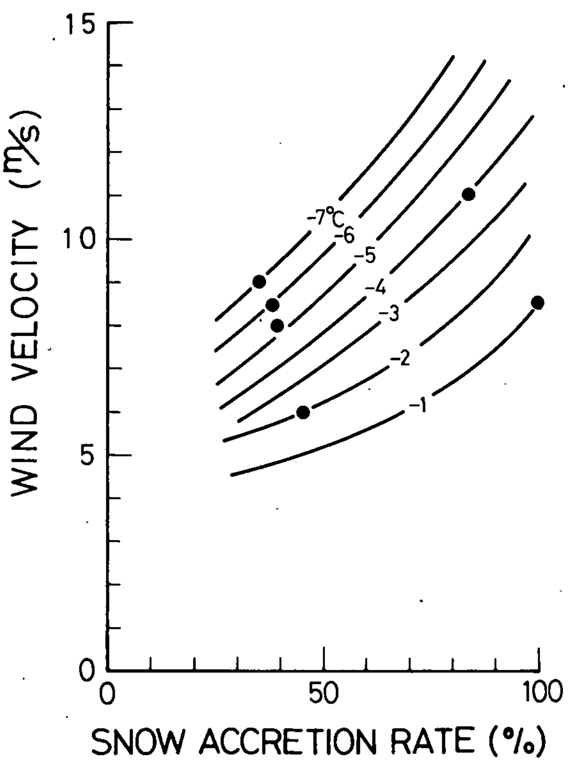


Figure 9. The snow accretion rate on the test board of 90 x 180 cm is shown as a function of wind velocity and air temperature.



Conclusion

As a function of wind direction, velocity, air temperature and characteristics of snow, the authors observed the snow accretion on sign board and discussed possible mechanism of snow accretion occurrence. In a strong wind, the snow accretion on sign board occurs more frequently with increasing wind velocity and, in the case of dry snow, increasing air temperature.

It appears that dry snow accretion is a phenomenon, in which the kinetic energy of air-born snow is converted into the inner one of it through its collision against the sign board to melt a part of it and after adhesion of this melted snow to the board the melted snow refreezes.

As for snow accretion prevention, experiments were carried out on the basis of the following three ways.

(1) Utilization of wind force,
(2) Surface treatment and
(3) Alteration of wind flow.

It was found that among them the alteration of wind flow is the most effective method.

Icephobic Coatings for Highway Pavements

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In the development of suitable icephobic substances to mitigate ice adhesion to pavement surfaces, a goal of functional usefulness was established. Specified objectives included cost effectiveness, minimum environmental pollution, use of standard materials and equipment, acceptable wear characteristics and minimum deleterious effects. Materials optimization progressed from laboratory tests to field testing. Factors investigated included various pavement and tire types, environment, toxicity, wear, ice/snow adhesion and sprayed or mix incorporated substances. Nineteen formulations were utilized at the Test Facility in 1976-77; sixteen in 1977-78. Substances are ranked on change in skid resistance, water beading efficacy, and snow/ice removal. The ratings are numerical, subjective and based on numerous iterative observations. Unusually mild winter weather conditions in Eastern Washington in 1976-77 restricted the desired operational parameters. More testing was accomplished in 1977-78. This report covers both winter seasons.

Testing

Objectives

The purpose of the project is to continue the development of a highway coating material, which when placed on existing highway surfaces, will significantly reduce the adhesion of ice to pavement surfaces.

Winter driving has increased significantly in recent years. The motorists expect the roadways to be safe and clear. Cities, counties and states are expected to keep the streets, roads and highways clear of snow and ice to facilitate these motorist needs. This is done to lessen the probability of accidents, accident injuries and fatalities.

Also to answer this need, tire manufacturers have developed winter tread tires, different rubber compounds and traction devices. However, these devices have limited use.

Winter tires do add to winter driving safety as they are more effective than regular tires. However, this use is limited to light snow and ice conditions. Rubber compounds have been tried with some success. Traction devices have limited usefulness under winter conditions.

Chains have been used successfully for years, but their use is limited to short distance driving because of limited durability of the chain links and reduced driving comfort. Studded tires have been more successful in that they can be used under most conditions, but they do cause pavement damage. (1,2,3). This damage has resulted in the refusal of many American and Canadian highway engineers to endorse or permit their use. In fact, the Federal Highway Administration, U.S. Department of Transportation, has recommended that their use be banned. Studded tires are allowed in parts of Europe but with the requirement that they be used on all four wheels (4). In the United States, several tire stud manufacturers have ceased operations.

The city, county and state highway departments have responded to help the motorist drive in the winter by plowing the roads, improving traction with sand and cinder applications and facilitating the melting of snow and ice by the use of chemical compounds, principally salt and salt compounds. Plowing the roads may cause some damage to the curbs, the pavement surfaces and the striping, but it is the only way to clear the roads of deep snow and drifts. Sand and cinder applications have aided traction and lowered minor accidents, but there is the problem of appearance, cleanup and pollution. The use of salt and salt mixtures are successful in melting the snow and ice but at some cost of environmental damage (5), pavement damage (6), accelerated bridge deck deterioration and bridge corrosion (7) and corrosion decay of automobiles and trucks. The costs incurred by snow and ice removal by salt use are significant and may outweigh the benefits (8).

Thus, there is a need to develop a compound which will provide the benefits of salt usage without its harmful side effects. The compounds should also be economical, easy to apply and long-lasting. The development of such a compound or compounds is the long-range purpose of this research.

Project Tasks

Mobilization. Mobilization included contacts, coordination and test scheduling. This portion of the overall task required the establishment of many arrangements necessary for the timely completion and effective performance of this research. This included the exact time-phasing for all consulting work, logistics with respect to other research, financial workings, timing, definition of various laboratory and Test Track efforts and the coordination of requests and purchases.

Laboratory Optimization. Formulations of paint/DC 732, DriSil 73/DC 732, Petroset AT and Viscospin B were selected based on tests concerning (a) the magnitude and stability of their contact angles, (b) their ice release abilities on both asphalt and concrete, (c) their skid resistance levels on asphalt only, (d) their durability/wear properties on both asphalt and concrete, and (e) their environmental contamination potentials. The tests were conducted by Ball Brothers Research Corporation. Based on recommendations made on the test results on Petroset AT and Viscospin B, two concentration levels in 4.25 cm asphalt overlays were determined for use at the WSU Test Track. Wear, skid resistance, environmental contamination potential and ice release ability were tested using laboratory techniques.

Test Facility Optimization. The results from the above tests showed which coating/substrate combinations would have the best possibility for success. These combinations were used on the WSU Test Track. Various combinations of tire types were used to study their effects. The data obtained from the WSU Test Track includes air and surface temperatures, visual observation of water beading and ice release, photographs of coatings and substrate conditions and coating skid values.

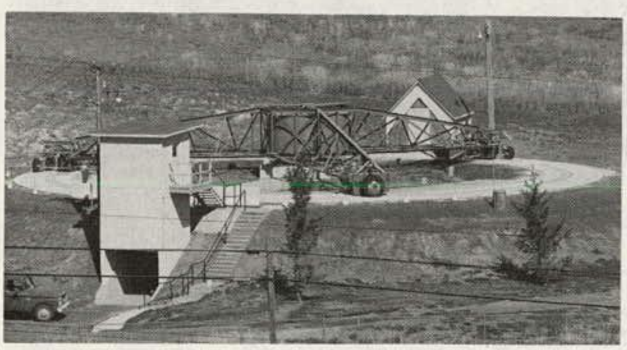
Description of Facility

Test Apparatus. The G.A. Riedesel Pavement Testing Facility consists of an apparatus with three loading arms supporting a water tank. These arms revolve in a circle on three sets of dual tires. A 60 hp direct current electric motor on each arm provides the motive power. An eccentric mechanism enables the apparatus to move so that a specified width of the pavement can be covered by the test wheels.

The apparatus was extensively modified in 1972 for studded tire research. The present facility has two sets of passenger tires inside the dual truck tires running in Wheel Paths #1 and #2, while the dual truck tires run in Wheel Paths #3 and #4. Two passenger tires are attached to each of two arms so as to travel in four separate wheel paths, #5, #6, #7 and #8. A total of 16 tires are mounted on the apparatus. Each passenger car tire carries a 454 kg (1000 lb) load, applied via individual load cells, and each set of the dual truck tires carries 2994 kg (6600 lb), except on Arm #3 where the duals carry 3901 kg (8600 lb) load.

An overall view of the G.A. Riedesel Pavement Testing Facility is shown in Figure 1. The observation tower houses the apparatus controls and recorders. The wheel and tire system is shown in Figure 2.

Figure 1. A View of the Present G.A. Riedesel Pavement Testing Facility



Tires (1976-77). Of the 16 tires which were used, six truck tires were all unstudded, seven passenger tires were unstudded and three were studded. The truck tires used were 11 x 22.5 inflated to 560kPa air pressure; the inside tire is the driving tire while the outside tire is free-wheeling. The truck tires were garnet dust impregnated retreads.

The passenger tires were all size 15 with different widths and snow tread designs, and consisted of 3 unstudded garnet retread tires size G78-15 in Wheel Path #1; 3 with 112 protrusion studs, tire size G78-15 in Wheel Path #2; 1 steel radial tire size GR78-15 in Wheel Path #5; 1 radial tire size HR70-15 in Wheel Path #6; one regular winter tread tire H78-15 in Wheel Path #7; and a radial tire with special soft rubber F-32, size GR78-15, in Wheel Path #8. Each tire was inflated to 224 kPa and carried a 454 kg (1000 lb) load. All the passenger tires were free-wheeling. Information about all the tires is given in Table 1.

Figure 2. The Arrangement of Wheels and Tires on the Apparatus

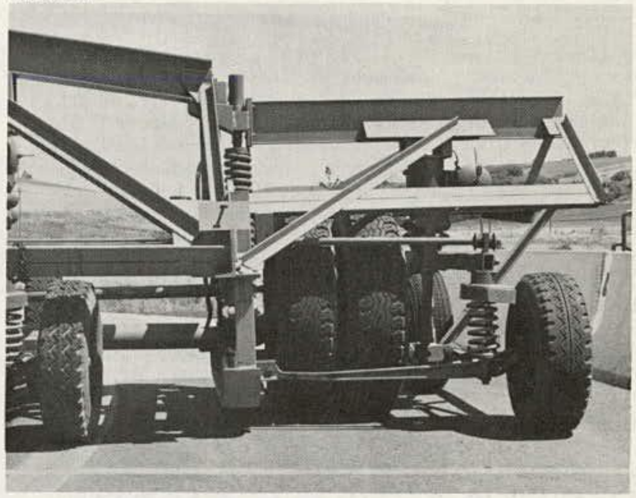


Table 1. Tire Types -- WSU Test Track

Wheel Path[1]	Number of Tires	Radial	Passenger	Truck	Garnet	Studded
1976-77						
1	3		x		x	
2	3		x			x[2]
3	3			x	x	
4	3			x	x	
5	1	x	x			
6	1	x	x			
7	1		x			
8	1	x	x			
1977-78						
1	3	x	x			x[3]
2	3	x	x			x
3	3	x		x		x
4	3	x		x		x
5	1		x			x
6	1		x			x
7	1		x			x
8	1		x		x	

Note: [1] The wheel paths are numbered consecutively from the inside edge to the outside edge of the track.

[2] One hundred and twelve studs in each tire, controlled protrusion type.

[3] Stud size and number varied.

Tires (1977-78). The tires used in 1977-78 were all studded except for wheel path #8. The passenger car tires were radial, bias belted, or bias ply. Wheel path #8 was a garnet tread tire. The studs varied in size from 6.5 to 9 mm in diam and 11 to 15 mm in length. Pavement wear as related to stud size and tire type are addressed in a separate report. The preponderance of studs had an obvious adverse effect on the durability of the coatings.

Instrumentation. Instrumentation of the Test Track included a Belfort Thermograph which recorded air and soil temperatures continuously. Surface pavement temperatures were measured using surface thermometers. Measurement of the revolutions and speeds were recorded continuously in the observation tower. Skid resistance measurements were made by a BBRC technician using a British Portable Skid Tester. Photographs of the project were taken by the WSU Engineering Photograph Service.

During the 1977-78 tests, pavement surface temperatures round the track were continuously recorded on a Honeywell 48-point thermocouple recorder.

Construction.

Test Sections (1976-78). The project consists of 30 test sections; each section has an average length of 2.4 m (8 foot) at the track diameter and a 3.3 m (11 foot) track width. Four portland cement concrete dividers were placed between sections for Sections 26 to 30. Two 1.2 m (4 foot) long transition zones were established between Sections 1 and 30, and between Sections 10 and 11, using the existing portland cement concrete.

Existing Surface (1976-1977). Approximately two-thirds of the existing Test Track pavement (Sections 11-30) consisting of both asphalt concrete and portland cement concrete, was removed to depths of 3.81-4.45 cm (1.5 - 1.75 inches). The remaining pavement surface was portland cement concrete (Sections 1-10), which was in place and utilized in this project.

Existing Surface (1977-78). The entire surface as used in 1976-77 was removed and replaced with various types of pavement. Types included portland cement concrete, asphalt concrete as used by the State of Washington, asphalt concrete which incorporated a "soft" basalt aggregate, open graded friction course asphalt concrete and asphalt concrete incorporating a special additive.

Preparation Procedure. The exposed subsurface areas were uneven in depth which made it necessary to level those areas. The exposed surface was primed with asphalt emulsion (SS-1) and leveled to a 1.91 cm (0.75 inch) depth with Class "b" asphalt concrete mix.

Between Sections 26 to 30, portland cement concrete dividers were placed to minimize contamination between the special asphalt overlays.

There was no need for any kind ot preparation for the existing portland cement concrete Sections 2 to 10. This procedure was used in 1976-77.

Pavements (1976-77). All of the asphalt sections were placed in the later part of October 1976. The Test Track section identification is shown in Table 2.

The paving contractor, United Paving, Inc., placed all of the asphalt mixes using standard highway paving procedures as much as possible. Due to the small amount of mix and the paving areas for some sections, some hand leveling, tamping, and compactions was necessary but was kept to a minimum. The mixes for the rubberized asphalt concrete sections were prepared at the United Paving plant but were placed by Yakima County Personnel. Some placing problems occurred with the Viscospin asphalt concrete mixes in Sections 29 and 30. Both mixes had a disagreeable odor and both mixes were hard to work. Their appearance was dull and lifeless, similar to cold-asphalt mixes, with similar handling properties. The 4 percent Viscospin asphalt mix was easier to compact.

The Petroset asphalt concrete mix in Section 27 with lower Petroset content was very easy to place and compact. In contrast, the 25 percent Petroset AT asphalt mix placed in Section 28 had the appearance of a cold mix and was difficult to place.

The placing of the asphalt mix in Sections 21-23 using the Blaw Knox paver is shown in Figure 3. Sections 27 and 28 included 8.33 percent and 25 percent Petroset AT additive in the Class "B" asphalt mix. The Viscospin asphalt mix placed in section 30 contained 8 percent Viscospin.

Pavements (1977-78). The portland cement concrete pavement consisted of 1.9 cm (3/4") aggregate, 6 1/2 sack mix, air entrained with slump of 7 cm (2 3/4"). The asphalt concrete mix was the Standard Type B hot mix which is deemed to be representative of northern tier states usage. The "soft" aggregate is a weathered basalt and was used as a correlation with a low standard wearing aggregate used on other projects. The open graded friction course design was as used by local agencies.

Figure 3. Placement of Asphalt, Sections 21-23, October 27, 1976

Table 2. Test Track Section Identification

1776-77 Section[1]	Type of Material	1977-78 Section[1]	Type of Material
1-10	Portland Cement Concrete	1-10	Portland Cement Concrete
11-20	Class "B" Asphalt Concrete Mix[2,3]	11-20	Class "B" Asphalt Concrete with Petroset
21-23	Open Graded Asphalt Concrete Mix	22-26	Low-Grade Asphalt Concrete[4]
24-26	Rubberized Asphalt Concrete Mix	27-28	Open graded friction course Asphalt Concrete
27	Petroset AT Asphalt Concrete Overlays	29-30	Class B Asphalt Concrete with Petroset
28	Petroset AT Asphalt Concrete Overlays		

Notes: [1]If more than one section, designation is inclusive.

[2]All asphalt concrete mixes were hot-mixes.

[3]Class "B" asphalt concrete mix is the Washington Department of Highways designation, and is deemed to be typical of northern tier of states.

[4]Mix design utilizing high wear aggregate for comparative purposes.

Formulation Application (1976-77). The Test Track apparatus was used to "break in" the pavement. A total of 3,798 revolutions was applied equivalent to 11,394 wheel loads in Wheel Paths 1-4 and 3,798 wheel loads in Wheel Paths 5-8.

Based on previous Ball Brothers Research Corporation tests, the formulations showing the most promise of success were to be used at the Test Track. These formulations and their Test Track location are shown in Table 3. The formulations were mixed and sprayed on between the 14th and 20th of January 1977 by a BBRC technician. The pavement surface was swept clean and dried by using a butane weed burner. The paint formulations were then hand sprayed on a 4-foot by 12-foot area using an electric hand sprayer. Some problems were encountered with strong winds which caused some over-spraying. Air temperatures ranged from 1°C and 6°C during the period. After skid resistance readings were measured, the pavements were ready for testing.

Sections 2,4 and 10 were the control sections on the portland cement concrete, while Sections 12, 14 and 20 were the control sections on the Class "B" asphalt concrete.

Figure 4. Formula Application by Spraying

Figure 5. Asphalt Concrete Sections After Formula Application

Formulations Application (1977-78). For the 1977-78 season, two applications were accomplished; one during the week of Dec. 10, 1977 and one during the week of January 18, 1978. The reapplication was done because the first one was made during severe weather conditions. Difficulties encountered during the second application were in curing time in sections 2 and 4. Figures 4, 5 and 6 illustrate the application and appearance of the coated sections.

Formulations and quantities applied to the surface for both seasons are shown in Table 3. Coated, untravelled areas exist between wheel paths; uncoated areas are adjacent to coated areas in each applicable section.

Figure 6. Portland Cement Concrete After Formula Application

Procedure

Wear Testing (1976-77). Before formulation application, 3,798 revolutions were accumulated by the apparatus. This is equivalent to 11,379 and 3,793 wheel traffic applications on Wheel Paths 1-4 and 5-8 respectively. After spraying, 14,408 revolutions were accumulated on the apparatus. This is equivalent to 43,224 and 14,408 wheel traffic applications on Wheel Paths 1-4 and 5-8 respectively.

The amount of time the apparatus was in operation was limited by the weather. It was planned to operate during and after snow storms. Snow did not materialize in any significant amounts. It was decided to spray the track with water so that ice would form on the pavements. This met with various success as the freezing temperatures needed for ice formation had to be below 0°C and had to last at least two or more hours. Unfortunately, the weather and air temperatures had started to warm rather prematurely and ice formation on the pavements proved to be a difficult task showing minimal success. It was then decided to use the apparatus for determination of traffic durability for the various paint formulations. Test Track operations ended on April 19, 1977.

Wear Testing (1977-78). During 1977-78 the studded tire-pavement wear research project was ongoing concurrently with the ice bonding mitigation research. Wear was accelerated but numerous observations and photos were taken to augment the results of 1976-77. Those formulations which continued to function after thousands of passes of studded tires do show excellent potential for use.

Weather Analysis (1976-77). The local population and area enjoyed a most mild and dry winter during 1976-77. The temperatures were above and the precipitation was below normal levels. This area was experiencing a drought of a magnitude never before recorded in any records. The climatological data is summarized in Table 4 showing maximum and minimum daily air and soil temperatures as measured locally. It can be seen that by the time the paint formulations were applied, most of the cold periods had passed. The freezing time had also been reduced.

Weather Analysis (1977-78). The 1977-78 season provided approximately the same average freezing time, maximum and minimum temperatures, but the precipitation was considerably greater. Observations and photos were taken frequently and coating effects noted.

Table 3. Formulations and Quantities Applied -- WSU

Track Section 1976-77	Track Section 1977-78	Formula Designation	Principal Ingredient Name	Amount cm3 1976-77	Amount cm3 1977-78	DC 732 gm 1976-77	DC 732 gm 1977-78	Other Ingredients-Amounts: Naptha Binder/DC 732 cm3 1976-77	Naptha Binder/DC 732 cm3 1977-78	Isopropanol cm3 1976-77	Isopropanol cm3 1977-78	Quantity Applied Litres[1] 1976-77	Quantity Applied Litres[1] 1977-78	Type of Section[2] 1976-77	Type of Section[2] 1977-78
19	20	B	LR8198	721	655	126	114	362/278	329/253	27	25	1.15	1.26	BAC	BAC
9	10			655	655	114	114	329/253	329/253	25	25	1.04	1.26	PCC	PAC
18	9	C	LR8198	598	544	207	188	299/461	272/415	52	47	1.16	1.28	BAC	PCC
8	19			544	544	188	188	272/419	272.419	47	47	1.05	1.28	PCC	BAC
	24				544		188		272/419		47		1.28		SAC
7	7	F	LR8652	1536	1536	95	95	576/307	576/307	29	29	2.04	2.44	PCC	PCC
17	17			1690	1536	105	95	634/338	576/307	32	29	2.24	2.44	BAC	BAC
	25				1536		95		576/307		29		2.44		SAC
	27				1536		95		576/307		29		2.44		OAC
6	6	G	LR8652	1327	1327	165	165	499/499	499/499	49	49	1.95	2.37	PCC	PCC
16	16			1460	1327	182	165	549/549	499/499	54	49	2.14	2.37	BAC	BAC
15	14	I	Drisil 73	1074	976	64	55	535/162	486/147	21	19	1.49	1.63	BAC	BAC
	23				976		55		486/147		19		1.63		SAC
5		J	Drisil 73	880		114		438/262		26		1.32		PCC	
3	4	K		800	400	160	160	400/358	400/358	40	40	1.31	1.60	PCC	PCC
13	2	L		810	736	210	191	404/485	367/441	49	46	1.41	1.59	OAC	BAC
22	12			810	736	210	191	404/485	367/441	49	46	1.41	1.59	OAC	BAC
11	29	Petroset AT		780						(3)				BAC	PAC
1	30			708						(4)				PCC	PAC

NOTES: [1]Applied to test track area of 4.5 m^2 (4' x 12'). Volumes as mixed included working excess allowance for compressor sprayer intake, naptha dilution, hose filling.

[2]Type of section designations: PCC = Portland Cement Concrete, BAC = Class "B" Asphalt Concrete, OAC = Open-graded friction course Asphalt Concrete, SAC = BAC with "soft" aggregate and PAC = Asphalt Concrete with Pestroset added (25% in Section 29; 8.33% in Section 30).

[3,4]Mix included distilled water; 1080 cm^3 in Section 1; 1170 cm^3 in Section 11.

LR 8198 is "AKROS" Paint, Type II without TiO_2
LR 8652 is Akron resin-only version
Drisil 73 is Dow-Corning Silicone Base Water Repellent
Petroset AT is Phillips Petroleum Asphalt Additive

Table 4. Temperatures and Precipitation

Date	Air Temp °C Ave Max	Air Temp °C Ave Min	Air Temp °C Freezing Time-Hrs	Soil Temp °C Ave Max	Soil Temp °C Ave Min	Pavement Temp °C Ave Max	Pavement Temp °C Ave Min	Pavement Temp °C Range	Precipitation Inches[4]	Precipitation Normal
12-76	4	-3	14	-2	-7				0.98	2.74
1-77	-1	-8	20	-6	-9				0.40	2.67
2-77	8	-1	8	3	-4				0.45	2.10
3-77	8	-1	5	3	-4				1.35	2.12
4-77	14	3	2	18	1				0.32	1.49
11-77[1]	6	-2	8	1	-4	5	-2	-8—12	9.5 (s) 2.51	2.47
12-77	2	-2	11	-3	-7	4	-1	-6—11	10.77(s) 4.43	2.47
1-78	2	-2	10	-3	-6	5	0	-4—11	5.00(s) 2.00	2.67
2-78	3	-2	8	0	-4	9	0	11—21	11.2 (s) 2.54	2.10
3-78[2]	6	2	6	2	-4					

NOTES: [1]From November 21 through November 30, 1977
[2]Through March 12, 1978
(s) = snow
[4]Conventional weather usage. One inch = 2.54 cm.

Skid Resistance Measurements. Skid resistance measurements, using the British Portable Skid Resistance Tester, were taken before testing, before and after spraying of the formulations and after all testing was completed. Due to variations in pavement surface temperatures during measurements, all skid values were corrected to 20°C according to accepted procedures (10).

Results

Skid Resistance Wear. The results from the British Portable Skid Tester, taken before testing, before spraying, after spraying and at completion of testing are summarized in tables available in the complete report on this project. An illustrative example is given in table 5.

It is apparent that the immediate effect of these formulations on both portland cement concrete and asphalt concrete pavement is to reduce the skid resistance. These reductions can vary from a high of 35 to a low of 2. The exception is Petroset AT application which increased skid resistance of both types of pavements. On the PCC Pavements, formulations C and J affected skid resistance the least. On the basis of increasing the effect on skid resistance, the ranking of formulations is C, J, K, G, B and F. On the Class "B" asphalt concrete pavements, formulations C, I and L caused the least reduction in skid resistance. The ranking based on increasing reduction of skid resistance is C, I, L, B, G and F respectively. The L formulations on the open-graded asphalt concrete overlay reduced its skid resistance by only 6 which was superior to any of the Class "B" asphalt concrete overlays. This is due in part to the open-graded nature of the pavement.

It is difficult to measure wear of a coating. In this project one criterion was the use of the change in skid resistance. A Skid Resistance Change Rate (SRCR) was developed as a measure of skid resistance change and wearing of coating. Under most circumstances, pavements suffer a loss in skid resistance with traffic and time. In this project, an increase in skid resistance as denoted by a positive SRCR indicates more wear than a negative SRCR. The reason for this use of skid resistance in such a manner is that the coatings reduce skid resistance and when they are worn off, the skid resistance will increase.

Using SRCR as a measure of change in skid resistance, Tables were developed in 1976-77 to show the comparisons of skid resistance changes for the different sections and formulations. The changes in skid resistance for the portland cement concrete sections are shown in Table 5. The BPN and SRCR show the following ordering on the basis of decreasing wear. formulations F, B, J, K, G, C, Petroset AT and the nontreated section. Formulation F had the least resistance to traffic wear while C had the most.

Wear is also a function of the type of tire. The testing apparatus had seven different types of tires. The effect of these tires of portland cement concrete pavements is also shown in Table 5. The garnet tread truck tires caused the most wear as would be expected, the inside driving tire more than the free-wheeling tire. Of the two inside passenger tires, the studded tire caused more wear and a polishing action on the pavement as compared to the garnet tread tire. The tires in Wheel Paths 5-8 had different treads and tire constructions. These were ranked 7, 5, 6, and 8 in order of the highest to lowest SRCR. The tire with the special compound F-32 in Wheel Path #8 appears to cause the least wear of any of the passenger tires.

For the Class "B" asphalt concrete sections, the BPN and SRCR show the following ordering on the basis of decreasing wear: formulations G, F, B, L, I, C Petroset AT and the nontreated sections. The studded passenger wheel tires (Wheel Path 2) increased the skid resistance more than the passenger wheel garnet tread tires (Wheel Path 1) thus indicating more wear of the formulations. In order of the highest SRCR, the ranking according to Wheel Paths is #5, #6, #7, and #8. The tire with F-32 rubber in Wheel Path #8 again caused the least wear.

For the open-graded asphalt sections, section 22 with formulation L had less reduction in skid resistance but the initial skid readings were lower. In the group of asphalt overlays, the tires in Wheel Paths #6, #5, #7 and #8 caused the most reduction in SRCR, respectively. The garnet tire lowered the SRCR more than the studded tire in these asphalt pavement types. The reason is that the garnet dust acted as an abrasive polishing the aggregates.

For the four asphalt overlays, skid resistance reduction values indicate that Section 27 with 8.33 percent Petroset was inferior to Section 28 with 25 percent, but the final BPN was still higher for Section 27 than for Section 28. The 25 percent Petroset Section 28 had initial lower BPN's. Comparing the two Viscospin asphalt overlays, Section 29 with 4 percent Viscospin had higher initial BPN's and also lower final BPN's than Section 30 with 8 percent Viscospin. In other words, for both types of overlays, the overlays with the most additive had a lower reduction in SRCR. This may indicate that additives help in lowering the reduction in skid resistance.

The garnet tread passenger tires in Wheel Path #1 caused the greates loss in BPN, agin indicating the abrasive action of the garnet dust on the aggregates. Of the other passenger tires, the tire in Wheel Path #8 caused the least loss in BPN, followed by the tire in Wheel Paths #5, #7 and #6 in that order. It appears that the F-32 rubber passenger tire has the least effect on pavement skid resistance in general.

The changes occurring in the skid resistance as wear progressed was noted in 1977-78. The skid resistance values are presented in Table 6. There were marked differences within the asphalt concrete types of pavement.

Beading-Wear. The mild winter of 1976-77 resulted in the necessity for utilizing another measure for the effectiveness of the formulations and the overlays. This measure was the beading of water. Beading is an evidence of the wetting characteristics of the substrate as the efficacy of the applied formulation changes over time. The Test Track operation did not include application of either salt or sand, therefore reduction in beading occurred as traffic wear progressed. Frequent observations were made on each section, with natural or artificial application of water to the surface. A wear ranking scale based on observations of beading was developed.

Ratings are stated in a Bead Wear Ranking Number (BWR). The final results are summarized in Table 7. Such ranking is entirely subjective. It does, however, provide an indication of the wear resistance of the hydrophobic substances.

For the portland cement concrete pavements, a ranking of traffic wear resistance can be made. In order of most to least wear resistance, the following ranking is obtained: K - Section 3, C - Section 8, J - Section 5, G - Section 6, F - Section 7, B - Section 9, and Petroset At - Section 1, respectively. Wheel Paths 1-4 showed more wear than Wheel Paths 5-8. This is expected because there is three times the number of passes per revolution.

On the Class "B" asphalt concrete pavements, the traffic wear resistance in the order of most to least wear resistance is: C - Section 18, F - Section 17, G - Section 16, B - Section 19, L - Section 13, I - Section 15 and Petroset AT - Section 11, respectively. Here too, Wheel Paths 1-4 showed the most wear. The studded tire in Wheel Path #2 caused more wear than the truck garnet tires or the passenger garnet tire. The single tires in Wheel Paths 5-8 did not abrade the formulations as rapidly as the inside tires.

On the open-graded asphalt sections, the formulation L appears to be more resistant than when applied on the Class "B" asphalt - Section 13. Some beading was noticed on the rubberized and Petroset asphalt overlays, but almost none on the Viscospin sec-

Table 5. Comparison of Skid Resistance Values for the Portland Cement Concrete Sections 7-10 in BPN (Corrected to 20°C)

Section	Formulations	Parameters for Skid Resistance Values	Skid Resistance Values in BPN at 20°C Wheel Paths								
			UT3	#1	#2	#3	#4	#5	#6	#7	#8
7	F	After Spraying	54	55	55	56	54	55	55	55	55
		After Testing	54	75	62	69	69	76	66	72	57
		Change	--	+20	+7	+13	+15	+11	+11	+17	+2
		SRCR	--	+463	+162	+301	+347	+763	+763	+1180	+136
8	C	After Spraying	78	74	74	76	71	74	74	74	74
		After Testing	78	73	64	68	68	78	77	79	67
		Change	--	-1	-10	-8	-3	+4	+3	+5	-7
		SRCR	--	-23	-231	-185	-69	+278	+208	+347	-486
9	B	After Spraying	81	64	64	64	64	64	64	64	64
		After Testing	81	71	63	74	74	74	73	79	76
		Change	--	+7	-1	+10	+10	+10	+9	+15	+12
		SRCR	--	+162	-23	+231	+231	+694	+625	+1041	+833
10	NT	After Spraying	88	88	88	88	88	88	88	88	88
		After Testing	88	69	61	60	60	75	76	79	84
		Change	--	-19	-27	-28	-28	-13	-12	-9	-4
		SRCR	--	-440	-625	-648	-648	-902	-833	-625	-278

NOTES: The formulations were sprayed on after 2,793 wheel applications, which is taken as zero wheel application

There were 43,224 and 14,408 wheel applications put on Wheel Paths 1-4 and 5-8 respectively, after spraying.

Skid resistance change ratio (RCR)=(ΔBPN/WL) x 10^{-6}

NT - Not Treated

UT = untravelled.

tions. On the basis of BWR, very little can be concluded as this criteria is not readily applicable for overlays.

The beading phenomenon is a function of pavement type, formulation type, traffic action and freeze-thaw cycle locations. The hydrophobic substances may act as a sealant for a porous surface and thus inhibit vertical movement of water. This may result in globules of ice or beads of water building up on the treated surface, with untreated adjacent uncoated areas apparently "free" of moisture. This is usually a temporary condition; the beads are easily dispersed by traffic. This is shown in Figure 7.

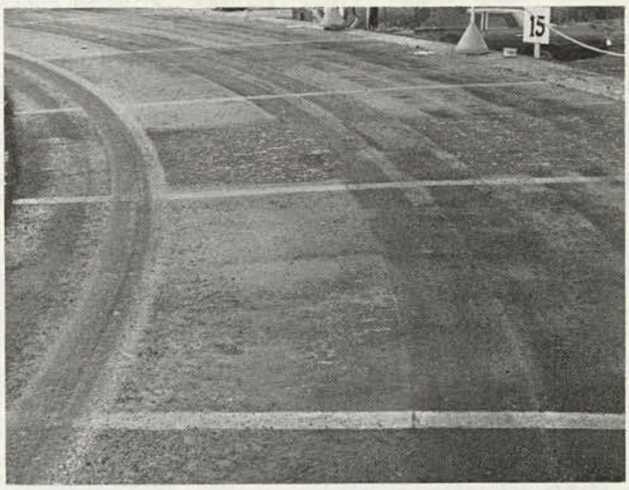
Snow and Ice Removal Properties. These results are based on subjective evaluation of the effectiveness of the various formulations and overlays in accelerating the removal of snow and ice from the pavement surfaces. Observations after traffic simulation operations were made of the snowy-icy conditions of the various pavements after a snowfall or after the formation of ice. The apparatus was operated in each case until there was noticeable differences in snow/ice conditions. The amount of snow/ice removed by traffic was estimated for each section and wheel path. A ranking was developed for each group of pavements - the portland cement concrete, the Class "B" asphalt concrete, and the asphalt overlays. Originally it was planned to use salt and sand-ice combinations to compare their ice mitigation capabilities.

As mentioned previously, the lack of suitable weather minimized the number of observations. Although there were many observations, only six were complete with observations obtained on all sections. There was difficulty in trying to estimate the amount of snow and ice removal. Time was a factor; it was very important to evaluate conditions before the ambient temperature increased.

The ranking of the various tests for the various types of pavements was determined. The rankings of the sections in order of "best" snow/ice removal properties are 7, 6, 8, 9, 1, 10, 3, 2, 5 and 10. The best formulations on portland cement concrete were F, G, C, B, Petroset, K and J respectively.

On the Class "B" asphalt concrete pavements, the rankings showed a slightly different ranking of the formulations than that obtained from portland cement concrete. The section ranking was 16, 17 and 19, 18, 13, and 15, 20, 14, 11 and 12, respectively. The best formulations for snow/ice removal properties were G, F and B about equal, C, L and I about equal and Petroset least.

Figure 7. Section 19, January 26, 1977. Very Little Ice is Visible



The rankings of the asphalt overlays were determined. The overall ranking for all overlays shows that the best overlays with respect to snow/ice removal properties were Sections 25, 26, 27, 24, 22, 28, 21, 30, 23 and 29 respectively. Overall, the rubberized asphalt sections performed the best with the Petroset asphalt sections next. The open-graded sections did not perform as well as expected but the formulation did some good. The Viscospin asphalt sections did not perform very well.

One observation noted was that the ice on the sections where formulations were applied appeared to be softer and had less adhesion than the ice on the untreated portions. Also, the untreated sections dried out more quickly than the treated sections. This was an indication of the beading properties of the materials. On the open-graded asphalt concrete sections, fine snow had a tendency to filter into the pores of the mix and took longer to melt. In Section 23, some pumping of the silt was coming through the concrete base from the silt subgrade. This indicates that this type of overlay should not be used over cracked bases or used to prevent reflective cracking by itself.

The rubberized asphalt concrete sections were quite successful in accelerating the removal of snow and ice. The flexibility apparently caused fatigue cracking in the ice and thus weakened the ice bonds. One problem with the rubberized asphalt concrete is that excessive rubber will permit raveling which occurred in Section 25. Even though it was superior to the other two rubberized pavements with respect to snow/ice removal properties, its surface raveling from the mix proportions used would require changes to be acceptable for highway use.

Neither of the four asphalt overlays with Petroset AT and Viscospin evidenced superiority. One thing is evident, more is not necessarily better because the pavements with less additive frequently performed better than the ones with more additive.

Tire types do affect snow and ice removal. The tires were ranked according to the most rapid snow/ice removal properties. The tires in Wheel Paths 1-4 should be compared separately as these wheel paths had three times the traffic of Wheel Paths 5-8. In the Wheel Paths 1-4, the ranking using the wheel path numbering system, is a follows: #3, #1, #4 and #2, respectively. The most effective tire was the inside driving truck garnet tread truck tire and the least effective being the studded passenger tire in Wheel Path #2. In Wheel paths 5-8, the ranking was as follows: #5 and #6 being about the same, then #7 and finally #8. The two types of passenger tires were the most effective while the winter tire with F-32 rubber was the least effective. It should be emphasized that the differences between tires were not large. Further consideration should be given to the fact that the tires (and wheels) were restrained in the transverse motion. The wander or "sweeping" action of tires could affect this rating. It is reported for information only and was not included in the ranking of the formulations.

Figures 8 and 9 are representative photos of effects of coatings. The marked difference between the treated and untreated portions of the wheel path indicates the ease with which traffic will remove light snow or ice from a treated area.

For the asphalt pavement, Figure 10 shows the difference between treated and untreated areas in icy conditions. A film of ice exists on the untreated area; there is no ice on the treated area.

Test Section Comparison (1976-77). Using the three criteria developed for ranking the different sections, an overall ranking was calculated which is shown in Table 8. The three criteria were Skid Resistance Change Rate (SRCR), Beading Wear Criteria (BWR), and Snow/Ice Removal Criteria. Each was weighed equally and on that basis an overall ranking was calculated for each pavement type.

On this basis, for portland cement concrete and in order of the most effective formulation, the ranking was as follows: formulation F, G and C about equal, B and K about equal, J and Petroset last. It can be seen that the nontreated sections were ranked low.

On the Class "B" asphalt concrete section the formulations in order of most effectiveness were ranked as follows: G, F, B, C,I and Petroset last. The nontreated sections were ranked lowest.

Of the asphalt overlays, the rubberized asphalt sections and the Petroset sections on overall ranking were superior to the other two types. It can be seen that the untreated open-graded asphalt sections did not rank as high.

The two Viscospin sections were not as effective and were accordingly ranked low.

Efficiency ratings of coatings is difficult if general rather than specific conditions or criteria are used. Variations result from the dynamic weather encountered during winter hours. Pavement type has an effect which changes with temperature and wear. The research effort documented these relationships among variables.

Table 6. Skid Test Summary - 1977-78 BPN Values

Pavment Type	Formulation B	C	F	G	I	K	L	P	P
BAC									
Sect. No.	20	19	17	16	14		12		
TU	68	68	67	62	67		60		
TC_o	53	56	57	43	52		57		
TC_F-TC_o	14	15	5	22	22		14		
SAC									
Sect. No.		24	25		23				
TU		69	67		69				
TC_o		55	48		62				
TC_F-TC_o		8	12		3				
OAC									
Sect. No.			27						
TU			70						
TC_o			50						
TC_F-TC_o			18						
Petroset									
Sect. No.								29	30
TU								78	80
TC_F-TC_o								11	17
PCC									
Sect. No.	10	9	7	6		4	2		
TU	70	76	78	77		74	75		
TC_o	61	66	61	46		58	56		
TC_F-TC_o	11	1	9	25		9	11		

NOTES: TU - Skid Number at time of formula application, 126,507 revolutions, wheel path, uncoated area, TC_o - Skid number at time of formula application, wheel patch, coated area TC_F - Skid number at completion of observation, wheel path, coated area, after 249,393 revolutions (19903 kilometers on single tire).

PCC - Portland Cement Concrete, BAC - Class "B" Asphalt Concrete, OAC - Open-graded friction Course Asphalt Concrete, SAC - BAC with "soft" aggregate and PAC - Asphalt Concrete with Petroset added - 25% in Section. 29, 8.33% in section 30.

Laboratory Test Comparison. The rankings obtained from the WSU Test Track were compared with laboratory rankings based on ice-adhesion force. These are shown in Table 8. It can be seen that the formulations F and G performed as predicted by laboratory tests while formulation B exceeded the laboratory performances indicated. Formulation C. results were as predicted on the asphalt concrete with increased performance on the portland cement concrete. In summary, the test results indicate good conformance with laboratory results.

Environmental Tests. Laboratory test results by BBRC indicated that the main concern insofar as environment and toxicity of the substances is the naptha component. This is considered to be a solvable problem. (Discussion is included in a separate report by Ball Bros. Research Corp).

Toxicity tests at the Test Track were of two types: water leachate from dried material and leachate from newly applied material. With the exception of Petroset, materials were not considered to be significantly toxic in either mode. (Discussion is included in separate report by Washington State University, Environmental Engineering Section).

Table 7. Wear Ranking of WSU Test Track Section at End of Test by Water Beading Criteria 1976-77

Type of Material	Section	Formulation Code	Wear Rankings[4] UT[2]	#1	#2	#3	#4	#5	#6	#7	#8
PCC	1	Petroset AT	1	0	0	1	1	1	1	1.5	1.5
	2	NT[3]	0	0	0	0	0	0	0	0	0
	3	K	5	2	1	3	3	4	4	4	4
	4	NT	0	0	0	0	0	0	0	0	0
	5	J	5	2	1	1	1	3	3	3	3
	6	G	5	1.5	1	1	1	2	2	2	2
	7	F	5	2	1	1	1	1	1	2	2
	8	C	5	2	1	2	2	3	4	4	4
	9	B	5	2	0	1	1	1	1	2	3
	10	NT	0	0	0	0	0	0	0	0	0
Class "B" A.C.	11	Petroset AT	4	3	1.5	1	1	1	1	1	1
	12	NT	1	1	0	0	0	1	1	1	1
	13	L	5	2	2	1	1	2	2	3	3
	14	NT	1	0	0	0	0	0	1	1	1
	15	I	5	3	0	0	0	1	1	1	2
	16	G	5	2	1	1	1	2	3	4	4
	17	F	5	3	0	2	2	3	2	3	3
	18	C	5	1	0	2	2	4	4	4	3
	19	B	5	2	0	1	1	3	3	2	3
	20	NT	1	0	0	0	0	0	0	0	0
Open-Graded A.C.	21	NT	0	0	0	0	0	0	0	0	0
	22	L	4	3	3	3	3	3	3	3	3
	23	NT	0	0	0	0	0	0	0	0	0
Rubberized A.C.	24	5%	2	1	2	1	1	1	1	1	1
	25	10%	2	2	2	1	1	1	1	1	1
	26	3%	1	1	1	1	1	1	1	1	1
Asphalt Overlays	27	Petroset AT	1	1	1	1	1	1	1	1	1
	28	Petroset AT	2	1	0	1	1	2	2	2	2
	29	Viscospin	1	1	0	0	0	0	0	0	0
	30	Viscospin	0	0	0	0	0	0	0	0	0

NOTES: UT[2]=untraveled
NT[3]=Not treated
[4]=Rankings based on 0 (no beading) to 5 (superior beading)

<u>Conclusions</u>. Although the winter conditions of 1976-77 were mild, the limited amount of test and data did allow a ranking based on skid resistance change, water beading and snow/ice removal properties of the different formulations. The four most effective formulations were F, G, C and B. These results, except for formulation B, compared favorably with laboratory results.

Of the overlays, the three rubberized asphalt sections and the two Petroset asphalt sections were most effective. The best rubberized asphalt section also showed reduced abrasion resistance which would negate its other performance. The superiority of the rubberized sections was due to their flexibility which, under cold temperatures of -10°C or less, may not be so effective. The Viscospin sections did not perform very well. The open-graded asphalt sections may not be effective in heavy snowfalls since the pores become clogged and frozen.

On the basis of toxicity tests, only the Petroset was deemed toxic. Other formulations showed little or no toxicity. The Petroset also showed high hydrocarbon levels from runoff.

Ice and snow removal from the highway is dependent on many factors. Some of these factors are the type of tire, the tread type, and presence of studs. Because this aspect of removal is based on interdependent factors, efficiency of icephobic substances is affected.

Petroset as a treatment for the surface presents problems of toxicity. As an additive to an asphalt mix the toxicity problem is confined primarily to the plant. It has shown promise as an icephobic substance.

Viscospin does not appear to warrant additional research as an ice de-bonding agent.

Depending upon the weighting of ranking criteria (including cost), the traffic paint-silicone rubber formulations appear to have some advantage over the silicon-ate-silicone rubber formulations. Specific short-range uses such as bridge decks, underpasses, over-passes and residential driveways may indicate long-range general useage benefits.

Table 8. Ranking of Coatings

Formulation	Ranking[1] Based on Ice-Adhesion Force	Overall Ranking PCC 1976-77	PCC 1977-78	Class "B" AC 1976-77	Class "B" AC 1977-78
B	8	3	3	3	4
C	4	2	2	4	3
F	2	1	1	2	1
G	1	2	4	1	2
I	5	NA[2]	NA	6	5
J	7	4	NA	NA	NA
K	6	3	4	NA	NA
L	3	NA	4	5	6

NOTES: [1]Laboratory Tests (Ref. 9)
[2]Not applicable

Figure 8. January 31, 1977. An Overall View of Sections 7, 6, and 5.

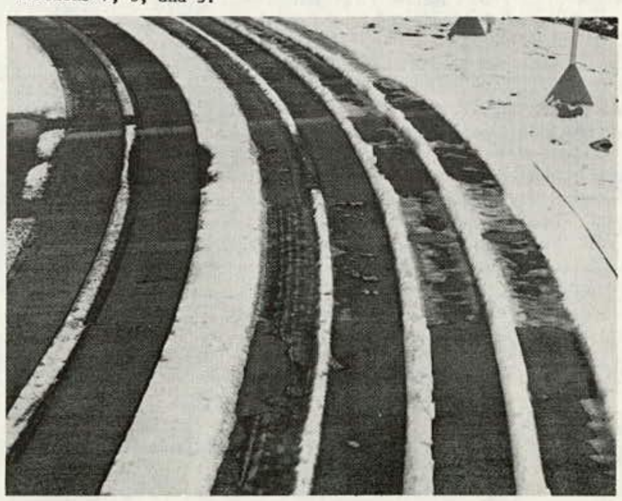


Figure 9. Section 7, January 31, 1977

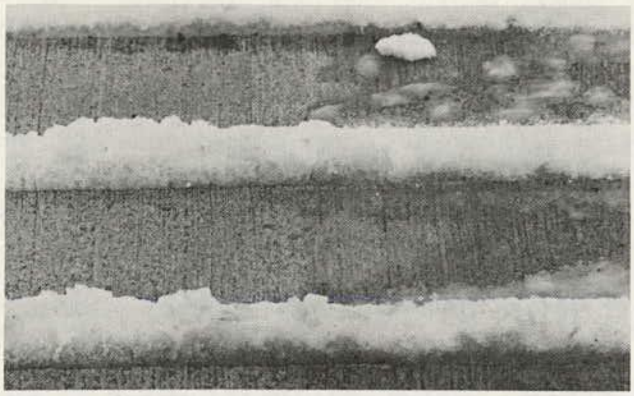
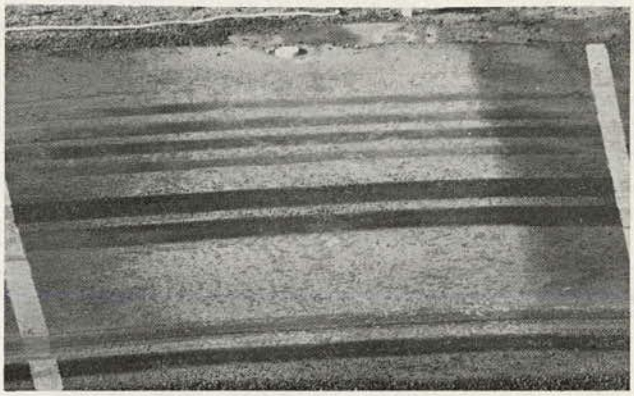


Figure 10. A Comparison of Ice Bead Formations Between Sections 17 to 14.



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A Method of Predicting Road Salt Runoff in New Hampshire

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A predictive method is developed to forecast the "worst case" amount of sodium (Na^+) and chloride (Cl^-) ions added to surface waters as a result of highway deicing chemicals. Assumptions are based upon hydrological, topographical and meteorological characteristics specific to the central New Hampshire region. This worst case model is a seasonal method which is based upon all salt running off during a six month salting season (November-April). Specific geographical names are omitted as the project for which this model was developed is not finalized at this writing.

The preparation of an Environmental Impact Statement (EIS) to identify potential effects associated with a proposed federal action which will significantly affect man s environment is required by the National Environmental Policy Act of 1969. The EIS must address all of the probable effects, both positive and negative, likely to be anticipated. These include social, economic and environmental considerations.

In the study of proposed new roadways, effects upon water quality often become a major issue. In particular, there is a need to identify the potential changes in water quality following construction and opening of the roadway. For instance, questions arise with regard to toxic heavy metals such as zinc, cadmium, lead and mercury, often found in vehicular coolants, fuels, lubricants and wearing parts (1). These elements will be incident upon the roadway pavement and find their way to runoff waters in sufficient concentrations to inhibit biological productivity.

Of all potential pollutants during the winter season, deicing compounds are the most obvious (2, 3). Two elements--sodium and chloride--lend themselves to direct quantification of runoff concentrations, except that the analyses are so complex that results obtained are largely estimates based upon professional judgment.

In New Hampshire, where relatively severe weather conditions and heavy snowfalls occur during winter, extensive road plowing and salting operations take place. Therefore, during the preparation of a recent Environmental Impact Statement for a proposed new roadway in that State, a method of predicting the runoff of road salt derived by the New Hampshire Department of Public Works and Highways, was used to evaluate the likely effects upon the many streams to be traversed by the new road. Described below are the existing conditions of the study area, the methodology employed in predicting road salt runoff concentrations and utilization of those predictions to define the probable impacts. This paper considers the potential salt impacts of the proposed roadway extension in central New Hampshire. The names of lakes, ponds and streams have been deleted as the outcome of the project is undecided and is facing divided public opinion.

Study Area

The study area is totally within the Merrimack River Basin (R) Watersheds of the Rivers A and B make up the headwaters of River R. (See Figure 1). River A flows through the corridor in a southerly direction near the west end of the proposed road. The path of River B is generally parallel to the proposed road across the southern portion of the study area.

Natural drainage in the region is reflected in the distribution of lakes, low areas and meandering streams. The terrain of the adjacent reaches of Rivers A and B is gradual with elevations ranging from 120 to 300 meters above mean sea level. All roadway drainage is directed into the closest downhill receiving stream. The number of lane miles of highway section is known for each drainage basin to be crossed.

Climatology

The watersheds in the study area have a variable climate characterized by moderately warm summers, cold winters and ample rainfall. The weather is especially severe in the upper tributaries of River A where it flows out of high mountains. The project lies in the path of prevailing winds from the west and cyclonic disturbances that cross the country, from the west and southwest toward the east and northeast.

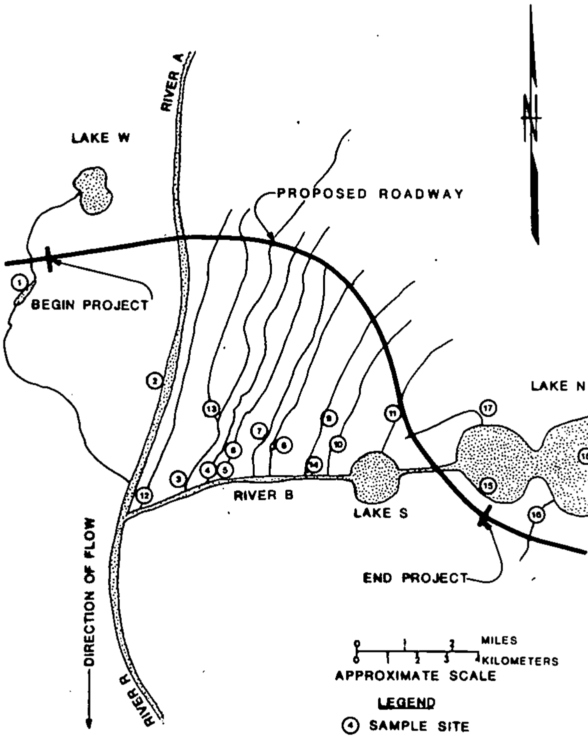


FIGURE 1
WATER BODIES IN STUDY AREA
(schematic)

Temperature

The average annual temperature in the basin is about 7°C. The average monthly temperatures vary widely throughout the year, between 18°C and 21°C in July and August to -4°C and -3°C in January and February. The extremes range from highs in the +30°C range to lows of -34°C.

Precipitation

Precipitation data was obtained from the U.S. Weather Bureau's Climate Survey (4) and is summarized for the study area in Table 1. Precipitation amounts are distributed equally throughout the year. It ranges from a low of 67mm in February to a high of 101mm in November. The mean and median precipitation is 86mm per month.

Table 1. Total average precipitation at a study area station.

Month	Average Precipitation (mm)
January	83
February	67
March	81
April	87
May	99
June	92
July	91
August	75
September	96
October	75
November	101
December	86
Annual	1030
Average Annual Snowfall (mm)	1750

Elevation of Station (m) 119 Period of Record 1931-1960

Lakes And Ponds

The study area has several small ponds, three major lakes and many streams. Lake W, located on the western end of the project, is a natural water body. The surface area is 248 hectares with an approximate maximum depth of 12 meters.

Lake S is also a natural water body. It is fed by waters of River B at the outlet of Lake N. Its depth ranges up to approximately 8 meters with a surface area of 72 hectares.

Lake N is by far the largest water body in the study area. It has two segments--an upper lake and a lower lake, connected by a channel. The upper lake has a depth of 52 meters and the lower lake of 18 meters. The upper and lower lakes have a combined surface area of 1,726 hectares.

Many smaller ponds are located throughout the study area.

For one year the various water bodies were sampled one day per month. The samples were analyzed within one day after retrieval to determine existing water quality. Table 2 lists 18 sample sites and respective drainage areas.

Table 2. Drainage area at sample sites

Site Number	Street Name	Drainage Area (Approximate hectares)
1	Pond i	4,940
2	River A	259,620
3	Tributary a	430
4	Tributary b	215
5	Brook a	310
6	Pond ii	35
7	Tributary c	50
8	Pond iii	400
9	Brook b	1,305
10	Tributary d	180
11	Tributary e	125
12	Brook c	615
13	Tributary f	410
14	Tributary g	215
15	Cove a	375
16	Brook d	910
17	Brook e	1,200
18	Lake n	116,610

Deicing Compounds

In New Hampshire, one of the major pollutants in highway runoff is deicing salt. The method used for this study in approximating salt impact involves estimating the total amount of additional salt to be applied for the proposed action within each of the small watersheds involved. This does not include any reduction of salt application to the existing system unless a section of the existing road is to be abandoned.

To approximate the "worst case" situation for environmental impact analyses the total amount of salt applied is assumed to reach the outflow of the watershed under study at the sample sites. Sample sites are located immediately downstream of the proposed location of the roadway. Two periods of the year are used to calculate the anticipated concentrations for the chloride (Cl^-) and sodium (Na^+) ions.

The first period is November through April. This is the assumed salting application season. Analysis for this six-month period assumes all applied salt (NaCl) is diluted by the total volume of runoff for these months and that no salt is held over throughout the summer season.

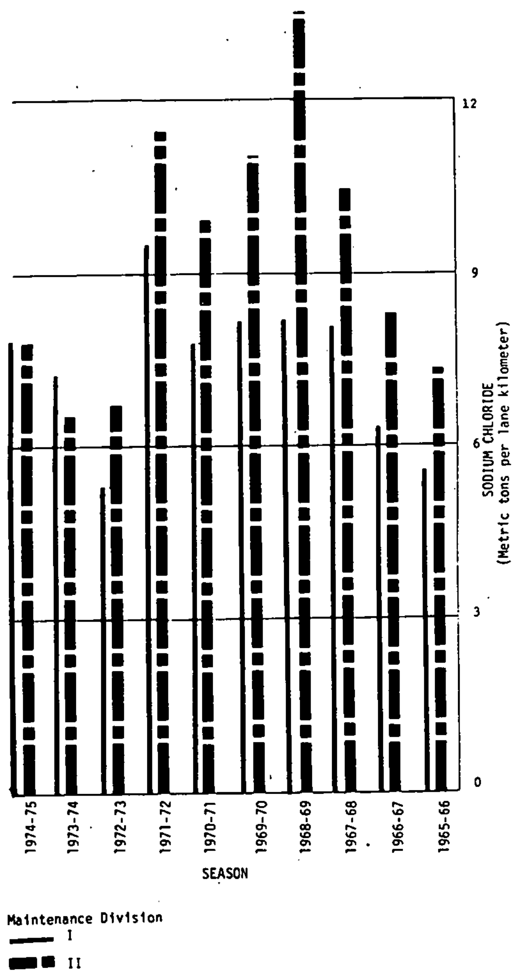
The second period assumes the total salt applied to new improvements is diluted by the total yearly runoff. This assumes that salt reaches surface water bodies throughout the year.

Depending on the assumptions and input data either method of calculating could yield higher ion concentrations. To determine the "worst case" situation, both methods are used. The higher value for a given month is then used as the worst output figure. The results in salt intrusion analysis indicate the former method may, as a rule of thumb, be considered a "worst average case."

Salt Application

The project overlaps two New Hampshire Department of Public Works and Highways maintenance divisions. Application rates for sodium chloride (NaCl) were obtained for these two divisions for the seasons of 1965-1966 through 1974-1975. The average application was found to be approximately 7.9 metric tons per kilometer per year. These are shown in Figure 2. The average application figure may now be considered high as the Department altered its policy on salt application just prior to the 1972-1973 season. Since then the amount of salt put on roadways has been reduced due to changes in the rate and method of application. These changes are reflected in Figure 2.

Figure 2. History of NaCl application in project area



The sodium chloride (NaCl) is further assessed (by atomic weight) to dilute into 60 percent chloride (Cl^-) ions and 40 percent sodium (Na^+) ions. All of the salt is assumed to be dissolved and carried in the runoff. This may be considered a worst case assumption as sodium ions often bond with soil particles for an indeterminate time, ions percolate into the groundwater system or are lost to aerosol formation.

Potential Loadings - Unknown Stream Discharge

The following is the method used in computing the potential loads for chloride (Cl^-) and sodium (Na^+) ions in the watersheds were average discharge is not known. In the study area, area average discharge is known only for Rivers A and B at sample sites 2 and 18, respectively. All original calculations were in English and only recently converted to Metric. Thus the units may be unfamiliar.

1. Conversion factors

   454,000 mg = 1 pound (1)
   28.32 liter = 1 cubic foot (2)

2. Average salting rate

   7.9 metric tons NaCl per lane kilometer per year. (Note: Average application rate since 1972 is less than 6.8 metric tons per lane kilometer per year).

3. Salting season

   November through April

4. Rainfall (See Table 1)

   Yearly Average = 1,030mm (3)
   Salting season = 505mm (4)

5. Restrict use of this procedure to areas where average discharge is not known. That is, it is not used on Rivers A and B.

6. Application of salt

   Salt application: Assume 7.9×10^9 mg/lane kilometer.

7. Salt dilution

   NaCl will dilute to $\pm$ 60.7 percent into Cl^- and $\pm$ 39.3 percent into Na^+ by weight.

8. Salt application season concentrations

   a. Runoff - Runoff (in liters) is computed in terms of Drainage Area (DA), (which is expressed in hectares). It is liberally assumed, for a worst case analysis, 80 percent of precipitation will result in surface runoff (5, 6). Groundwater recharge, evapotranspiration and sublimation are some sources of lost runoff.

$$\text{Seasonal runoff (liters)} = (\text{DA ha}) \times (10{,}000 \text{ square meter/ha}) \times (0.8) \times (505\text{mm}) \frac{1}{1000} \frac{\text{m}}{\text{mm}} \times (1000 \text{ liters/cubic meter}) = 4.04\text{DA} \times 10^6 \quad (5)$$

b. Chloride concentration

Cl^- (mg/l/lane km)

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane kilometer)}}{4.04 \text{ DAx}10^6 \text{ (liter)}}$$

$$\text{x } 0.607 = \frac{1187}{\text{DA}} \quad (6)$$

c. Sodium concentration

Na^+ (mg/l/l/lane km)

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane kilometer)}}{4.04 \text{ DAx}10^6 \text{ (liter)}}$$

$$\text{x } 0.393 = \frac{768}{\text{DA}} \quad (7)$$

9. Average annual concentrations

a. Runoff - It is assumed 44 percent of precipitation will result in runoff due to surface cover a hydrologic characteristic of central New Hampshire (7).

Annual runoff (liters) = (Da ha)

x (10,000 square meter/ha)

x (0.44) x (1030mm/1,000mm/m)

x (1,000 liters/cubic meter)

$= 4.53 \text{ DAx}10^6.$ (8)

b. Chloride concentration

Cl^- (mg/l/lane km)

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane kilometer)}}{4.53 \text{ DAx}10^6 \text{ (liter)}}$$

$$\text{x } 0.607 = \frac{1{,}059}{\text{DA}} \quad (9)$$

c. Sodium concentration

Na^+ (mg/l/l/lane km)

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane kilometer)}}{4.53 \text{ DAx}10^6 \text{ (liter)}}$$

$$\text{x } 0.393 = \frac{685}{\text{DA}} \quad (10)$$

Potential Loadings - Known Stream Discharge

For large areas where Q stream discharge (liters per second) is known, an average annual daily dilution by discharge can be calculated. Though the value of Q varies widely over the season no other source of daily discharge information was available.

Runoff per year = (Q) x (24 hours/day)

x (60 minutes/hour)

x (60 seconds/minute) (11)

x (365 days/year) = 3.15 $\text{Qx}10^7$ liters

The computation of chloride and sodium concentrations adhere to the following:

1. Chloride concentration

Cl^- (mg/l/l/lane km)

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane km) x } 0.607}{3.15 \text{ Qx}10^7 \text{ (liters)}}$$

$$= \frac{152}{\text{Q}} \quad (12)$$

2. Sodium concentration

Na^+ (mg/l/lane km) = $7.90\text{x}10^9$ (NaCl

$$= \frac{7.90\text{x}10^9 \text{ (NaCl mg/lane km) x } 0.393}{3.15 \text{ Qx}10^7 \text{ (liters)}}$$

$$= \frac{98.6}{\text{Q}} \quad (13)$$

At River A the salt is assumed to be diluted by the average annual daily discharge. This is approximately $5.89\text{x}10^4$ liters per second. In this case the formulae reduce to:

Chloride Cl^- concentration (mg/l/lane km)

$= 2.58\text{x}10^{-3}$ (14)

Sodium Na^+ concentration (mg/l/lane km)

$= 1.67\text{x}10^{-3}$ (15)

At Lake N the salt is assumed to be diluted by average annual daily discharge supplying Lake N, approximately $1.51\text{x}10^4$ liters per second. In this case the formulae reduce to:

Chloride Cl^- concentration (mg/l/lane km)

$= 1.01\text{x}10^{-2}$ (16)

Sodium Na^+ concentration (mg/l/lane km)

$= 6.53\text{x}10^{-3}$ (17)

The maximum loads of chloride (Cl^-) and sodium (Na^+) ions that may be expected over the average year of salting season are outlined below.

Impact Analysis

If one assumes the average annual concentration or average seasonal concentrations of salt (NaCl) could occur at any instantaneous moment when the diluted concentrations are highest, the maximum degree of impact may be observed. As higher concentrations of sodium ions are normally experienced in the summer months it could be concluded, however, this period of the year could become critical to stream biota.

Table 3 (8, 9) tabulates the amount of annual chloride and sodium concentrations that could be added to each watershed throughout the year. Also shown are seasonal computations if one assumes all roadway salt applied is removed by runoff by the end of April. If one assumes total thawing in a short duration then the salt would be further diluted and thereby reduce the amount of concentrations.

Table 3. Summary of salt (NaCl) concentrations.

Site No.	Maximum[a] Lane Distance	Drainage Area (hectares)	(mg/l) Potential Increase Seasonal Cl^-	Seasonal Na^+	Annual Cl^-	Annual Na^+	Existing Annual Means Cl^-	Existing Annual Means Na^+	Total Expected Annual[b] Cl^-	Total Expected Annual[b] Na^+
1	3.2	4,940	0.8	0.5	0.7	0.4	5.7	3.9	6.4	4.3
2	25.8	259,620	T	T	0.1	T	6.4	5.0	6.5	5.0
3	8.4	430	22.9	14.8	20.4	13.2	4.9	4.0	25.3	17.2
4	4.5	215	24.4	15.8	21.7	14.0	9.1	6.0	30.8	29.8
5	3.2	310	12.2	7.9	10.8	7.0	14.2	8.1	25.0	16.1
6	3.2	35	109.7	71.0	97.4	63.1	11.9	7.7	109.3	70.8
7	3.2	50	74.6	48.3	66.3	42.9	18.8	11.9	85.1	54.8
8	24.5	400	71.6	46.3	63.6	41.2	11.7	7.7	75.3	48.9
9	7.7	1,305	6.9	4.5	6.2	4.0	32.3	17.5	38.5	21.5
10	6.5	180	41.4	26.8	36.8	23.8	7.7	5.9	44.5	29.7
11	5.2	125	48.1	31.2	42.7	27.7	6.9	3.2	49.6	30.9
12	6.5	615	12.3	8.0	10.9	7.1	13.7	8.4	24.6	15.5
13	8.4	410	24.0	15.5	21.3	13.8	4.6	3.0	25.9	16.8
14	6.5	215	35.2	22.8	31.3	20.2	11.8	6.1	43.1	26.3
15	9.7	375	30.2	19.6	26.9	17.4	8.3	4.9	35.2	22.3
16	3.2	910	4.2	2.7	3.7	2.4	12.2	8.3	15.9	10.7
17	3.2	1,200	3.1	2.0	2.8	1.8	7.7	5.7	10.5	7.5
18	19.4	116,610	0.2	0.1	0.2	0.1	12.4	7.4	12.6	7.5

T = Trace

a Includes Potential Interchange ramps and cross roads.

b Standards: Chloride not to exceed 250 mg/l in drinking water as per U.S. Public Health Service and a desirable level of 25 mg/l in water used for certain industrial purposes as per U.S. Department of the Interior. Sodium not to exceed 22 mg/l in drinking water for persons on low salt diets as per American Heart Association

To derive a relative degree of impact the annual mean concentration levels for chloride and sodium are added to the annual concentrations. The results of these comparisons are shown in Table 3.

Impact Evaluation

The U.S. Public Health Service (USPHS) recommends a maximum level of chloride in drinking water of 250 mg/l (10). The U.S. Department of the Interior lists 25 mg/l as a desirable level for certain industrial uses (8).

USPHS has not set standards for sodium content in water. However, the American Heart Association (AHA) recommends a level of 22 mg/l of sodium should not be exceeded for those persons on low salt diets.

No evidence exists that drinking water is taken directly from surface runoff at any location in the study area, including the sampled streams.

Further, it is recognized these are waters classified by New Hampshire as suitable for public water supply only after adequate treatment.

The impact classification adheres to the following:

Critical - Contamination of public supply of drinking water.

Great - Projected chloride levels exceed 250 mg/l limit in drinking water.

Moderate - Projected chloride levels equal or exceed desirable concentrations of 25 mg/l or projected sodium levels exceed desirable 22 mg/l levels.

Based upon this analysis it is anticipated eight samples will exceed the AHA recommended limit for sodium. No sample sites will exceed the USPHS's level for chloride, however. The long term cumulative effects of this added salt is unknown.

Conclusion

Pursuant to requirements to identify and evaluate potential impacts associated with planned public works projects, a method to analyze road clearing operations was developed by the New Hampshire Department of Public Works and Highways. This was particularly important in view of the many water bodies which could be detrimentally affected.

The salt intrusion relationships of deicing compounds, runoff and soil conditions are complex. They do not readily lend themselves to simple analysis for environmental impact purposes. Therefore, during the preparation of a recent environmental impact statement, a simplified seasonal procedure to predict road salt runoff to determine probably "worst average case" effects was used. With appropriate modifications to reflect local climate, topographic and hydrologic conditions the method may be applied elsewhere for impact analyses.

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The Use of Synthetic Snowfalls in the Evaluation of Snow Removal Systems

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The concept of a standard statistical snowfall is introduced for use in a systems approach in the evaluation of long-term strategies for snow control. A model for a standard statistical snowfall is suggested which is based on a mathematical representation of the partitioned historic hourly snow trace. One hundred years of synthetic hourly snowfall is used to compare the following four strategies for snow removal in the cities of Worcester, Massachusetts and Nashville, Tennessee: 1) optimal removal strategy, 2) constant critical removal strategy, 3) constant critical budget strategy and 4) trial and error budget strategy. Use is made of the Russell-Butler snow damage model in conjunction with two generalized snow removal cost functions to ascertain annual total penalties resulting from snow accumulation from synthetic traces. Results are presented which suggest: the usefulness of the standard statistical snowfall in the snow control evaluation process, the advantages of the constant critical budget strategy for snow control over the trial and error budget strategy and the economic advantages of removing snow at levels above the optimum then at levels below the optimum.

In an effort to keep vital traffic and supply arteries functioning, large financial commitments are made by municipal governments in the "snowbelt" to snow removal and control programs. Failure to do so often results in a disruption of these arteries causing substantial monetary losses to the community.

The stochastic aspect of snowfall accumulation on transportation routes subject the planning, budgeting and operation of snow removal systems to uncertainty. When they occur, extreme snow falls and storms closely spaced impose a disproportionate stress on snow removal and control efforts, often leading to severe penalties. Extreme snowfalls and sequences are generally not predictable in advance with an acceptable degree of reliability. Nonetheless, models of hourly snowfall may be constructed which capture the stochastic aspects of hourly snowfall sequences. The use of these models permit the generation of a large number of synthetic hourly snowfall sequences each of which represent an equal likelihood of future snowfall occurrence. When synthetic snowfalls are standardized for a particular municipality or geographic region and used conjunctively with a simulation of the snow removal system permits managers and planners to sample the outcome to approximate the statistical properties of economic response for evaluation of alternative snow control strategies; permits the estimation of future demands on the system, which often are not observable in advance; and permits observations of extreme responses of the system in terms of snowfall depths and snow storm sequences.

Of the various snow removal strategies favored by smaller communities, the "trial and error" strategy predominates. In this strategy, snow control budgets are formulated in terms of an evaluation of the previous year's experience and the expected average snowfall accumulation for the particular season. In this form of adjustment, the snowfall information is limited to the historic record. Therefore, extreme snowfalls of the past which have not been recorded are neglected or underevaluated. The adjustment depends on past snow control experience and the evaluation of the adequacy of past snow removal programs. This experience is only partially transferable and evaluation methods are often subjective, being based on the registered annoyance and perceived losses by individuals, businesses and industries. The above factors often leads to an inadequate adjustment to the snow hazard.

Rooney (1) has pointed out the need for municipalities to employ a more refined evaluation technique, than simply the average expected snow accumulation as a criterion for allocation of funds for snow removal and control programs.

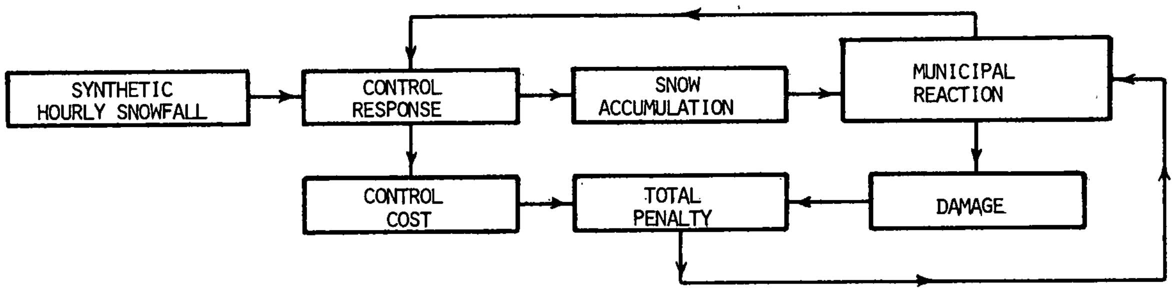
As an alternative to the "trial and error" strategy Russell (2) introduced the systems approach for an evaluation of long-term municipal adjustments to snow hazards using the hourly historic snow record in an economic study of snow removal practices.

For the analysis of systems sensitive to hourly snowfall, new methodologies based on mathematical statistics have provided several alternatives to reducing deficiencies inherent in the use of only the hourly historic snow record.

The long-term municipal adjustment to snow hazards is viewed in the framework of a system in which the snow accumulation on traffic and supply routes engenders a reaction from the municipality creating a set of penalties, Figure 1.

The snow accumulation at a particular time, is a direct consequence of the hourly snow sequence less the snow removal rate. The snow accumulation may then be adjusted by a strategy chosen by the municipality in response to the hourly snow sequence and a set of specific criteria. Although municipalities have been hesitant in adopting the systems

Figure 1. Flow diagram for snow hazard system.



approach to the planning, management and operation of snow removal and control programs; the systems approach is often being used in other programs within the municipality.

In this paper, the author introduces the concept of the standard statistical snowfall for use in the evaluation of long-term strategies of snow control and for establishing levels of contingency funds for these various strategies. To demonstrate it's use, the standard statistical snowfall is applied in an evaluation of four different snow control strategies for two cities: Worcester, Massachusetts having an average annual snowfall of 200 centimeters and a large number of moderate to heavy snowfalls over average storm durations of 6 to 11 hours; and Nashville, Tennessee, having an average annual snowfall of 29.5 centimeters and a small number of moderate snowfalls over average storm durations of 5 to 9 hours.

Standard Statistical Snowfall

The standard statistical snowfall was introduced as a set of synthetic hourly snow sequences generated by use of a stochastic model based on a mathematical representation of the historic snow sequence.

Early efforts in the formulation and use of synthetic traces of environmental time series were made by Hazen (3), Sudler (4), Barnes (5) and Thomas and Fiering (6) in deriving design criteria for storage reservoirs and for the analysis of river flows. A limitation of these models is their inability to model events which include consecutive null events. Time series of this type include the hourly precipitation and hourly snow precipitation sequences.

Two approaches characterize attempts to model hourly precipitation traces: 1. Markov chains which include a large number of null events (7) and 2. partitioning the time series into durations of null events and durations over which the event has real positive values and modeling the partitioning structure and the details of events over the duration in which the events are real positive (8) (9).

As pointed out by Matalas (10) of the many properties required to adequately represent the historical trace, only those properties that exert a meaningful influence on the response of the system need be considered. In the case of long-term municipal adjustments to snowfall hazards, the frequency, duration and intensity of snow events coupled with the sequence in which these events occur exert meaningful influence on decisions affecting these adjustments. The snow model used in this study preserves these properties.

The model from which the standard statistical snowfall was generated and used later in this paper for the evaluation of alternative snow control strategies employs the concept of partitioning. In this model the time series representing hourly snowfall was partitioned into durations of consecutive hours in which snow occurs ($x_1, x_2, \ldots x_n$) and into durations of consecutive hours in which no snow falls ($y_1, y_2, \ldots y_m$), figure 2. The sequence of snow durations was them modelled separately from the sequence represented by durations in which snow did not fall. The hourly sequence of snowfall intensities ($z_1, z_2, \ldots z_t$) over each snow duration (x_n) was then modelled. The three sequences were then combined to represent the standard statistical snowfall characterized by alternation of sequence of hourly snowfall followed by a sequence of hourly zero snowfall for a large number of years.

In this construct, each of the sequences; snow duration, hourly snow intensity and no-snow duration; was transformed in order to normalize their respective frequency distributions and then was modelled using a first-order regressive equation of the form:

$$\gamma_i = \bar{\gamma} + \rho(\gamma_{i-1} - \bar{\gamma}) + \sigma\sqrt{1-\rho^2}\,\eta_j \qquad (1)$$

where

γ_i = i^{th} event in sequence, i = 1,2,3...

γ_{i-1} = event previous to the i^{th} event

$\bar{\gamma}$ = mean of the distribution of γ

σ = standard deviation about the mean

ρ = auto-correlation coefficient of lag (1) for the pooled events

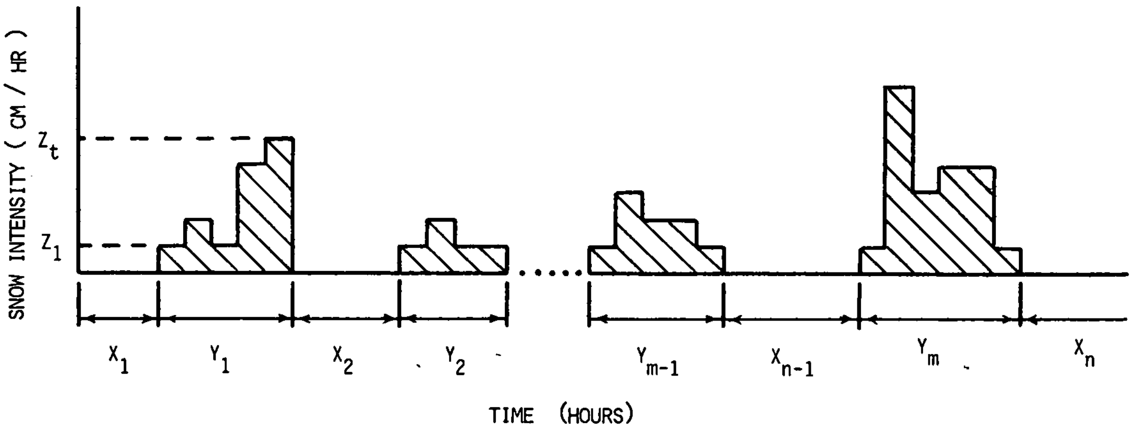
η_j = random multiplier obtained from a nor-population, $N(0|1)$.

An inverse transformation was then performed on the generated variates and the standard statistical snowfall formed. A cube-root transform was used. The procedure for constructing and verification of this model is detailed elsewhere (11).

Model parameters for many stations in the U.S. can be obtained from the historic hourly snow sequences which are readily available from the climatological data publications of the Weather Bureau issued monthly from 1900 to the present.

Tables 1 and 2 are summaries of the statistical properties for the standard statistical snowfall. For purposes of comparison, the data tabulated in

Figure 2. Partitioned Snow Sequences



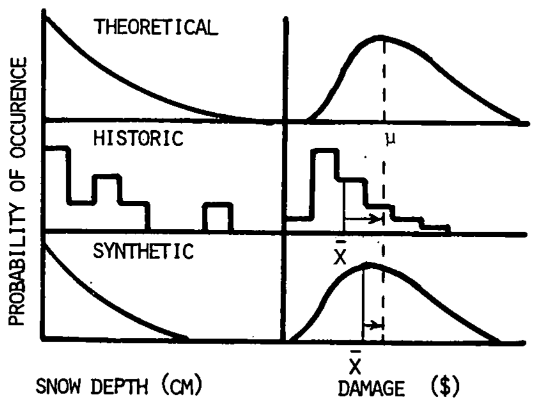
the Local Climatological Data Sheets are also included. In the case of Worcester, the mean yearly snow fall from the synthetic trace equaled the historic trace. For Nashville, the mean yearly snow fall from the synthetic was 8 centimeters or 3 percent less than the historic trace.

The use of synthetic snowfall sequences are important in those situations where the penalty function is strongly nonlinear and for which extreme values of snow accumulation exert a disproportionate influence. The damage function resulting from snow accumulation on transportation and supply routes is of this type.

The effect is illustrated with reference to figure 3, in which probability distributions of both the snow accumulation and the resulting penalties are represented for the theoretical case, the historic case and the synthetic case. If the probability distribution of the historic trace as measured by the mean and standard deviation from the mean is less than for the theoretical or long term trace, then the penalties from the synthetic trace (which is based on the statistical characteristics of the historic trace) more closely approximates the theoretical. Conversely, if the historic trace is greater than the theoretical trace then use of the synthetic trace over estimates the penalties. The use of the synthetic trace is therefore a conservative compromise that has a tendency to overestimate the projected snow removal level.

Consideration of differential penalties resulting from snow accumulations later in this paper, suggests that there is an economic advantage to removing snow above the optimum removal level than below.

Figure 3. Probability distributions of penalty function from snow accumulations



As the length of the historic record increases, the more closely the record is representative of the theoretical sequence and less useful the synthetic traces becomes.

The snow model used was considered a first approximation to the synthesis of hourly snowfall sequences for use in snow sensitive systems in which an ordering of the hourly snow fall was considered important. This particular snow model proved particularly useful in evaluating snow removal strategies for long-term adjustments to snow hazards. It proved most suitable in representing those snow environments having moderate to heavy snowfall over long durations, and least suitable for light to moderate snowfalls. From a statistical viewpoint, the cube-root transformation function used is not necessarily the most satisfactory for all geographic regions. Other transformation functions, such as a log function, may be more applicable to other geographic regions and should be considered.

Although the preservation of the structure of the historic snow sequence was found to be adequately preserved, a few comments on the composite properties of the generated synthetic snow sequences is in order. As in all synthetically generated sequences, which adequately represent the historic series, the sequence is still dependent on the statistical properties of the historic sequence. Therefore, if these statistical properties are unstable in the time domain, as a whole or in part, which is often the case for short historic records, then the synthetic trace characterizes this unstable trace. What is gained in synthetically representing the historic trace is the representation of a fuller range of the combinations of the events than the historic trace. Thus, extreme values and extreme sequences are represented in the synthetic trace which may not be represented in the historic trace. However, the stability in the time domain of the synthetic trace is dependent on the duration of the synthetic trace and can be made as stable as one wishes simply by generating the sequence over a longer number of years. Therefore, as the length of the historic snow record increases the synthetic trace should be updated and long synthetic traces used when economically feasible.

Strategies for Snow Removal

Most of the strategies available to municipal managers for snow removal and control, implicity assume a desire to minimize the penalties resulting from snow accumulation. These penalties may be expressed functionally in terms of costs as,

Table 1. Summary of Standard Statistical Snowfall and Historic Snow Statistics.

	Worcester, Massachusetts						Nashville, Tennessee					
Mo.	Mean Monthly Snowfall (cm)		Max. Monthly Snowfall (cm)		Max. Snowfall In 24 Hours[c] (cm)		Mean Monthly Snowfall (cm)		Max. Monthly Snowfall (cm)		Max. Snowfall In 24 Hours[c] (cm)	
	LCD[a]	SYN[b]	LCD	SYN	LCD	SYN	LCD[a]	SYN[b]	LCD	SYN	LCD	SYN
Nov.	8	15	53	58	38	38	2	2	23	43	23	43
Dec.	35	26	82	91	40	35	6	5	34	32	26	20
Jan.	45	46	112	158	48	75	10	5	48	42	19	23
Feb.	50	48	115	178	61	65	7	4	38	45	19	17
Mar.	50	50	93	135	42	57	5	6	41	50	23	24
Apr.	11	14	29	56	26	25	-	-	-	-	3	21
Total	199	199	115	178	61	75	30	22	48	50	26	43

[a]LCD - as reported in Local Climatological Data, Worcester (1974), Nashville (1969)
[b]SYN - calculated from standard statistical snowfall of 100 years
[c]Maximum Snowfall in 24 hours for SYN listing based on 1st hour to 24th hour of any day and doesn't include case where the 24 hours is in two consecutive days.

$$T(R) = D(R) + C(R) \tag{2}$$

where

T(R) = total penalty function, dollars
(R) = snow removal or control level, cm/hr.
D(R) = snow accumulation damage function, dollars
C(R) = snow removal cost function, dollars

Therefore, in terms of a strategy in which the snow removal level (R) is varied, the minimum penalty will result when R is chosen in such a way that the following relationships are satisfied,

$$\frac{\partial T(R)}{\partial R} = 0 \qquad \frac{\partial^2 T(R)}{\partial R^2} > 1 \tag{3}$$

$$\text{or} \quad \frac{\partial D(R)}{\partial R} + \frac{\partial C(R)}{\partial R} = 0 \tag{4}$$

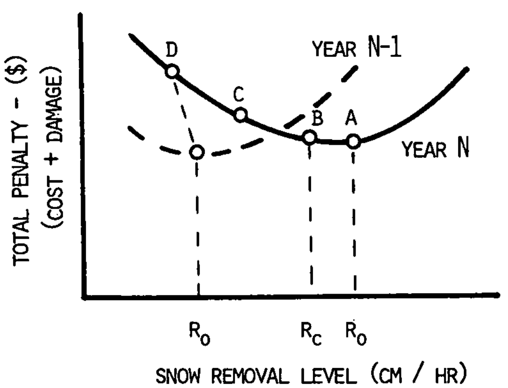
and R_o = the optimum removal level to satify the above relationships

Of the many long-term strategies available to municipal managers, the following four are considered in this paper

1. Optimal Removal Strategy
2. Constant Critical Removal Strategy
3. Constant Critical Budget Strategy
4. Trial & Error Budget Strategy

With reference to figure 4, the optimal removal strategy involves snow removal or control at point A,

Figure 4. Snow Removal Strategies



the minimum point on curve relating the total penalty (cost + damage) to snow removal level for each storm, month or year. It represents a game-theoretic to which other strategies may be compared and approached. The constant critical removal strategy involves snow removal at a guaranteed constant level for each year. The critical level, represented by point B on the curve is in general not the optimal value for any single year but represents the average optimal control values for all years.

The constant critical budget strategy involves snow removal at a level at point C consistent with a fixed yearly budget determined from the mean critical removal level for the particular city. The snow removal level therefore varies from year to year since the yearly budgeted funds remain constant, whereas the snow to be removed varies from year to year.

The trial and error budget strategy involves snow removal at a level at point D consistent with a fixed yearly budget determined from the budget required to attain an optimal removal level in the previous year.

In general, where the last three strategies are used, additional funds or returns from a contingency fund are required in order to approach the optimum level of snow removal for any particular year, the movement of points, B, C, D to point A on the curve.

Snow Accumulation Damage Function

For the purpose of evaluation of the four snow removal strategies, the Russell-Butler Snow Damage Model was utilized to estimate the snow damage. This model evaluates the snow damage in terms of delayed and deferred travel of workers and non-workers of a community resulting from hourly snow accumulation on vehicular transportation routes. The model is detailed elsewhere (11) (12).

It has been shown (9) using synthetic hourly snow sequences in conjunction with the Russell-Butler Damage Model, that the damage function in terms of snow removal level may be satisfactorily represented by the following relationship,

$$D(R) = bR^m \tag{5}$$

where

D(R) = mean annual damage in 10^6 dollars,
R = snow removal level, centimeters per hr.
b = constant, Table 2
m = constant, Table 2

Figure 5. Mean annual total penalty curves.

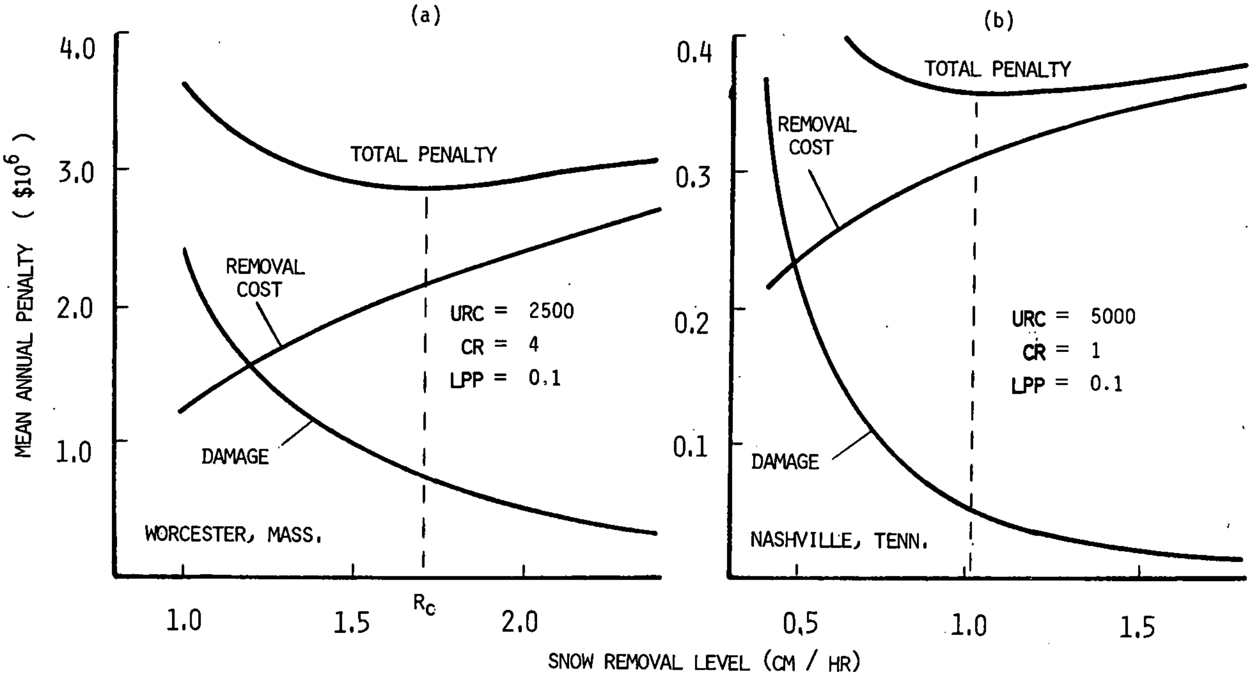


Table 2. Cost and Damage Constants for Critical Removal Strategy

City	h 10^6	g 10^6	m	b 10^6
W	1.660	1.235	-2.276	2.466
N	0.0990	0.305	-2.130	0.052

City W - Worcester, Mass. URC = 1500, CR = 4
City N - Nashville, Tenn. URC = 5000, CR = 1
basic economic data from Russell (2), (12) lost production parameter equal to 0.1

Snow Removal Cost Function

The snow removal cost function, C (R), represents the expenditures for removal of snow from the transportation arteries of a city in terms of snow removal or control level. Russell (12) has pointed out the measurement difficulties associated with evaluating the cost of snow removal programs. After an extensive gathering of data on the costs of snow removal programs, he found that although cost data were available, the level of snow control associated with these costs was often masked.

For this study, an expected range of cost values in terms of a unit snow removal cost per centimeter of snow accumulation (URC) and a cost ratio (CR) was assumed in simulating cost functions.

The unit snow removal cost represents the mean annual cost per centimeter of snow accumulation for removing snow at a guaranteed removal level of 1.0 centimeter per hour. The cost ratio represents the ratio of the cost of removing snow at a guaranteed removal level of 3.00 centimeters per hour to the unit removal cost.

The cost ratio term permitted a differentiation between the unit cost of removing snow at a removal level of 1.00 centimeter per hour to that of removing snow at a removal level of 3.00 centimeters per hour. Therefore, if the unit removal cost for a city is $2500 per centimeter and the cost ratio equals 4, then the cost of removing snow at a level of 3.0 centimeters per hour is equal to $10,000 per centimeter of snow accumulation.

This simulation procedure for evaluating snow removal costs was constructed such as to assure a snow removal level up to and including some maximum level, R_{max}, and permitted the inclusion of at least a 3-hour lag prior to reducing the level of snow removal.

The cost function in terms of snow removal level may be estimated by use of the following relationship, (9)

$$C(R) = h \ln R + g \tag{6}$$

where

- C = mean annual snow removal cost, 10^6 dollars,
- R = guaranteed snow removal level, centimeters per hour
- h = constant cost function parameter, table 2
- g = constant cost function parameter, table 2

Minimum Total Penalty

For the particular adjustment strategy in which the snow removal level is guaranteed, the mean annual total penalty function may be expressed as,

$$T(R) = bR^m + (h \ln R + g) \tag{7}$$

where the first term of the relationship is the damage function and the second term is the snow removal cost function.

In terms of a strategy which minimizes the total penalty, we obtain

$$\frac{\partial T(R)}{\partial R} = 0 \tag{8}$$

Table 3. Summary of Associated Annual Costs, Damages and Total Penalties for Various Snow Control Strategies Based on Standard Statistical Snowfall Sequences, 1977.

City	Strategy	URC $\$10^3$	CR	Removal Cost $\$10^6$ Mean	SD	Damage $\$10^6$ Mean	SD	Total Penalty $\$10^6$ Mean	SD	Max.	P.R.
W	1	10	1	2.86	1.00	0.25	0.11	3.11	1.09	5.04	1.0
	2			2.81	0.82	0.60	0.95	3.41	1.52	9.64	1.1
	3			2.86	0.00	7.69	25.65	10.55	25.65	152.89	3.4
	4			2.86	1.00	20.50	45.42	23.39	45.06	152.90	14.5
	1	2.5	4	2.50	1.21	0.69	0.28	3.06	1.45	7.70	1.0
	2			2.12	0.62	1.55	2.18	3.67	2.56	15.46	1.2
	3			2.50	0.00	1.80	3.82	4.30	3.82	28.25	1.4
	4			2.50	1.21	2.86	6.92	5.36	6.72	55.87	1.8
N	1	5	1	0.31	0.23	0.04	0.03	0.35	0.26	1.18	1.0
	2			0.31	0.21	0.09	0.27	0.40	0.40	3.00	1.1
	3			0.31	0.00	1.49	4.26	1.80	4.26	20.35	5.1
	4			0.31	0.23	3.78	7.08	4.09	7.02	44.52	11.7

Damages are for case in which the lost production parameter equals 0.10 in Russell-Butler model.
City W - Worcester, Massachusetts
City N - Nashville, Tennessee
Strategy 1 - Optimum removal, 2 - Constant critical removal
Strategy 3 - Constant critical budget, 4 - Trial and error budget.
URC - Unit removal cost; CR - cost ratio; SD - standard deviation;
P.R. - Penalty ratio.

or

$$\frac{\partial}{\partial R}\left[bR^m + (h \ln R + g)\right] = 0 \tag{9}$$

or

$$\frac{\partial bR^m}{\partial R} = -\frac{\partial (h \ln R + g)}{\partial R} \tag{10}$$

or the marginal damage function equals the negative marginal cost function.

Solving for the critical snow removal level to satisfy the above relation, we obtain,

$$R_o = \left(-\frac{h}{bm}\right)^{1/m} \tag{11}$$

For the constant critical snow removal strategy the mean annual snow removal costs, the mean annual snow damage in terms of dollar losses to the community and the mean annual total penalties are shown graphically in relation to the snow removal level, figures 5a and 5b. The critical snow removal level is located at the point where the total penalty function is a minimum.

Evaluation of Snow Removal Strategies

The standard statistical snowfall and the penalty functions were utilized conjunctively to evaluate and to contrast the four different snow removal strategies previously described.

The standard statistical snow fall consisted of 100 years of synthetic hourly snowfall. It was used to generate for each snow removal strategy a series of annual snow removal costs, damages and total penalties for two different cost functions for Worcester and a single cost function for Nashville.

For a comparison between strategies, the mean and standard deviation from the mean of the annual values were calculated and tabulated in Table 3. Since the optimal removal strategy represents the minimum mean annual total penalty which may be realized, the other strategies were compared in terms of this strategy and the mean annual total penalty for the optimum strategy was calculated and also tabulated in Table 3.

For the cost functions considered, the results in Table 3 suggests that the constant critical budget strategy, when viewed over the long-term, leads to significantly lower expected annual total penalties then the "trial and error" budget strategy.

In the case of Worcester, for a cost-function having a URC equal to $10,000 and CR equal to unity, the trial and error budget strategy leads to expected penalties of 23 million dollars annually. These mean annual losses are lessened to approximately 11 million dollars when the critical budget strategy is applied at the same level of investment in control efforts. A similar comparison exists for Nashville. The magnitude of this advantage is lessened for the analysis using the other cost function.

The reduction in the penalty ratio from 14.5 to 3.4 for Worcester and from 11.7 to 5.1 for Nashville, when the constant critical budget strategy is used. reflects the more efficient use of the snow control funds in affecting snow removal at levels around the optimal level or critical level for any particular year.

Penalty Differentials

The change of long-term mean annual total penalty with respect to snow removal level (R) may be expressed functionally as

$$\frac{\partial T(R)}{\partial R} = bmR^{m-1} + hR^{-1} \tag{12}$$

At the minimum point $\partial T/\partial R = 0$, which increases on each side of the minimum, $\partial T/\partial R$ is represented by the slope of the total penalty curves in figures 5a and 5b. This relationship is important in that it shows the long-term mean annual differential penalty to a community which uses as an adjustment, snow removal levels other than the critical long-term snow removal level and therefore, represents the cost of a non-optimal long-term strategy.

Table 4. Summary of Contingency Fund for Various Snow Control Strategies Based on Standard Statistical Snowfall.

City	Strategy	URC $\$10^4$	CR	Funds Needed $\$10^6$ Mean	SD	Max.	Funds in Excess $\$10^6$ Mean	SD	Max.
W	2	10	1	0.27	0.26	1.07	0.21	0.14	0.61
	3			0.89	0.65	2.66	0.76	0.50	2.36
	4			1.14	0.82	3.50	1.08	0.74	2.90
W	2	2.5	4	0.73	0.71	2.90	0.37	0.22	0.97
	3			1.05	0.99	3.91	0.87	0.55	2.26
	4			1.23	1.13	4.89	1.27	1.03	4.64
N	2	5	1	0.05	0.06	0.28	0.03	0.02	0.08
	3			0.20	0.19	0.70	0.18	0.10	0.35
	4			0.23	0.18	0.75	0.29	0.23	0.84

City W, Worcester, Massachusetts; City N, Nashville, Tennessee

Snow removal levels based on short snow traces or trial and error methods may lead to cost differentials.

For purposes of comparison, the differential mean annual penalty was expressed as a percentage of the minimum total penalty.

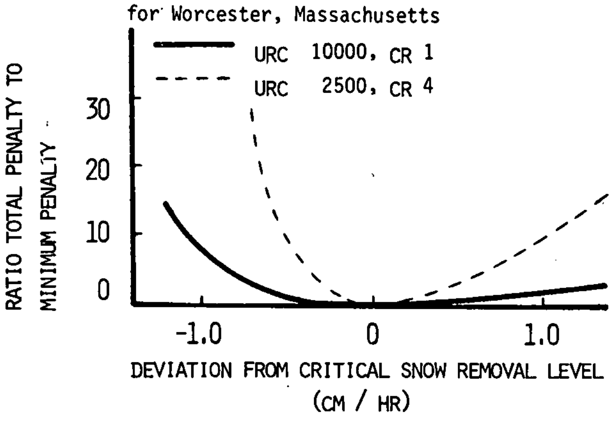
$$DC = \frac{T(R) - T_c}{T(R)} \qquad (12)$$

where

DC = differential mean annual penalty, %
$T(R)$ = mean annual total penalty at a snow removal level, R
T_c = mean annual total penalty at the critical removal level.

The long term differential total penalty for Worcester expressed in terms of deviations of the actual removal level from the critical removal level is graphically represented in figure 6. In this case, for an assumed unit removal cost of $10000 per centimeter, a lost production parameter of 0.1 and a cost ratio of 1, the critical removal level equals 2.6 centimeters per hour. Therefore, if the actual snow removal level used was 1.6 centimeters per hour, then a penalty differential of 8 percent of the total minimal penalty or $270,000

Figure 6. Mean annual total penalty differentials for Worcester, Massachusetts



would result. Stated another way, it would cost the city an additional $270,000 per year in penalties for removing snow at a level of 1.6 centimeters per hour instead of 2.6 centimeters per hour.

If the actual snow removal level was greater than the critical level by the same amount as the above example was below the critical level, then the penalty differential of 2 percent or $70,000 per year would occur. A similar example could be made for Nashville.

The shape of the differential penalty functions suggest that if a municipality remove snow, it is more advantageous to remove it at levels greater than the critical level then at snow removal levels below the critical level.

In an effort to avoid these differential penalties associated with non-optimal strategies, additional funds are required to approach the optimum level in a particular year if the budgeted or planned removal level is below the optimum. In those years where the budgeted removal level exceeds that required for operations at the optimum, the excess funds may be utilized elsewhere. In the use of a contingency fund for the snow removal system in conjunction with other systems within the municipal or state network which are not serially correlated with snow removal efforts permits a flexibility of response. This flexibility permits avoidance of extreme penalties to extreme snow years.

The structure of a contingency fund for the cases considered in this paper is tabulated in table 4.

Closure

The concept of a standard statistical snowfall was introduced for use in a systems approach in the evaluation of long-term strategies for snow control. It is the opinion of the author that synthetic snow sequences provide a feasible alternative to the use of short historic traces as input to snow control systems.

The snow model presented was considered a first approximation to the synthesis of hourly snowfall sequences in which an ordering of the hourly snowfall was considered important. Although useful for the purposes of this paper, other constructs may prove more appropriate for other geographic regions and for use as input to other control systems.

Although used for the evaluation of long-term snow control strategies, the concept of a standard statistical snowfall may prove useful in the evaluation of short-term systems involving the scheduling, operation and management of current snow control programs.

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Control of Snow and Ice on Road and Communication Facilities in the Himalayas

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Introduction

India, with its vast Himalayan mountains in the north has its share of snow hazards and connected problems. The unnegotiable and formidable vast Himalayas carry within them a hidden treasure of natural resources. Their forests are rich, the soil contains precious minerals, and the blanket of snow ensures the supply of sweet water. The Indian Himalayas are sparsely populated with concentrations along the river waterways and their valleys. To tap these resources and to keep pace with the increase of population and growth of industry, it is imperative that the road communication system should remain open throughout the year. This task involves the study of Indian snow and ice conditions, along with terrain and weather patterns, and the evolution of effective methods to keep the traffic moving even in the severest of winters. This is a challenging problem for the engineers.

In this paper an effort has been made to spell out the problems as related to Indian snow conditions and to cost-effective methods of snow and ice control with a view to keep the roads/tracks open for traffic for the longest period. The study of terrain, its topography, the meteorological conditions, the snow patterns, the ice formation, the avalanche behaviour and some of the suggested clearing techniques and avalanche control measures form an essential part of a humble beginning to arrive at a reasonably workable solution.

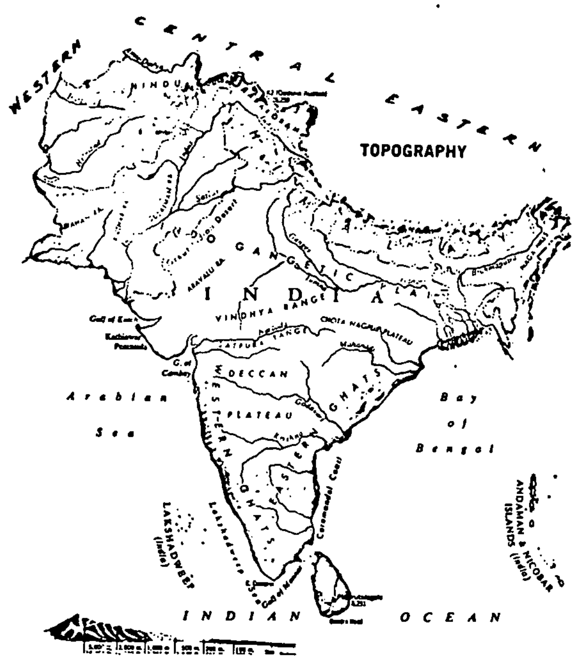
Topography and Meteorological Feature

The Indian Himalayas can be divided into three regions (Fig. 1).

(a) Western Himalayas
(b) Central Himalayas
(c) Eastern Himalayas.

Each zone of these Himalayas, which covers approximately 260,000 km^2, has different topography and meteorological conditions. The mountains are steep and the altitudes are high. The highest peak is located in the Indian Himalayas, which shows the type of altitude which one has to face. The vegetation and soil conditions in each region are different, depending upon the soil and the precipitation behaviour of snow.

Figure 1. Map showing Western, Central and Eastern Hamalayas.



Western Himalayas

The Western Himalayas have an average altitude between 3,000 to 5,500 m through which the roads and pedestrian tracks have to pass. The tree line ends approximately at 3,000 m. Between 3,000 and 4,000 m the growth of grass at places is quite common. Beyond 4,000 m the hills are almost barren and devoid of vegetation with rocks and steep slopes. The snowfall is maximum between 3,700 and 5,000 m. The steep mountain faces offer an ideal triggering surface for the avalanches. The worst area known so far, from the avalanche point of view, may be the Zojila sector in J&K State. The minimum air temperature in the snowbound areas ranges from +20° to -30°C. There is a considerable variation between day and night temperature which causes fast changes in the temperature gradient of the snowpack. Wind activity is very severe, and winds with as much as 130 km per hour velocity have been recorded at the height of 4,000 m. The steep and the narrow valleys further aggravate the high wind activity along with the tremendous problem of snowdrift. The temperature gradient on the southern slopes of the hills is the lowest and it has been seen that melt rate of snow on south-eastern slopes is maximum. Northern slopes are the coldest. The snowfall in this zone starts as early as November, carries on til May-June, and is maximum in this region.

Western Himalayas have a maximum snowbound area and the population in the snow-belt is approximately 8,000,000. The road network is both of tarmac and water bound macadam. The population is widespread in different green belts and their existence depends upon keeping the road communication open for the maximum period. In this region, there are two major roads, i.e. Jammu-Srinagar-Leh and Chandigarh-Manali-Leh. These two roads are the lifeline for the people living in various valleys. These roads have to pass through a number of avalanche-prone areas besides skirting the high-altitude mountains where cold regions problems affecting roads are at a maximum.

MAXIMUM AND MINIMUM TEMPERATURES °C

(Trail site an observatory in the Western Himalayas)
Height: 2,410 m

	73-74		74-75		75-76		76-77	
Month	Max	Min	Max	Min	Max	Min	Max	Min
Nov	+19	-5	-	-	-	-	+18	-7
Dec	+10	-12.5	+2	-18	+7	-16	+12	-17
Jan	+08	-14	+2	-18	+5	-18	+03	-18
Feb	+12.5	-18.5	+7	-18	+6	-20	+09	-14
Mar	+12.5	-06.5	+12	-11	+10	-11	+12	-11
Apr	+17.5	-02.9	+15	-05	-	-	+06.5	+03

MONTHLY AVERAGE DIURNAL VARIATION, °C

Month	73-74	74-75	75-76
Nov	-	-	-
Dec	10.4	6	9.6
Jan	10.2	6.3	9.6
Feb	10.7	11.3	9.5
Mar	08.2	10.5	9.6
Apr	13.3	7.4	-

Central Himalayas

The Central Himalayas have an average altitude between 3,000 and 5,000 m through which the road and pedestrian tracks have to pass. The snowfall regions are above 3,000 m and the high-intensity snowfall is between 3,000 and 6,000 m. In this region the soil is loose with steep mountain slopes covered with loose rocks. The tree line in this region ends at about 3,800 m and the climate is such that enough moisture is available for adequate grass and bush growth up to 4,000 m. However, in depth, the mountains are dry with very little rainfall. Maximum snowfall is experienced between December and March and the intensity of snowfall is not very high. The pattern of snowfall is the same as in the Western Himalayas. Minimum temperatures in this region vary from +30° to -20°C, and this helps in melting the snowpack faster. The high temperature gives rise to wet snow conditions. The wind activity is not very severe, though winds as high as 100 km per hour velocity have been recorded in certain areas through which the roads are passing. The easternly and southernly aspects experience high temperatures and more rainfall and have more trees. However, the northerly aspects have adequate vege--tation. Beyond certain regions, due to high day and night temperature difference, loose rocky faces create landslide problems. The avalanches in this zone invariably are accompanied by large amounts of loose rock and soil.

This region is more densely populated than the Western and Eastern Himalayas. The population in this region is approximately 9,000,000. It has a major road network connecting Spiti and Joshimata Valleys of Himachal-Pradesh and Uttar Pradesh with the plains.

MAXIMUM AND MINIMUM TEMPERATURE °C

(Trial site an observatory in the Central Himalayas)
Height: 3,000 m

	70-71		71-72		72-73	
Month	Max	Min	Max	Min	Max	Min
Nov	-7	-	+17.8	+02.2	-	-
Dec	+17	-03	+17.2	-01.1	+11	-02
Jan	+15	-05	+13.3	-02.8	+14	-06
Feb	+17.5	-07.5	+13.3	-10.0	+15	-06
Mar	+24.5	-04.0	+17.1	-02.2	+15	-06
Apr	+21.0	+09.0	+18.9	-09.0	-28.9	+04

Eastern Himalayas

The Eastern Himalayas are greener and the tree line is much higher. The climatic conditions are entirely different from those of the Western or Central Himalayas. The tree line at places is as high as 3,800 m. Up to 4,800 m height adequate bush undergrowth has been seen which grows as high as 2 m with thick branches interwoven to form a network. Thus bushy growth is an ideal snow trap and acts as an avalanche control measure. Temperatures are not very low and vary between +35° and -10°C. This part of the Himalayas is very humid and experiences heavier rainfall and low wind activity. The population is about 800,000, which is widely spread out. The movements are normally based on mules and foot columns passing through snowbound regions but not through much of the avalanche prone areas. The hidden resources in the rich soil of the Eastern Himalayas are yet to be tapped and the good road communication facilties have to be established to keep pace with the development and increase of population.

Snow Conditions

The Himalayas are the world's most formidable snow-covered mountains. The snowfall pattern from the Western Himalayas to the Eastern Himalayas is quite different and varied. In the Western Himalayas the snowfall starts in November and continues up to May. The snowfall is frequent and of high intensity. The temperatures are reasonably high after the snow fall as compared to the European Alps. On the average about 20 metres or above of snowfall is experienced each winter. The avalanche activity is basically due to dry snow conditions in the early winter and wet snow conditions in the late winter. In the Eastern Himalayas, the snowfall is followed by more clear days and the intensity of snowfall is also lower, varying from 2 cm/hr to 8 cm/hr. The high temperature melts the snow much faster and the snow slides are basically of wet snow.

In the entire Himalayas, short snowfalls of high intensity, followed by number of clear days, are very predominant. This factor makes the snow conditions quite wet and it has been noticed that this has a unique influence on the cycle of metamorphism.

TOTAL SNOW FALL AT SITE A - 2410 m HEIGHT
(WESTERN HIMALAYAS)

Month	1973-74	74-75	75-76	76-77
Dec	49	375	133	169
Jan	297	325	249	439
Feb	334	362	429	109
Mar	155	258	283	Nil
Apr	8	40	60	Nil
Total Snowfall	843	1360	1154	717

Cycle of Metamorphism

Due to the high temperatures prevailing immediately after the snowfall and there being a wide difference between day and night temperatures, the cycle of metamorphism is quite enhanced. In all areas a unique phenomenon was noticed that in most places avalanches occur at the round and square grain stages of snow crystals. This, when compared with the European Alps avalanche conditions, is quite different. In the Alps, the avalanches basically occur at the end of constructive metamorphism and with the snow crystals having reached depth hoar formations. In the Himalayas at a very few places depth hoar crystals have been noticed. Due to the high temperature pattern during the day and fast melting of the grains, the lubrication between crystals creates an ideal situation at the beginning of constructive metamorphism for avalanche occurrence. This melting of snow followed by a drop in temperature at night creates another major problem of refreezing the water on the road surfaces. The thin layer of ice on the roads causes disruption of the traffic. During late winter, i.e. March-April, the high temperature takes the cycle of metamorphism from destructive to melt phase, and with adequate liquid layers present between the crystals, the lubrication is increased and normally melted snow avalanches occur accompanied with tremendous amounts of rocks and earth.

The absence of depth hoar crystals, in the cycle of snow metamorphism, appears to be a unique phenomenon. A number of trials have shown that as the Eastern Himalayas are approached, the cycle of metamorphism tends to shorten by directly changing from destructive metamorphism. However, the appearance of round grain crystals at the end of destructive metamorphism and at the beginning of constructive or melt metamorphism is very predominantly observed. Further, most of the avalanches in the Himalayas are at the round grain stage of snow crystals, followed by wet avalanches. This phenomenon being a unique one in the Himalayas requires a laboratory analysis of the snow temperature patterns and their effect on the snow metamorphism.

Wind

The wind pattern observed in the Himalayas shows that immediately after the snowfall there is a lot of wind activity and the night temperature drops considerably, whereas during the day the strong radiation of the sun increases the temperature. In the early winter, i.e. November-December, an enormous amount of snowdrift occurs and most of avalanche activity is of the dry snow type. During midwinter, i.e. January-February, the wind activities further increase, increasing the snow drift, and this combined with heavy accummulation in the formation zones of the avalanches creates dry slab avalanches.

The high velocity winds at the heights above 5,500 m have been noticed to be of the order of 150 km/hr and above. This blows the snow away and leaves the mountain faces barren on certain aspects whereas on the other aspects a thick snow blanket exists and keeps on accummulating over a long period. This gives a base for the formation of snow beds. The snow beds of various layers have been noticed and the thickness of layer which is accumulated each season is predominant. Heavy wind velocity and drifting of snow is another problem which has been studied in the Himalayas. In the Western Himalayas, the winds of the order of 130 km per hour have been noticed and interesting results have been seen. At a trial site:

> It was noticied that while a snow blower was clearing the road surfaces and giving a cut of 1 m deep, the drift snow was so strong, that, by the time the blower reached 500 metres the accumulation of the snow due to drift on cleared road surface was again as high as 0.7 m. This shows the clearance effort which is required during the high velocity winds.

The chill factor at the high altitude along with the drift snow further complicates the snow clearing operation on the roads. During the night the temperature drops and it solidifies the snow layer which is left overnight after mechanical snow removal. This snow layer creates icing problems in large stretches. Various experiments conducted on de-icing on road surfaces are dealt with separately in this paper.

Avalanches

A unique phenomenon of avalanche occurrence that has been in the Himalayas is that most of the avalanches, particularly in the Western and Central Himalayas, come down more than once in a season. The most frequent average occurrence of avalanches is about 5 to 6 times in a season as compared to the avalanche occurrence in Europe which is generally once or twice in a season. From this, it is apparant that the avalanche engineer must plan for waves of avalanches while designing avalanche control structures for Himalayas. This not only affects the economics of avalanche control but also creates tremendous technical problems to be overcome in the construction of protective structures.

DE-ICING

The isothermal analysis of the Western Himalayas suggests that a large part remains at subzero temperatures even during the day time throughout the winter months. This, combined with snow precipitation caused by the low pressure systems induced by extra-tropical cyclones moving on comparatively southern latitudes, adds to the problems of icing on the roads, Further, overflow of water on to the road surface due to defective drainage systems and sudden low temperatures at night are responsible for the formation of thin layers of ice on the road surfaces. This ice formation on the road leads to the disruption of the traffic.

A trial was conducted on de-icing techniques to find a suitable one for Himalayan conditions. Some of the results obtained are given in the subsequent paragraphs. The common practices adopted for overcoming icing problems are melting by heat, use of abrasive materials such as stone chipping and sand on the iced surfaces for increasing sliding friction, and preventing of ice formations by the anti-icing capacity of certain chemicals.

The de-icing trials were carried out by using sodium chloride, calcium chloride and urea. A comparative study using the three salts mentioned above, along with coal dust, river sand and soil mixture gave startling results (see below).

Normal soil, river sand, or fine clay, duly graded and sprinkled on the snow or ice surface, increases heat absorption. Thus, the melting of ice takes place using the heat of radiation.

The seepage from drainage is the biggest source of water available for freezing at night. Rock salt, in rock form packed in gunny bags, showed appreciable results as an anti-icing agent when kept in the drains for slow mixing along with seepage water. It is interesting to note that this technique is very effective during early winter when the temperatures are slightly above 0°C. The use of rock salt is not only considered suitable in the Himalayas, but may be of great use wherever the temperature pattern and seepage problems from overflowing drains exists. The use of rock salt has advantages as the replacement may not be required for a number of nights. It was noticed during trials that by this technique most of the ice melted during the first night. No ice formation was observed during the second night. However, during the 3rd and 4th night, the salt solution became weak and thin layers of ice formations were observed on the outer edges of the road. This shows that charging of drains with 20 to 40 kg rock salt packed in bags may be required every 3rd night depending upon the quantity of water seepage and weather conditions.

During the trials with the chemicals on de-icing, it was further observed that in the initial stages, as the temperature fell below 0°C, that the decrease in percentage melt was statistically significant at the 95% level in most of the cases, even at a reduction of 1°C of atmospheric temperature. The table given below shows the percentage melt at various durations and temperatures in respect of the three chemicals.

TABLE A

Sodium Chloride

Thickness of ice slab = 2 cm
Rate of spread = 500 g/m^2
Wind = calm

Temp/min	10	20	30	40	50	60	70	80	90
-2	12	23	33	42	49	53	56	58	60
-3	11	21	31	39	45	50	54	55	56
-5	10	20	28	34	42	47	50	52	54

Calcium Chloride

Thickness of ice slab = 2 cm
Rate of spread = 500 g/m^2
Wind = calm

Temp/minute									
-2	13	24	34	42	48	52	54	55	56
-3	12	22	31	38	44	48	52	53	54
-15	11	20	29	37	42	47	50	52	54

Urea

Thickness of ice slab = 2 cm
Rate of spread = 800 g/m^2
Wind = calm

Temp/minute									
-2	12	22	31	41	46	49	51	53	54
-3	11	21	30	38	43	48	51	52	52
-5	10	19	28	34	40	44	47	49	50

Effectiveness of Chemicals used for Deicing

It has been observed that, out of the samples studied, sodium chloride was the most effective. The percentage melt generally attains a higher average, though the desired rate of 60% could not be achieved when the thickness of the ice samples exceeded 1 cm. The percentage melt rate in respect calcium chloride follows a path similar to that of sodium chloride, but the average melt percentage is slightly low at all temperatures. It was observed that for calcium chloride, the melt rate during initial 30 minutes was faster than the other chemicals by 1% to 3% but shows abrupt fall off thereafter. This can be attributed to the additional heat produced by the exothermic reaction of calcium-chloride. In the case of urea, the spread rate is generally greater than sodium chloride and calcium chloride but the average percentage melt is significantly lower.

Snow and Avalanche Control Technology

Ice, snow and avalanche research in India is still in its infancy. This field was neglected due to socio-economical reasons. However, the availability of minerals, the development of a tourism network and vast settlement problems of the past few years have increased its importance.

Snow Physics

In India, the winter lasts for a period of 3 to 4 months and severe winter conditions prevail only between December to February. During this period the temperature rises at times. The formation of snow crystals in the atmosphere under such conditions is mostly wet snow and the life of star-like crystals is short-lived. The temperature pattern on the ground shows high diurnal variations and it has been observed that the cycle of metamorphism, starting from fresh snow to felt-like grains and then up to melt grains (in the order of ET* metamorphism, TG metamorphism and MF metamorphism), does not go in a sequence. The snow crystals in the Indian Himalayas enter the phase of TG metamorphism. This is due to the proximity to the freezing level over a longer period. The crystals reach the round grain stage within a very short time and further change to irregular grains within a period of 6 to 7 days during low atmospheric temperatures. This irregular grain crystal structure directly goes into the melt phase and the cup crystal or depth hoar phase is left out. For accurate prediction of avalanches in India the norms used by foreign scientists have to be modified since those are based basically on cup crystal or depth hoar formation.

Snow Mechanics

Swiss guidelines for avalanche control structures are mainly based on the deformation characteristics of dry snow which is prevalent in that country. However, the Indian snow being semi-dry and wet, the same deformation characteristics may not be applicable. Using the Swiss guidelines, we have tried avalanche control structures, but these have been only 70% effective in Western Himalayas. The studies to find the guidelines for Indian snow conditions are in progress but no final solution has so far been found.

Avalanches

Identifying avalanches according to the avalanche classification evolved by de Quervain is being followed in India and it has been noticed that the results are quite satisfactory. The Swiss method of zoning of avalanches is quite accurate and informative but time-consuming. In India we find that this method can only be applied where major settlements are being planned. The French method of avalanche mapping is found to be more useful, i.e. use of aerial photographs, but its accuracy appears under Indian conditions to be lower than that of the Swiss method.

Avalanche Control

For designing the supporting structures for the control of avalanches, Swiss guidelines specify two types of loading. In the first type of loading, the snow depth is at a maximum but the density is moderate; in the second type of loading, density is at a maximum and the snow depth is moderate. Under Swiss winter conditions, the designing is based on one of these conditions depending upon location and the purpose of avalanche control. In India it has been seen that both these conditions of loading are experienced at the same time at most places. Further the average density of 270 kg/m^3 as used in Swiss guidelines is considered much too low for Indian conditions. In India, design at a value of average density greater than 350 kg/m^3 gives better results; however, this figure is not yet final and absolute for Indian conditions. Since the density is higher and both loadings are prevalent at the same time, we have to go in for massive design of supporting structures which involves very high expenditures.

The height of avalanche control structures has to be designed for 4 to 6 waves of avalanches unlike in Swiss practice where only 1 to 2 waves are anticipated. This makes the structures very massive. Further, the avalanche control structures have to be erected almost always above 4,000 m which adds to the construction cost and high altitude engineering problems.

Economics of Control Structures

Economics of snow and ice control is the biggest hurdle for a snow engineer. How to keep total costs low and how to find which control technique can be the cheapest and the best suited are the most difficult parts of the design. India, with its vast and deep Himalayas, has hundreds of kilometers of roads and tracks passing through snow, avalanche and ice prone areas, offering a challenge for snow control engineers. This is further aggravated by the fact that a developing country is always short of funds. The weather pattern, the difficult Himalayan terrain conditions, and lack of technical norms suitable for Indian snow and ice conditions make it a still bigger task. Some of the factors which affect the snow control measures in Indian Himalayas are enumerated below.

(1) Design problems. Snow conditions being semi-dry, density of snow being high and with annual avalanche occurrence being above 4, control structures have to be massive and costly.

(2) Construction problems. The construction of snow and ice control structures has to be mostly above 5,500 m. This adds high altitudes construction problems and increases the cost further.

(3) Construction time. The construction time available is short due to the limited number of clear days available. Due to extreme cold conditions, the number of working hours available daily is also very limited. The working time is hardly 6 hours in a day.

(4) Store carriage. The structures have to be fabricated at a great distance from the site. The carriage in vehicles over long distances of roads adds to the cost. At the site the prefabricated control structures have to be manually hauled up for hundreds of metres where the erection is to be done. This is a slow and laborious process and a big time consuming factor.

(5) Labour. At most of the places the skilled and unskilled labour has to be imported from the plains or the towns which may be hundreds of kilometers away. The labour camps have to be in safe places and at much lower altitudes. The movement of labour to or from the work site takes a major share of the time. The energies are half-consumed in travelling only. The labour cost is as high as 60% to 70% of the total budget of construction.

(6) High altitude living conditions. The living in high altitude areas for long periods without facilities discourages the best tradesmen. Thus at times one has to depend upon second-rate tradesmen which affects the construction speed and quality.

Having known the problems which a snow engineer has to face, his task of correct selection of sites and the type of control measures and technology to be followed becomes very difficult. The most difficult question to answer is whether the avalanche control should be at the formation zone, which is high and far above the tree line, or in the avalanche

* MF - melt phase metamorphism, ET - equitemperature metamorphism, TG - thermal gradient metamorphism

path or run out zone. Of course, the requirement for which the avalanche and snow control is envisaged holds an upper hand.

At the formation zone, the cost of erecting snow bridges and snow fences is extremely high. However, at times, the site conditions through which the roads are passing force the use of this control technique.

In the avalanche path it has been seen that retaining dams made of earth with a combination of earthen mounds are the most economical. Some of the avalanches which have been controlled by retaining dams/structures have shown encouraging results and it appears that the use of local resources, i.e. earth, rock and timber, is the most economical method. However, the designs have to be massive.

At the run out zone, diversionary and retarding earthern dams/mounds have proved to be the most useful and best suited from the cost point of view.

The use of galleries and tunnels is the most expensive method of avalanche control. However, due to the road location and type of avalanches which have to be controlled, such structures have proved very successful. This has proved very economical in the long run and ensures that the road is open for traffic for the longest period.

Drift control structures have not been tried out much in India. However, the cost of these is considered quite high and one has to use them only sparingly.

The de-icing and anti-icing techniques have their own logistical and storage problems which make them unsuitable for long stretches of road. However, for short stretches the use of NaCl (sodium chloride) is considered to be most economical. The use of rock salt packed in gunny bags placed in water seepage areas, drains, and culverts proved to be very successful and economical. This may help the de-icing problems all over the world where similar situations exists.

Considering the different weather patterns and varied terrain conditions from the Western to Eastern Himalayas, it is imperative from a cost point of view to restrict the use of avalanche control structures to selected places only. However, avalanche forecasting to regulate the movement in isolated areas is considered to be most economical. The avalanche forecasting in the Western Himalayas has proved considerably successful. This has reduced the avalanche casualties in that area to a great extent. It appears that for mass usage the most economical method may be for the avalanche forecast technology to cover the complete Himalayas. The following chart shows the lives which have been saved due to timely warning of avalanches.

No avalanche forecast		Avalanche forecasts issued		
	Before '74	'74-'75 Winter	'75-'76 Winter	'76-'77 Winter
Avalanche deaths in number-Western Himalayas	Over 100	73	32	14

Conclusion

The control of snow and ice on roads and communication facilities in the Indian Himalayas is a task of high importance. The vastness of the Himalayas and the varied climatic conditions in different regions add to this challenge. The technical norms of Swiss snow conditions cannot be applied to Indian snow conditions. The temperature pattern affects the metamorphism of snow crystals much more quickly and almost all avalanches are triggered at the round grain or square grain crystal stage, unlike those in the Alps where depth hoar is responsible. This poses a problem because norms which have been worked out for Swiss snow conditions cannot be applied to Indian conditions. The metamorphism cycle from the destructive phase directly changes to the melt phase in India, giving rise to semi-dry or wet snow avalanches. Nowhere in the world has the density of wet flowing snow avalanches been worked out and the values of density for Indian conditions have to be much higher than normal for satisfactory results. This problem, when combined with the number of waves of avalanches for which control structure are designed, adds to the massiveness of design, which in turn adds to the cost. Whatever the method of control of snow and ice, the economics and the engineering requirements have to be well balanced.

Snow and Road Pavements in Western Himalayas

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The Paper deals with snow effects on road pavements in the Western Himalayas with special reference to the upper reaches where high altitudes, rugged topography & difficult working environment, & heavy depositions of snow combine to produce characteristically difficult road conditions. The Paper discusses the salient aspects of road work, including the over-all effects of snow depositions on pavement performance. It is brought out that granular crusts topped with thin bituminous surfacings, which are otherwise satisfactory, undergo considerable damage every year due to the effects of snow clearance operations. The aspects of direct mechanical impingement and water action are discussed. The Authors hold the view that due to conditions of deep ground water table, frost action is only of low intensity & there is no significant problem of frost heave. The work already done and further work indicated for the solution of the said recurrent damage to pavement are also discussed.

In Western Himalayas, roads may be said to provide the most important means of linking the population pockets in far-flung and high altitude areas with the rest of the country. Over the years, need is being felt for higher and higher level of road access, both in quality and quantity. Provision and operation of road net-work involves a number of special features, relating to high altitudes, rugged terrains, and associated climatic and other factors. Snow action, in its various forms, exerts a dominant influence on the various pavement aspects - design, construction, maintenance, trafficability, etc.

By now, considerable amount of road work has been handled in this region, thus providing fairly good insight into the various special regional road problems. Described in this paper are the prevailing road conditions, the evolution of various practices, and the outstanding problems.

General Road Conditions

Terrain

Road work in Western Himalayas involves very high altitudes and extremely steep cross slopes. At some of the passes, roads have to negotiate altitudes of the order of five thousand meters and there are roads with average altitude above three thousand meters. The horizontal and vertical alignments change almost continuously and there is a heavier component of formation work & of retaining and drainage structures. Change of elevation in relation to the limiting gradients necessitates the use of zigs, involving hair-pin bends at times (Photos 1,2,3). The road lengths are therefore considerably more in relation to the distance in plan.

Photo 1. A view of the typical topography encountered in the region.

Photo 2. Distant view of a road section with bends and zigs.

Photo 3. Road winding around a steep hill slope.

The terrains involved include solid rock, weathered rock and schists, conglomerates, soil-boulder mixtures, and soils of low to medium plasticity. On account of various factors, a road is generally developed in stages from foot-path to mule-track, to jeepable track, etc.

Climatic Factors

Quite severe temperature conditions may be said to prevail in theses parts. Summer-time day temperature may well exceed 30 degrees C, whereas the night time temperature in winter may dip to minus 20 degrees C, or even to minus 40 degrees C. Within a span of twenty-four hours, temperature variations in the range of 30 degrees C are not uncommon. Rainfall is generally not heavy, being scanty at higher altitudes where most of the precipitation is in the form of snow-fall.

Conditions with regard to snow-fall vary widely in the region. Snow-fall is light in the valleys at lower altitudes. At the same time, there are locations with snow depositions of as much as 30 meters. With the prevailing terrain and climatic conditions, snow slides and avalanches are fairly common. Shown in Figure 1 is the position with regard to snow-fall and avalanches for a section(negotiating a pass) of an arterial road connecting Ladakh with the northern plains through Jammu & Kashmir. For its conditions of terrain, snow-fall & avalanches, & transportation needs, this road section may be said to present a characteristically difficult case. At the present, the road remains blocked due to snow from November to May-June. The cost of protective structures (Photo 4) & effort involved in the arduous task of continuous snow clearance come in the way of keeping the road section open during winter. Durin April-June, snow clearance is carried out within a span of about 2 months for the 78 km length of road on the two sides of the pass, involving snow volume of the order of 1.5 million cubic meters.

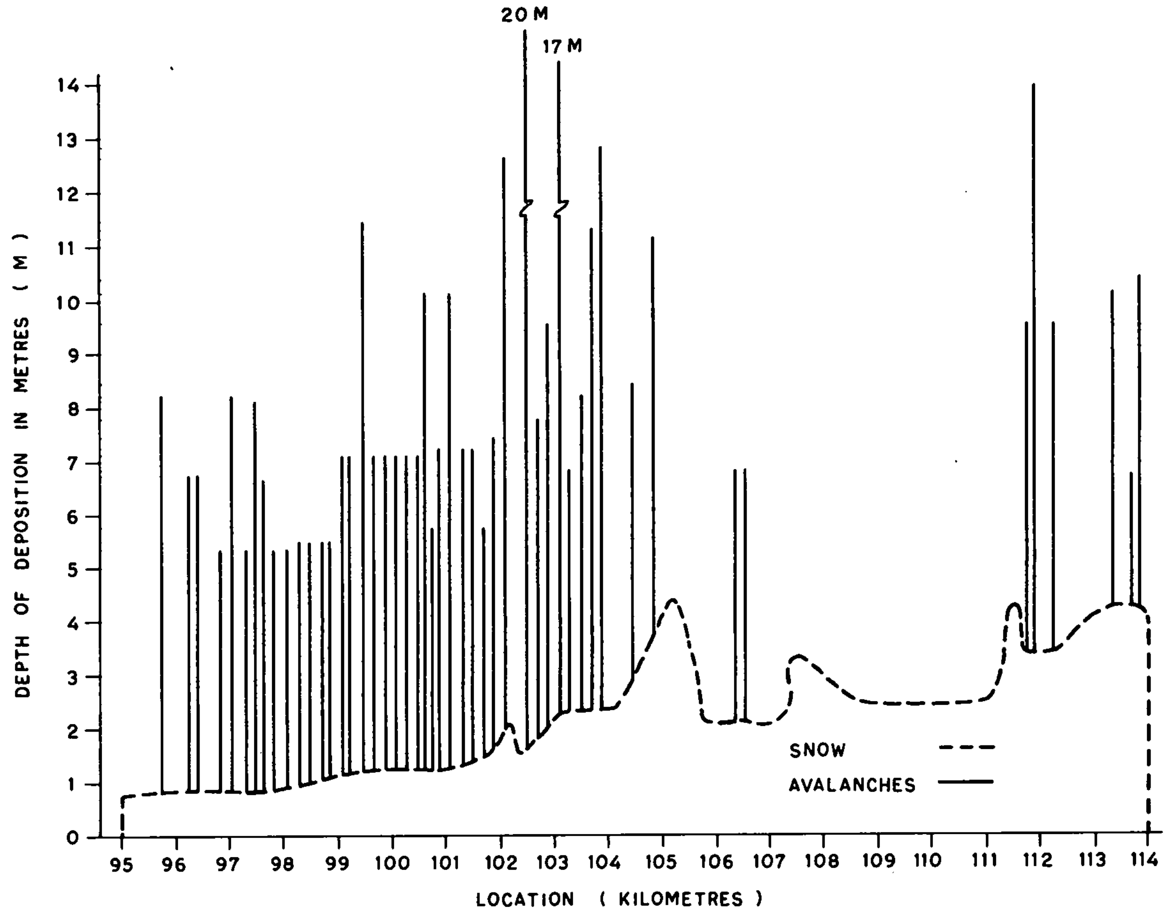
Photo 4. A typical snow-shed - one of the few protective structures provided for safe & unhindered movement of traffic.

Work Organisation

It goes without saying that the high altitudes with raefied air, rugged terrain, low temperatures, & unfavourable general physical environment combine to lower considerably the efficiency of both the man & the machine. A different pattern of organisation has been found to be necessary for road works in difficult areas.

Varying mixes of man & machine are being adopted for different operations, & for the same operation in different situations. Vis-a-vis practices in developed countries, manual inputs are higher in all operations (Photos 5 & 6).

Figure 1. Extent of depositions due to snow-fall & avalanches on a section of road at a high pass.



Pavement Aspects : Snow & Associated Factors

Carriageway Conditions

The non-urban roads have single carriageways of one to two lane width. The shoulders are generally unpaved although they are covered with pavement here and there for providing extra widening of the carriageway on curves & for providing lay-byes for crossing & storage of vehicles. On the downhill side is provided a discontinuous parapet of 0.6 meter width & of about the same height. On the hill side is provided a shallow longitudinal drain. The retaining walls and breast walls are done in stone masonry in cement mortar, dry stone work, or stone rubble crated in wire-netting. Of late, crib walling is also being used. Bridging & cross drainage works are largely with conventional methods. Initial temporary bridges are being progressively replaced with permanent structures.

Pavements are of flexible type, by and large. Barring limited stretches here and there with sub-bases of stabilised soil or soil-gravel, the crust is composed of granular sub-base and base courses, generally topped with thin bituminous surfacings(surface dressings or thin open-graded premix surfacings). In the recent years, pavement strengthening measures have included the use of 5-8 cm thick bituminous surface courses. Excepting a few important links carrying medium to heavy traffic, the traffic is generally light. For the fair to good subgrade conditions,therefore, the crusts required are not heavy.

Snow Deposition & Its Clearance

In the region under reference, extent of snow deposition varies rather widely. In southern parts at lower altitudes, snow-fall may range from none in a particular year to about a meter. There are no significant problems of avalanches or snow slides in these parts. Larger accumulations result only here & there due to deposition of drift snow. Further north at higher altitudes, the position is quite different. Snow falls quite frequently, amounting to a few meters during the season. In a case like that shown in Figure 1, however, the depositions may be as much as 30 meters, largely due to drift action, slides, avalanches, etc.

The approach to and methods for snow clearance tend to vary quite notably. In southern parts at lower altitudes,snow-falls are occasional. Light depositions from a snow-fall, if not melted by the warmer weather the next day, is taken care of largely with manual methods. In the case of a single fall, or two or more falls in quick succession, one lane is first cleared on the carriage-way and additional clearance follows, depending upon the weather, the need and resources available. In towns also in these parts, the above approach is followed largely. For bye-passes and other trunk facilities, however, equipment is used for snow clearance as per availability.

On the other end of the scale is the case of the arterial road section, presented in Figure 1, where the depositions are much heavier, falls more frequent, & working conditions extremely difficult. In these northern parts at higher altitudes, the snow

Photos 5&6 : Some typical mixes of man and machine.

Photo 5.

Photo 6.

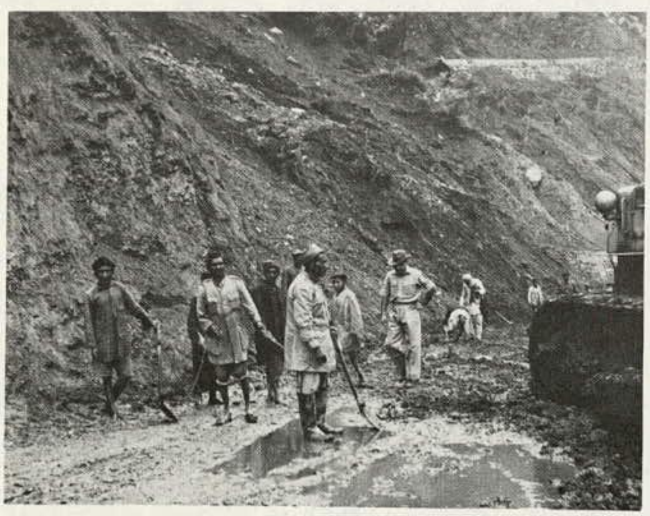


Photo 7. A view with glacier in the back-ground.

Photo 8. Start of the snow clearance operations towards the end of snow -fall season.

fall season is essentially from November to April although some snow may be received in October and May also in the upper reaches. Upto November and after April, the weather is generally balmy enough to cause melting of snow. Total intensity of snowfall and its distribution during the snow season tend to vary from year to year. The month of heaviest snowfall is invariably between January and March. It has been observed that the intensity of snowfall can be 3 cm per hour and more. Short-term (for a few hours) intensity of upto 4 cm per hour has been recorded for this reach. Heavier snow-falls at higher intensities lead to triggering of avalanches (Photo 7). At the start of the snow season, there are simple flakes which change to compound flakes later.

As stated earlier, the road section is

normally closed to traffic from about November to about May. The work of snow clearance is started in April, by when temperatures have risen enough & snow starts melting. The clearance work is usually completed by early June.

Over the methodology for this work has been undergoing change. Earlier the back-bone of the operations was the dozer. Then were brought in snow-ploughs & low-capacity snow machines. Currently, quite high capacity & heavy duty machines are being employed for these operations. After some preliminary work by the tracked dozers these snow machines are brought in to clear the snow, in two or more runs, from central one lane width (Photos 8, 9 & 10) for the initial corridor. Sufficiently high route-markers provide the much needed navigational guidance for these operations. This corridor permits movement of controlled traffic. Further clearance work is carried out by the various items of snow removing equipment. The dozer continues to be a very expedient means of shoving small snow banks down the hill-slope. Gaining experience over the years, a fairly effective regimen has been evolved to complete the task in good time and in safety.

For conditions in between, the methodology consists in the deployment of smaller machines and less over-all mechanisation.

Pavement Aspects

The effects of snow deposition and associated factors on pavements vary from location to location, depending upon the deposition, its clearance and other related conditions. The pavement composition normally used(as described earlier) has been a fairly satisfactory low-cost solution for cases where snow depositions are light. For a case like the one of Figure 1, however, conventional pavement undergoes considerable surface & structural damage as a result of clearance operations, requiring be made up every year. Therefore, discussed in the following paras are the various pavement aspects for this case.

The direct mechanical effect occurs in two ways: from the sliding down debris and the clearance operations. Avalanches and glaciers bring down debris which interalia causes boulders of various sizes to impinge upon the pavement with considerable impact. As a result , spot damage is caused to the pavement. More significant and wide-spread damage is brought about by the operation of clearance machinery. Even though most of these machines are intended to operate so that 15 to 20 cm thick cushioning layer of snow is left, there is impingement due to error in judgement accentuated by the changing vertical profile. The operation of tracked tracked vehicles causes still higher damage. Mounting of rubber shoes on the tracks has since been introduced but significant damage is still caused during fast directional changes which are sometimes unavoidable and which at other times result from deficient skill in work or pressure for time. An associated aspect is that of breaking and removal of thin layers of ice formed on the pavement surface with the freezing of water present, from melting snow or otherwise.The relatively gross methods used for this situation also add to the pavement damage.

Photo 9. Snow clearance in progress.

Photo 10. Initial corridor cut through a deep snow deposition.

It is believed that deeper damage , though at a slower rate, is however caused to the pavement by water action involved in clearance operations. By April, when snow clearance is started, conditions of snow melting start operating. When the initial corridor is being cut, there is a tendency for the water from molten snow to flow in this corridor. Wherever there is already some surface damage or where there are conditions of water stagnation, this water finds ready access into the relatively pervious pavement. At locations of slides/ avalanches and even otherwise, debris and mud are generally present. These also tend to go into the pavement. Drainage channels are being cut across the snow banks to minimise the flow of water in the corridor ; but continuous supply of water, blocking of regular drainage systems and continually changing profiles, etc. lead to profuse entry of water to saturate the pavement. It goes without saying that there is heavy traffic soon after the road is opened, having remained closed for over half an year. Softening of the subgrade, profuse water present in the pavement structure & on the surface, and heavy pneumatic tyred traffic combine to weaken the pavement structure in various ways, leading to deformation and surface deterioration.

Even though frost formation is a fairly common occurrence, it is felt that conditions do not exist generally for frost action to become significant. Freezing index/frost penetration is quite considerable at a number of locations, some of the soils are also fairly frost-susceptible, temperature change rate can also be conducive to formation and growth of ice lenses but it is believed that frost action is not able to assume any significant proportion because of the generally prevailing condition of deep ground water table. From enquiries & various field observations, no locations could so far be established that had suffered from any notable heave due to frost action.

Possible Solutions for the Recurrent Pavement Damage

In the back-ground of pavement conditions described above for locations of heavy snow depositions, a number of alternative solutions come in for consideration :

1. Having pavement with low-cost surfaces which can be readily restored at the end of the snow clearance operations each year.
2. Having special pavement that can withstand the clearance operations though may not necessarily provide high enough serviceability level.
3. Having pavement with high type surface courses which while providing high serviceability levels can also last longer against clearance operations.

As stated earlier, the locational factors are such as favour development of road in stages with regard to alignment & geometrics, formation width, & pavement. With regard to alternative 1, pavement for the case of Figure 1 remained unsurfaced for some time. Top course of water-bound-macadam was reprepared each year. Provision of thin open-graded surfacing does not alter the situation very much except that better-riding surface is available. The main handicap of this solution is the high frequency of surface renewal required. The serviceability level obtained is also not high.

Earlier work had shown that stone-set pavement is able to withstand better the operation of tracked vehicles. Some limited field trials have already been made with this type of pavement and it would appear that further work is necessary from the point of its construction and riding quality. Provision of cement concrete pavement entails the problems of higher initial cost, higher construction time in the face of little scope for diversion of traffic, and of course higher losses in reaches susceptible to slides or warranting improvement of alignment/geometrics. Use of higher types of bituminous surface courses offers a good compromise from the point of cost,durability, and serviceability level. Their use, on progressive basis, is to be considered in stable and finalised reaches. Low-void bituminous mixes would need to be studied from the point of performance under conditions of very low temperatures and large temperature variations.

Concluding Remarks

In Western Himalayas, there are, in the upper reaches, the conditions of very rugged terrains and high altitudes with the associated low temperatures and heavy depositions of snow. In some of the reaches, there are very heavy accumulations of snow on the roadways due to the combined effects of direct deposition, drift action, slides, and avalanches. For various reasons, a number of road sections are allowed to remain closed to traffic, due to blocking with snow, for a good part of the year. Towards the end of the snow season, snow clearance work is started. These clearance operations cause adverse conditions of mechanical impingement, water action, etc. As a result of these effects, flexible pavements made up of granular crust topped with a thin bituminous surfacing undergo extensive damage recurrently. Such a pavement is found to be fairly adequate otherwise. Some work has already been done with modified/different types of pavement. Simultaneously, measures have been evolved for minimising adverse conditions from clearance operations. Further work is indicated for trials with stone-set pavement, stabler low-void bituminous surface courses for the pertinent environmental factors, & other possibilities.

Acknowledgements

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Snow Clearance — West Himalayan Road — Some Problems

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Highway construction and maintenance at high altitudes in the snow-bound regions of the Himalayas is now not only necessary but essential in the overall development of India. This paper indicates the present position in this regard and highlights some of the special problems faced in snow-clearance work. A few suggestions for future improvements have also been made.

Highways and roads have long been regarded as the physical symbol by which a country's progress may be measured. The Indian road network is one of the largest in the world. The Border Roads Development Organisation was set up in 1960 to build communication links to the inaccessible and neglected regions of the North and North-Eastern border States for economic development. This organisation has constructed, among other routes, some of the very high altitude roads; one such is the road from Srinagar to Leh. This route is now open for traffic for only about six months in a year and remains closed for the rest of the period. The sparse population of these outlying isolated regions in Ladakh, who have for long been living under the rigours of severe cold for most of the year, lead precarious lives, subsisting on the meagre produce of lands which support just bare vegetation. This population is now linked with the mainstream of life of the country in economic development.

The above high altitude roads are highways with a difference. The road under discussion stretches from Srinagar to Leh which passes through an average altitude of 3,000 metres above MSL and is completely snowbound from November to May every year. The snowfall in peak winter is very heavy and with the difficult terrain traversed by treacherous avalanches, it is well nigh impossible to clear the snow so as to keep the communication open throughout the year. The road, therefore, remains closed completely for six months in a year, due to a critical stretch about 80 km (Fig. 1). The second reach of over 250 km, although practically open for the best part of the year, has to be closed down during short spells of very heavy snowfall and intense activity of avalanches. This paper attempts to bring into focus the problems faced in the crucial sector.

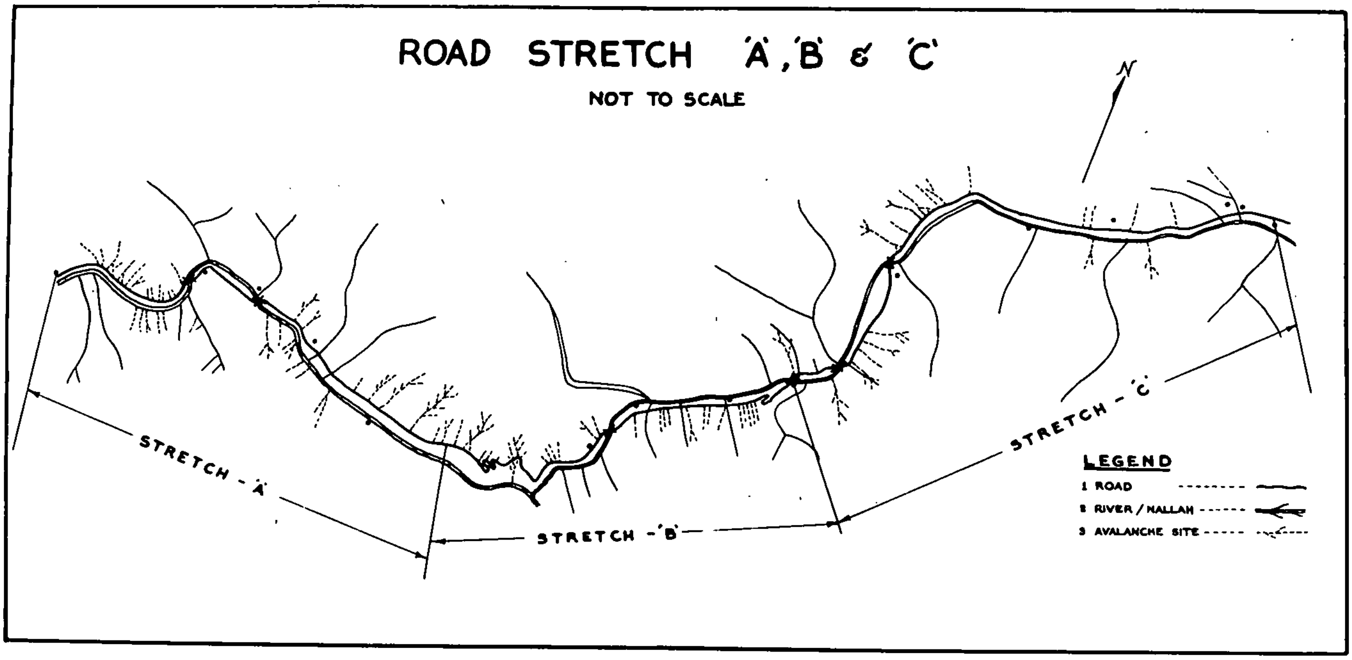
The methods adopted in snow clearance by men and machinery have been dealt with separately, detailing advantages and limitations of various kinds of operating machinery. Some suggestions have been made for improving the machinery to meet the special needs and difficulties observed during execution. The present technique, while aiming at keeping the road open for a short period of six months in a year, will require considerable improvements in methodology apart from additional resources to meet the increasing demand of keeping the road open throughout the winter. It is needless to emphasise that a greater element of risk is also inherent in this. The present limitations have also resulted in lack of mobility in the movement of men and materials. There is, therefore, an urgent need for evolving long-term solutions, and with this in view, some studies are already in progress. These would cover detailed ground and snow surveys, and installation of high-altitude snow laboratories equipped with advanced methods of remote measurement of all relevant snow data in collaboration with experts drawn from all related disciplines. There is presently scope for developing a system of prognosis of avalanche movement, on which considerable research has been done in India and outside. Research work also exists on methods to precipitate avalanche movement under certain conditions and for design of structures to arrest avalanche movement where such contingencies arise.

Terrain

The Srinagar-Leh road traverses a series of mountain ranges tapering into the Leh Valley. The road crosses the Great Himalayan Range and Zanskar Range which are the two main mountain complexes. The tangled mountain ranges extend over several kilometres on either side of the ridge. Of these two, it is the Great Himalayan Range which is subject to heavy precipitation of snow and intense avalanche activity during winter. The "critical stretch" lies wholly in this complex.

The critical sector can broadly be sub-divided into three distinctive sectors designated for convenience as "A", "B" and "C." Each sector has its

Figure 1.



own special characteristics in respect of terrain, climatic conditions, snowfall and avalanche activity. A general description of the reach as a whole is given in succeeding paragraphs and followed by each sector's features.

The hills along which the road runs in the above stretch have generally steep slopes ranging from 30° to 60°, rising to bare, rocky cliffs and ridges. The valleys are very narrow and meandering. At places, there are deep gorges flanked by rising mountains on either side.

The vegetation is limited to south of Zozila Pass. Only scanty vegetation consisting of small bushes, shrubs and grass can be found in the north of the pass - a distinctive characteristic of Ladakh. Trees, which are mainly of the Pine and Birch species, grow only up to altitudes of 3000 m.

The region along the "critical stretch" is very sparsely populated, there being only five villages. Population of each village varies from 100 to 200.

Sector 'A' (14 km)

In this sector, the road ascends from 2310 m to 2720 m, generally passing through flat ground in Sindh Nullah Valley. It enters a short 2.5 km long, 'V' shaped gorge. This gorge is flanked by precipitous cliffs on both sides having slopes 30° to 70° with heights up to 3812 m on the north and 4855 m on the south. At places, there are vertical cliffs for a stretch of a kilometre or more. This stretch gets very limited amounts of sunlight and is subject to avalanche activity from the flanking hills. These avalanches wedge into each other to form a continuous avalanche belt of 3 km length. Snow deposit varies from 2 m up to 10 m. The road cuts through the terminal zone of avalanches and, therefore, receives huge deposits of snow. The soil is sandy clay and gets easily eroded by the thawing water and the river. The river, which is almost at the same level as the road, cuts into it easily at various sections.

Sector 'B' (27 km)

This sector of road traverses the southern side, starts ascending from 2720 m to 3529 m and then descends gradually to 3360 m. After crossing the watershed the road moves in the northerly direction.

The soil in the entire sector is sandy clay. The valleys all along are flanked with rugged mountains of towering height ranging from 4000 m to 5500 m and consisting of mostly granitic rocks. The road also passes through hairpin turns gaining quickly in height. Being one above the other, the turns pose a problem for snow clearance. The worst stretch of the road is at about 16 km, which offers the greatest problems in snow clearance work. High altitude, extremely low temperatures, heavy snow precipitation, fierce winds, incessant drift snow deposition and treacherous avalanche activity characterise this stretch of 16 km, making it virtually impassable and inaccessible during peak winter months. The snow deposit varies from 4 m to 30 m. It may be said without any exaggeration that every bit of this stretch is a potential avalanche site with its attendant hazards. In fact, any plan in this reach aimed at reducing the closure period or to keep the road opened throughout the winter must envisage construction of continuous RCC snow sheds or possibly a tunnel or similar structure for this stretch.

Sector 'C' (23 km)

This sector of the road traverses a comparatively wide valley except for a stretch of 7 km. The road alignment runs along the eastern aspect.

In this stretch the hill slopes are completely devoid of vegetation. The valley is flanked by high mountains having slopes of 25° to 60° with heights rising to as much as 6000 m. In this stretch, the road is crossed by numerous avalanches in their terminal zones. Some of these have long travel and deposit large quantities of snow on the road. Generally, this stretch is less problematic. The average depth of snow deposit varies from 3 m to 20 m.

Climatology

Climatically, the problem stretch experiences extremely low temperatures, heavy snow precipitation and fierce winds during winter months. Diurnal variations are quite high and vary from 10°C to 30°C. Typical observations at a location of the road stretch are recorded at Figure 2.

Temperature

The mercury starts dropping rapidly in the whole sector from October until the middle of February and then gradually increases. Generally December, January and February are the coldest months of the winter. The minimum temperature in the worst portion would probably be in the neighbourhood of minus 50°C. Due to the low ambient temperature and due to lack of direct sunlight, ice formation takes place during early winter and thawed water is solidified into ice slabs during night in late winter months. The mean temperature during 24 hours remains sub-zero during the winter months. It is unnecessary to over-emphasise the need for maintaining regular temperature data. No meaningful analysis can be made of avalanche activity and related matters in the absence of authentic records.

Wind

The entire sector is subjected to fierce winds during the winter months, particularly in the pass areas. Direction and velocities of wind recorded at the observation station do not bear any noticeable relation to those blowing at higher reaches. This is mainly because the winds are channelized along the valley by the flanking ridges. Winds are generally gusty and accompany the snow falls quite frequently. During November to February, snow deposition occurs by wind drift resulting in the formation of avalanches. The wind velocity in some of the worst reaches would probably be 100 km/hour or even higher. In some stretches, there is no set pattern of the wind direction. Maximum wind velocities are recorded during the months of February and March, which are also the maximum snowfall months. During early winters, the powdery snow is blown around in the form of snow clouds, reducing the visibility to near zero. It is almost impossible to face the wind and the feeling by men during this condition is that "some one is cutting your face with a sharp knife." The deadly cold is a menace for men carrying out the snow clearance by manual methods and in open types of machines.

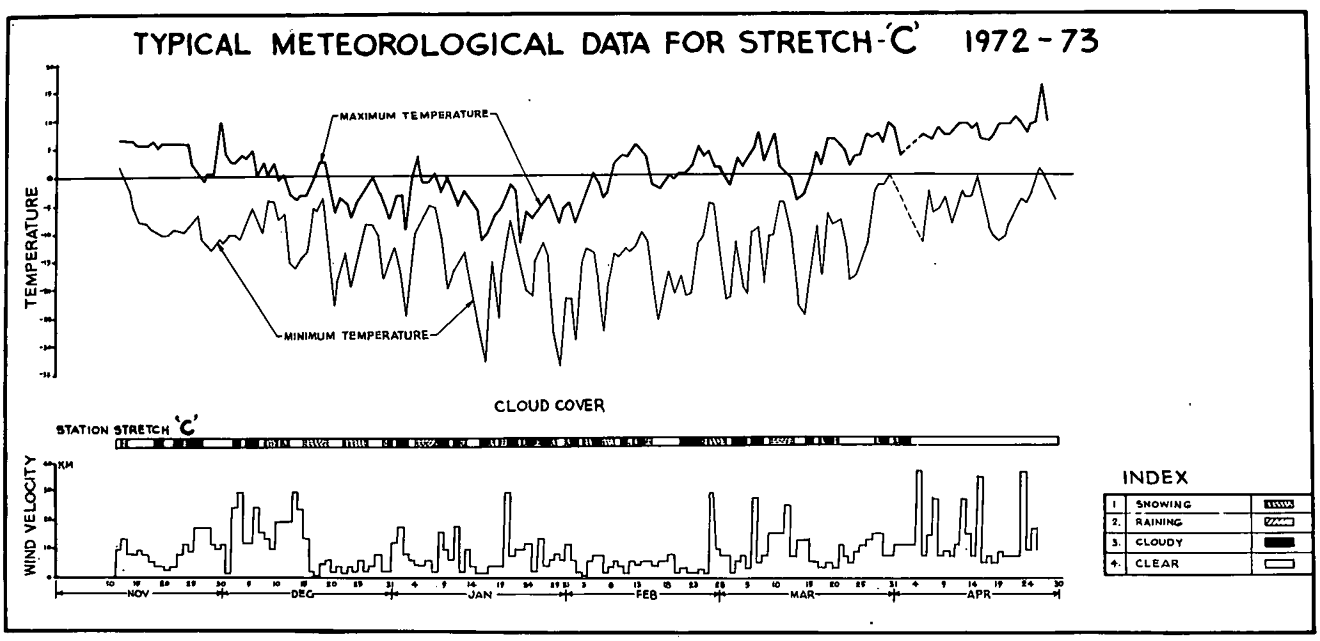
The number of clear days observed during June to April varied from 10 days to 20 days with hardly any possibility of carrying out continuous snow clearance operation. During non-clear days even driving of vehicles is hazardous in snow cleared roads.

Snow Observations

Snowfall data

Regular snowfall observations and data are essential for planning and designing any work related to snow clearance. Although long-term patterns of snow precipitation can be observed, there are years of lean and heavy snowfall like rainfall. There are areal variations and cycles too. The intensity of precipitation and daily totals are also very important. The "problem stretch" of over 70 km, being within "snow belt" receives heavy snow precipitation during winter. Generally, the entire section is subjected to heavy snow precipitation from November to April. At upper heights, snowfalls are experienced even

Figure 2.



during October and May. Precipitation is heaviest at the pass area and gradually decreases towards north or south of the pass.

In one of the stations south of the pass, the results of observation for five years is given at Table 1. From this, it will be seen that two or three consecutive heavy snowfall years were preceded by similar years of light snowfall. The total snowfall varied from as low as five metres to as high as twenty metres. The monthwise pattern which influences occurrence of avalanches also varies.

A typical snowfall record with its characteristics from November to April is shown in Figure 3. The snowfall over the pass would be much higher than this.

Intensity of fall

Generally January, February and March are heavy snowfall months. During these months two to three major snowfalls occur, the average intensity being 4 to 5 cm/hour, totalling a high figure of 200 cm in a period of two to four days. It is significant to note that quite often the intensity of snowfall rises to as much as 10 to 15 cm per hour extending over 4 to 5 hours, followed by intense snow avalanche activity in the vulnerable sites. The intervals of time between major snowfalls is of considerable importance as it is directly related to avalanche activity. Successive snowfalls at small intervals pose serious problems for planning timely snow clearance and to permit passage of vehicles. There is also the added hazard of heavy avalanche movement.

Snow characteristics

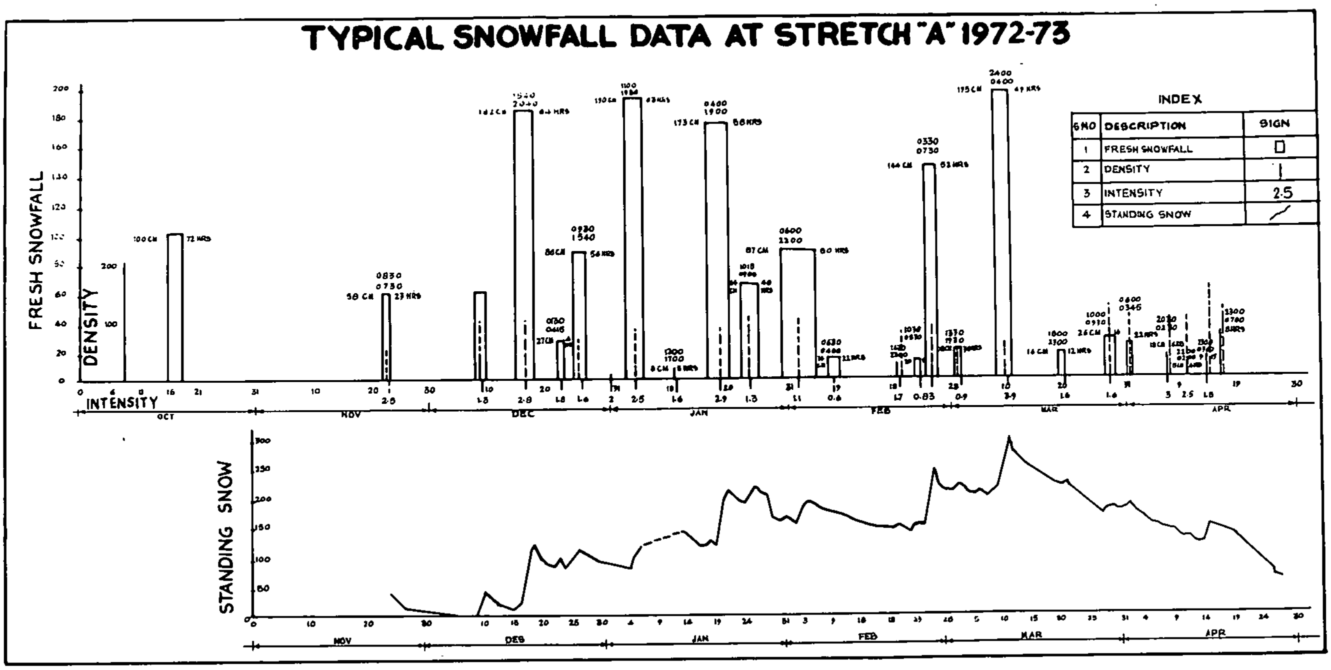
The density of the precipitated snow varies from as low as 0.05 g/cm^3 in November/December to 0.15 g/cm^3 in the late winter snowfalls. Low density snow during November, December and January is a major factor contributing to airborne avalanche activity and deposition of snow by drift. There is a gradual increase in the density of snow as accumulation takes place over a period of time. The rate of settlement of snow during the snowfall varies from time to time of the year. The rate of settlement observed varied from 0.2 cm per hour to 1.5 cm/hour in different months. This change is due to a variety of reasons, the more important of which are changed conditions of temperatures, humidity, irradiations of the sun and heat exchange through the ground. The density of standing, undisturbed snow has been found to be as much as 0.61 g/cm^3 which approaches the density of snow found in avalanches.

Structure of snow flakes varies from needles, platey crystals during early winter months and large-sized compound flakes of star, dendritic and stellar crystals during the later part. Snowstorms during March contain large quantities of soft hail which runs down quickly onto the road surface causing blockage.

Snow cover

The snow cover on the road is due to the combined effect of direct precipitation, snow slides, avalanches, bank slides and snow drift. Direct precipitation accounts only for depths varying from 1.0 m to 4.5 m at different stretches. Large deposits of snow on the leeward side of spurs are caused by winds carrying snow. The snow which is generally blown and carried from the adjoining peaks and high ridges is deposited to create what are designated as wind-borne avalanches. Formation of snow mounds up to a height of 1 m has also been observed. Even after the road is cleared, quick deposition of snow by wind drift blocks the road and holds up movement of vehicles; instances of long convoys stranded due to drift snow deposits are innumerable. With the available knowledge, it is not possible to predict the rate, place and time of buildup of snow due to wind drift even approximately, resulting in certain areas near the pass

Figure 3.



virtually becoming death traps during the months of November, December and January.

Ice formation

The phenomenon of ice formation on the road surface exists on practically the complete stretch of the road. Thin layers up to 0.5 m thick of ice formation on the road surface due to melting of snow during positive daytime temperatures and subsequent freezing during nights present a serious problem to vehicular traffic and clearance. The removal of these ice layers by rotary machines is impossible. The machines themselves skid and the blades get damaged. Even for a dozer, it is very difficult to cut these layers. The formation of ice also results in blocking the mouths of culverts and drains, resulting in spillage of water on the road surface and freezing into ice. At places, even subsoil water seeps onto the road surface and solidifies into ice slabs. The ice formation poses big problems in the proper maintenance of roads for which satisfactory solutions have still to be found. Added to this are the problems due to the snow left on the road sides and boxcuts during snow clearance by the machines.

Avalanches

The problem posed by avalanches in snow clearance is one of the single largest factors. In the preceding paragraphs, passing reference to the threat of avalanches has been made at relevant places. This problem is now dealt with exclusively in greater detail in view of its severity. Although direct snow precipitation is a cause of closure of the road, the duration of holdup is only for a limited period and is, therefore, capable of being tackled with well deployed snow clearance teams. The problems caused by avalanche activity are enormous in magnitude and complexity particularly as they are treacherous in character. This problem is acute in the pass area and one or two more stretches lying to the south and north of it totalling to 25 km. The suddenness of the attack is primarily due to the airborne avalanches which are very destructive and widespread, originating as they do and even from the opposite hills. Deaths and severe damage to property by such avalanches are now regarded as routine. Some of the recorded major avalanche sites are shown in Figure 1. Figures 4 and 5 show a typical avalanche site during and after snow clearance, respectively. Table 2 indicates the magnitude of snow clearance in quantitative terms which vary monthwise. Approximate estimates indicate that a quantity of 2 to 6 million m^3 would be required for clearing in the month of April alone. These figures give a fair idea of the work involved if the road is to be kept on throughout the year, as this operation would have to be repeated a number of times during the year.

Present avalanche data

The R&D Organisation team has collected substantial data on some of the avalanche sites which have been identified. An attempt has also been made to suggest remedial measures. The recorded data covers only a few years. Every year some new avalanche sites are identified. The data collected covers certain salient factors, viz the nature of the originating zones, catchment areas, vegetation, steepness of slopes, soil condition along the

Figure 4.

Figure 5.

avalanche path and their longitudinal section and other important features of these sites. It is seen that in a number of cases the avalanche paths are confined only up to short distances after which they become unconfined and spread out in the form of detritus fans. The lengths of avalanche paths vary from 1000 m to 1500 m. The starting zones are located at altitudes varying from 3800 m to 4400 m. The road crosses some of the avalanche paths in their middle zones and in some cases at the terminal zones. In the critical stretch of road of over 70 km, the identified number of major avalanches (which extends at least 50 m along the road) is about 90, the medium and minor avalanches are about 50 with numerous slides. In certain stretches on either side of the Zozila Pass, the conditions of snow precipitation, drift snow activity, extremely low temperatures, steep side slopes and high velocity winds render the entire sector highly prone to avalanches, particularly of the airborne type. In fact, this sector is truly the crucial problem sector where every bit of it can be regarded as a potential avalanche site. A number of fatal accidents have occurred in this area.

Forecasting avalanches

Much research work is known to have been done outside India on making reasonable forecasts of the onset of avalanches. Attempts are being made in this direction by the Snow and Avalanche Study Establishment of the R&D set-up. The studies referred to above are already related to observation of snowfall, terrain and climatic conditions which vary from year to year as any system of prognosis has to take due account of all these variables. As more and more vital data become available and analysis of these are made, it will be possible to draw up reasonable guidelines for prognosis of avalanches.

Snow Clearance Equipment

In any mechanised work, the efficiency of execution depends on the suitability of the operational machinery, the skill of operation, maintenance and other factors. As snow clearance work in this country is comparatively new, reliance has to be placed on machinery used outside the country, until improvisations become possible. Most of this equipment though not ideally suited to prevalent conditions in this sector, have to be accepted for want of another suitable indigenous alternative. The various types of equipment presently used for the snow clearance operations are:

1. Crawler tractors
2. Rotary snow cutters
3. Motor graders
4. Wheeled tractors

Out of the above equipment, rotary cutters are specially meant for snow-clearance. Special features, their merits and limitations as per our ground experience are discussed below.

Crawler tractors

The relative advantages and limitations of crawler tractors which are essentially used for dozing work are as follows:

Advantages

1. They can be utilized in other than snow clearance operations reducing the idle depreciation.

2. As they are on tracks, they do not slip on snow and can transmit considerable tractive effort.

3. They have good maneuverability and turning radius especially for restricted locations.

4. The presence of boulders and rock pieces in snow and glaciers does not affect their performance.

5. They can conveniently tackle the hardest snow except frozen ice.

6. Output of tractors varies from 1000 to 1200 tonnes per hour.

Limitations

1. Since it is a tracked vehicle, it damages the road considerably if sufficient precautions are not taken during snow clearance. Normally 15 to 30 cm depth of snow could be left in the initial clearance to reduce the damage. However, in subsequent moves for clearing stone-infested avalanches the road surface gets damaged badly.

2. No closed cabin is provided as a result of which the efficiency of operator gets reduced due to weather conditions. But this disadvantage sometimes proves a blessing in disguise as it facilitates operators' visibility and in times of avalanches falls, the driver can jump and escape to a place of safety.

3. Difficult to transport.

Rotary Snow Cutters

This organisation has had the benefit of using rotary snow cutters of different manufacture. While each particular piece of equipment has its own special advantages, certain limitations are also inevitable to meet the special locational requirements. The more important aspects of the above are discussed below.

Advantages

1. They can attack snow up to 3 m high.

2. They are generally highly maneuverable.

3. They have builtin cabins which keep the operator quite comfortable during snow clearance in severe winter conditions.

4. Their output varies from 500 to 800 tonnes per hour on soft snow.

5. Being mounted on wheels, they do not damage the asphalted road surface.

6. The cutter height can be adjusted so that not more than 7 mm snow on the surface is left.

7. Unlike a tractor, these discharge the cleared snow into the air through a chute which is adjustable on either side of the road and can cut a nice box out.

8. They generally require only the operator.

9. During idle season, some of them can be converted into payloaders and can be used as cranes, reducing the idle depreciation.

Limitations

1. As they are mounted on pneumatic wheels, they tend to be slippery on ice and hence non-skid chains will be required.

2. They cannot be used singly on glacier sites and have to be used in conjunction with a dozer.

3. In the rotary cutters fitted with shear-pins this often gets sheared off when stone fragments are not within the snow mass. Hence, frequent stoppage and replacement of shear-pins will be necessary in such machines.

4. These are not ideally suited for snow mixed with stone fragments.

5. In machines which are water cooled, sufficient care is necessary to prevent engine bursts due to a solidification of water.

6. In some machines width of road cut is not adequate to take heavy vehicles. Perforce machines have to do two cuts involving additional movements, or alternate use of two machines is required.

7. If the snow is hardened and very dense their cutters get damaged and they cannot cut.

8. If the snow deposit is wet their chutes get choked very frequently resulting in loss of time.

Other equipment

Many other kinds of equipment made by other countries, such as wheeled dozers and motor graders are also used but with limited success. Hence, they are not elaborated upon in this paper.

Snow Clearance

As emphasised earlier, the problem is to study and find solutions to keep the Srinagar-Leh road open throughout the year instead of six months, as at present. No piecemeal solutions will answer the requirements; the problem has to be tackled in its totality to arrive at the most economical and feasible solutions. As already stated, steps have been undertaken towards finding long-term remedial measures.

A brief description of the present snow-clearance technique adopted, the organisation, the type of machines with their characteristics, and the problems encountered are given below.

Operation

The snow clearance teams commence the clearance work during first week of April and open the road to traffic by the end of May every year. It is clear from the earlier chapters that snow clearance operation on this road is a major task full of hazards and, therefore, needs advance planning and coordination for execution. In order to ensure smooth and orderly progress during snow clearance, considerable preparatory work has to be readied from middle-October onwards. Some of the more important steps that are taken in the preparatory works are summarised below.

1. Checking up serviceability of snow clearance equipment, snow blasts, rotary cutters, crawler tractors, vehicles and availability of manpower, etc., and their placement before the onset of snow, especially for the north sector.

2. Advance procurement of spares for imported and local equipment, vehicles, etc.

3. Procurement and storing at suitable places of winter grade fuel, lubricants, starting aid capsules, etc. It is pointed out that the approximate quantity of diesel sub-zero that has to be stored every year for tackling this single stretch is about 0.2 million litres.

4. Procurement of winter clothing and heating stoves to men, as well as to machines and equipment, which also need to be warmed up.

5. Procurement and storing of ration items.

6. Procuring and fixing of road marking pillars at intervals and in difficult stretches of road to help with the identification of road alignment.

7. Procuring and installing markers in avalanche-prone zones.

8. Building suitable fresh shelters for the snow clearance parties wherever required.

9. Laying out actual campsites with high markers to identify the same in the snow deposits.

10. Improving the drainage system before the closure of the road.

11. Dismantling any special structures, viz bridges, etc., in avalanche-prone areas and making suitable diversion.

Organisation

The snow clearance work of the problem stretch of 80 km of road is tackled from the south up to the pass and also from the north. Each sector is adequately provided with the required number of men, staff and machinery for the clearance work. All requirements mentioned in previous paragraphs are ensured to be in position by the 15th of every year. The deployment of men and machinery is shown in Table 3.

Methodology

Snow clearance operations adopted on this road consist of a judicious combination of men and machinery. Men are basically employed to help the machines at difficult spots of hazard, warning operators where necessary, and for machine maintenance and repair. Drainage improvements and pavement marking maintenance jobs such as deicing, etc. are also carried out. The main snow clearance is carried out by the machines.

The snow clearance work is commenced from both faces more or less in the same pattern. A crawler tractor or rotary cutters are used, depending on density of snow and the overburden of snow. If the standing snow height is less than 3 to 2 m then the ideal combination would be to lead with a crawler tractor with a road guide on it. After the initial alignment cut, the tractor is followed by combinations of one crawler tractor and two rotary cutters. The crawler tractor loosens the snow and feeds both the cutting machines. These latter can cut and as well as throw the snow fed by the tractor. This method was tried in the working season of 1975 and was found to be quite suitable in most of the stretch.

Where the depth of the deposit was less than 2 m and not interspersed with stones and boulders, use of two rotary cutters in tandem (to obtain full width of road for a 3 ton vehicle) proved better. In this method, the crawler tractor pushed up to the nearby avalanche sites (if any) or opened new faces at intervals of 200 to 300 metres for deployment of additional cutters. This combination helped in preserving the pavement structure from damage. Also, the quantity of snow removed from the road surface would be smaller, as compared with the

Table 1. Total snowfall at a typical location (cm)

Month	1965-'66	1966-'67	1968-'69	1971-'72	1972-'73	1973-'74	1974-'75	1975-'76
October	---------------- Not recorded ---------------				100			
November	32	Nil	not recorded	26	58			
December	36	40	88	72	358			
January	9	107	157	308	435			
February	185	296	269	349	269			
March	313	253	116	373	255			
April	45	not recorded	200	139	84			
TOTAL	520	696	830	1267	1559			

Table 2. Typical deposition of snow on road.

Stretch	Monthwise snow accumulation in cubic metres									
	December		January		February		March		April	
	Aval.	Direct	Aval.	Direct	Aval.	Direct	Aval.	Direct	Aval.	Direct
'X'	2895	34200	3840	5400	7742	76200	9600	66200	11000	63000
'Y'	12000	38000	30000	56000	30000	74000	35000	87000	47000	53000
'Z'	40000	28000	56000	30000	74000	35000	87000	46000	53000	-

Table 3. Organisation of snow clearance groups

Serial No.	Item	North Group	South Group
1.	Supervisory staff officers/subordinates	6	8
2.	Technicians (mechanics, electricians, etc.)	8	5
3.	Plant operators and drivers	30	25
4.	Medical officer and assistants	3	3
5.	Unskilled labour	200 - 500	200 - 500
6.	Plants:		
	(a) Tractor with angle dozers size I	5	6
	(b) Rotary snow cutters	5	5
7.	Vehicles:		
	(a) Jeeps, closed body including ambulance 4x4 with non-skid chains	3	3
	(b) 1 ton vehicle, 4x4 with non-skid chains	2	2
	(c) 3 ton vehicle, 4x4 with non-skid chains and heating arrangement	3	3
8.	Radio station	2	2
9.	Camping site kit with snow tents, heaters, cooking arrangements, etc.	2 sets	2 sets
10.	Fuel pumps with suitable filters for quick refuelling of plants directly from the vehicles	2 nos	2 nos
11.	Salts for use in icy area	1 ton	1 ton
12.	Winter heavy clothing including snow goggles, etc.	Full	Full
13.	POL and lubricants dumped various known locations	0.1 million litres	0.1 million litres

clearance by a tractor. This method ensures full utility of all the machines. A number of trial combinations were made to find out the most suitable alternative for a given situation.

In heavy avalanche sites, this combination of tractor and rotary cutter was found to be most suitable. Even in shallow valley stretches, where box cuts are required to be done, this combination proved to be most economical.

Where the standing depth of snow is more than 3 m, the rotary type of cutters by themselves are generally not capable of doing the task due to their limitations. In order to achieve linear progress, only one carriageway in the width of the road is cleared of snow except at a few passing places and the rest of the snow is allowed to be melted away by the natural heat.

One or two tractors accompanied by one or two rotary cutters have to be left in the portions already cleared to clear any fresh avalanches, slides and fresh snow deposits or drift snow. This is very essential to keep communication to the camp sites for evacuation of casualty - a fact which should be thoroughly borne in mind. Figures 6, 7, and 8 show some of the combinations of machines deployed in this region.

Figure 6

Figure 7

Figure 8

Special problems

Problems faced by the field staff to keep the road open have already been sufficiently detailed; however, certain special problems in addition to those described earlier are enumerated below.

1. Realignment of stretches of road to avoid shallow valleys is quite expensive but even so will not completely solve snowfall problems.

2. Afforestation will be useful, but it is a matter for experts in the field to say whether this is possible in the climatic conditions of the region.

3. Stabilisation of hill slopes, especially at stretches where the rock is fragmented and soil is loose, is quite expensive.

4. Extreme cold, gusty winds, blizzards, uninhabited snow mountains with hardly any sunshine for days on end produce adverse psychological effects. Further, the climatic conditions result in a number of physical disabilities like hyperthermia, exhaustion, frost bite, sun burns, snow-blindness, etc., all of which are effects of high altitudes. This reduces the efficiency of men employed. Such handicaps have to be removed by suitable preventive measures.

Control Measures

There are no known methods by which natural calamities like floods, cyclones, avalanches, etc. can be completely eliminated. We have to admit that in problems like these ultimate and complete safety cannot be assured. As with flood control measures in India, which have improved as the country has developed, the control measures to mitigate snow hazards on the road in question are being gradually developed. There is, however, scope for the control measures to be intensified, so that most of the hazards can be checked to a large extent.

There are a number of control measures which are in vogue in various foreign countries. Some of these techniques have been tried with success on the road in question but only on an experimental scale.

The control measure generally include braking, containing, channelization and diversion of avalanches. Prevention of drifting snow by afforestation, baffles, snow fences, diversion barriers and channels has also been found to be useful. Activating avalanches by explosives and artillery fire, construction of snow avalanche sheds, and tunnelling are also well-known control measures.

A comparatively recent development is the prognosis of avalanche onset which has already been referred to. Methods have also been developed to identify avalanches which are likely to advance, after the lapse of an estimated interval of time. Such avalanches can be activated and put into motion to suit the programme of snow clearance operation. Construction of bunds at intervals along the avalanche path has also proved to be successful on the road in question.

Suggestions for Future Improvement

The foregoing paragraphs clearly indicate the magnitude and complexity involved in maintaining the high altitude roads which are of vital importance to the economy and related matters of the country. While the long-term solution should await adequate organisational and institutional arrangements to be completed, it would be advisable to undertake expeditiously the more important corrections for future improvement as given below.

1. The broad lines on which the existing organisation has to be strengthened have already been referred to. Immediate action should be taken by the above setup to collect further salient meteorological data and carry out such other ground surveys as may be found necessary.

2. As a first step, a high altitude laboratory should be set up to locate vital observation stations.

3. A thorough techno-economic study should be initiated to compare the present working costs versus maintenance of a year-round road with ancillary structures and the recurring maintenance costs.

4. A system for quick analysis and dessemination of the data collected should be developed to facilitate operations by snow clearance parties on field.

5. Much is required to be done in design of snow clearance equipment. Ideal snow clearance equipment for this region should be able to cut through soft to very hard snow (density 0.1 g/cm^3 to 0.6 g/cm^3 and break ice sheets. The equipment should be capable of cutting and throwing off snow of depths of 1 metre to 30 metres. They should be capable of removing snow interspersed with stones and boulders by the addition of an automatic angle blade or some digger attachment. This attachment should be capable of being activated by pressing a lever or a switch. It should also be capable of negotiating gradients of 45° on ice slabs and cut through snow. This may have to be a combination of a tractor with tracks and rotary cutters. The machine should be capable of changing from tracks to pneumatic wheels as the situation demands by operating suitable controls.

6. The tendency of snow throwing chutes to get choked while working with wet snow deposits should be reduced by a suitable design of impellers and chute system.

7. A very useful type of light snow vehicle would be one that can travel on soft snow, hard snow or ice slabs, move fast and be capable of negotiating steep gradients up to 45°. Such a vehicle would facilitate evacuation of casualties quickly and would carry out day-to-day reconnaissance of the road stretch.

8. Sufficiently high snow markers and electronic devices should be designed to locate the road stretches at avalanche sites and at locations where snow deposits exceed 6 m in depth.

Conclusion

The construction of highways at high altitudes and their maintenance in the snowbound regions is a comparatively new development in India. The foregoing paragraphs leave no doubt that the complexities and hazards it opens for traffic, even for a limited period of a few months in a year, are gigantic. The road in question is a typical example which bristles with all the challenging problems.

The challenge for the future is tremendous. The possibilities of meeting the challenge are unlimited, both for design by research engineers and manufacture of equipment by the construction industry. These have been dealt with at length in the body of this paper. Although rapid strides have been made in India in the efficient maintenance engineering of high altitude roads afflicted with snow problems, we cannot stop until we achieve an acceptable measure of efficiency but should continue our efforts in gradually improving on what we have already done. Suggestions have been made on what should be done to achieve the long-term objective of keeping such vital roads open for traffic year-round, although interruptions can occur due to circumstances beyond human control.

Overview of Some of the Factors Influencing Snow and Ice Control and the Resultant Impacts of their Implementation

Paper prepared by: M. C. Belangie, Utah Department of Transportation

The costs of winter maintenance represent a substantial portion of the maintenance budgets of the snow belt states. These snow control expenditures are justified on a variety of basis. Principally accident reduction and maintaining traffic flow The latter being justified as the basis for alleviating economic and social impacts to the community. However, the actual substance of these impacts and the methodology to measure them, in many instances has been inadequate. This paper outlines methodologies for measuring delay, speed reduction, volume changes and accident rates as a function of weather modified pavement surface condition. It cites the results of modified accident rate evaluations in three states. A principal finding is that accident injury rates increase as pavement conditions deteriorate, which is contrary to current views. Both public opinion polls and business polls were conducted. The business polls indicate that many costs attributed to storms have probably been over stated. The public opinion poll was conducted in four states. It has an error of estimate of ±5%. the results indicate that driver expectations increase in the middle and lower age groups. One possible result of these higher expectations is an increase in the number and size of liability actions against all levels of government. Vehicle corrosion costs are on the decline and have been substantially overstated. Structural deterioration remains the highest substantiated indirect cost of winter maintenance salting programs.

Table 1. Speed Reductions by Road Surface Condition

PERCENT REDUCTION FROM NORMAL TRAFFIC

	INTERSTATE						NON-INTERSTATE		
	UNCONGESTED			CONGESTED					
ROAD SURFACE CONDITION	CARS OBSERVED	PERCENT REDUCTION	STANDARD DEVIATION	CARS OBSERVED	PERCENT REDUCTION	STANDARD DEVIATION	CARS OBSERVED	PERCENT REDUCTION	STANDARD DEVIATION
DRY PAVEMENT		0			16				
WET PAVEMENT		0			16				
WET PAVEMENT & SNOWING	997	13	5.0	398	21	4.5	676	17	5.2
SNOWING & SLUSHY	3,888	22	5.1	292	36	4.9	2,978	21	5.1
SNOWING & NOT STICKING IN WHEELPATH	1,548	30	5.1	518	35	4.8	831	26	4.7
SNOWING & STICKING IN WHEELPATH	2,194	35	5.2		**			**	
SNOWING & PACKED*	1,696	42	4.2		**			**	

	ADT	NO. LANES	PAVEMENT	ACCESS
INTERSTATE	61,607	6	CONCRETE	NO
NON-INTERSTATE	18,059	4	ASPHALT	LIMITED

*1CM (1/2 INCH) OR LESS
** DATA NOT AVAILABLE

State, county, and municipal governments spend over $500 million annually on snow and ice control activities (1, p.2). Actual amounts expended by individual agencies can be highly variable. In the four years for which we have data; expenditures as a percentage of state maintenance budgets have ranged from a high of 49.4% in Vermont to a low of 1.6% in North Carolina. Variation within a state's maintenance budget can also be considerable. New Jersey spent 5.2% of its maintenance budget on snow removal in 1972-73 and 21.7% the following year. the variation in dollars expended can be somewhat more illustrative than percentage variations. Minnesota expended between $8.5 million and $9.7 million in the three years preceding the winter of 1974-75. That winter, snow fighting cost Minnesota $16.7 million. Expenditures per lane mile is the indictor having the greatest variability. Data for 1973 showed that Texas had expended $16.73/lane mile in that year while Connecticut had spent $1,758.86/lane mile.

Typically, expenditures for snow and ice control are justified on the basis of accident reduction and maintaining traffic flows. Both areas were evaluated in depth over the course of the study (2, 3, 4, 5). The mechanics of delay, speed reduction and volume reduction were closely examined. Time delay was isolated as a key component for measuring the dollar value of various levels-of-service.

Delay

Savings achievable from higher levels-of-service can be substantial. For automobiles these savings are typically a result of time saved by driving at increased speeds. Since all categories of assignable value for traffic delay are a function of the magnitude of the time delay; an adequate estimator of delay is essential if valid dollar values are to be developed. No adequate estimator was available. It became a principal goal of the study to develop one. The following derivation is the result.

The magnitude of delay for any one vehicle is given by:

$$\text{DELAY} = \text{TRIP LENGTH} \times \left(\frac{1}{\text{Snow Speed}} \quad \frac{1}{\text{normal Speed}} \right) \quad (1)$$

The speed under snow conditions will vary from vehicle to vehicle, as will the speed under normal (dry-road) conditions. The delay will also vary, and the way it varies will depend upon the probability distributions of snow speeds and normal speeds. (Trip length will also vary, but sufficient data was not available to define its probability distribution, hence it was assumed constant.) Dry-road speeds have been observed to generally follow a normal distribution, and it was assumed that speeds under snow conditions would follow this same distribution. Under these assumptions, the probability that the delay D is less than a given value w is given by

$$F_D(w) = \int_0^{W/T} \frac{1}{2\pi\sigma_S\sigma_N} \int_0^{\infty} \frac{1}{y^2(y+t)^2} \exp\left[-.5\left(\frac{1-u_S(y+t)}{\sigma_S(y+t)}\right)^2\right] \times$$

$$\exp.\left[-.5\left(\frac{1-u_N y}{\sigma_N y}\right)^2\right] dy\, dt \quad (2)$$

wt.ere

T = average tip length, in miles

u_S = mean value of vehicle speeds under snow conditions

σ_S = standard deviation of vehicle speeds under snow conditions

y,t = dummy variables

u_N = mean value of vehicle speed under dry-road conditions

σ_N = standard deviation of vehicle speeds under dry-road conditions.

The function $f_D(w)$ is the density function associated with this delay and is given by

$$f_D(w) = \frac{d}{dw} F_D(w) \quad (3)$$

This expression has been checked by simulation. It enables the calculation of expected comfort and convenience cost and lost wage costs, neither of which could be accurately calculated from the single value obtained in equation 1. Nor could accurate values be obtained by modifying equation 1 using the mean values for Snow Speed and Normal Speed.

The mean value of delay can be computed from equation 3 by

$$\text{MEAN DELAY} = w \times f_D(w)\, dw \quad (4)$$

The total delay for all vehicles traveling on a given roadway segment can be calculated from

TOTAL DELAY = MEAN DELAY X AADT X MONTHLY FACTOR X DAILY FACTOR X VOLUME REDUCTION FACTOR DUE TO SNOW X ROADWAY SEGMENT LENGTH / AVERAGE TRIP LENGTH

This is then summed over all hours in the storm.

Speed Reduction

In order to utilize the delay formula both the mean speed and the standard deviation for the pavement condition under consideration are required. The data available from the literature was inadequate and it was necessary to develop the required information.

Speed reduction studies were conducted in Illinois, Minnestoa, and Utah. Utah data showing percent speed reductions as a function of pavement condition, highway type, and traffic congestion are summarized in Table 1. Pavement conditions in Illinois and Minnestoa never dropped below the wet surface condition during the periods that observations were made. However, the speed reduction data collected for the dry to wet condition did substantiate that portion of the Utah results.

Rain has no apparent effect on traffic speed. But if the precipitation become intense enough to impair visibility an immediate and significant speed reduction was noted, regardless of pavement condition.

Figures 1. through 3. are derived from Table 1. (4,). Each figure indicates the expected speed reduction distribution for a given pavement condition. The heavy dashed line on Figures 2. and 3. is the average speed reduction line from Figure 1. Its inclusion on these figures was to aid in visualizing comparative effects for different traffic conditions and to help estimate expected effects where no data for that pavement condition was available.

Volume

Significant modifications in traffic volume can result from impaired road surface conditions do to adverse weather. These modifications in flow are not necessarily reductions. Table 2. indicates that although decreases in volume during the storm are probably typical; it is also possible to have substantial increases. This is particularly true for road network having alternate routes with different levels-of-service.

In developing the data shown in Table 2. fourteen road segments were evaluated under storm conditions over a three year period (1971-1973). The adequacy of the sample size is reflected in the relatively high correlation coefficients shown in parenthesis under their respective regression equations. The size of the percent changes in traffic flow falls within common expectations. However, the increases in flow, and particularly the 42% increase ($R^2 = 0.91$) on the Minnesota 8-lane Urban Commuter; and the 11% increase ($R^2 = 0.99$) on the Idaho 2-lane Rural Commuter, are probably not consistent with normal expectations. In all instances where increases in traffic flow were noted there were alternate routes having lower levels-of-service than the roadway on which the test segment was located.

Utilizing the same data base from which Table 2. was derived; eighteen variable were examined to determine if it was possible to correlate elements of a storm with a change in traffic volume during

Figure 1. Speed Reduction by Road Surface Condition (Uncongested Interstate)

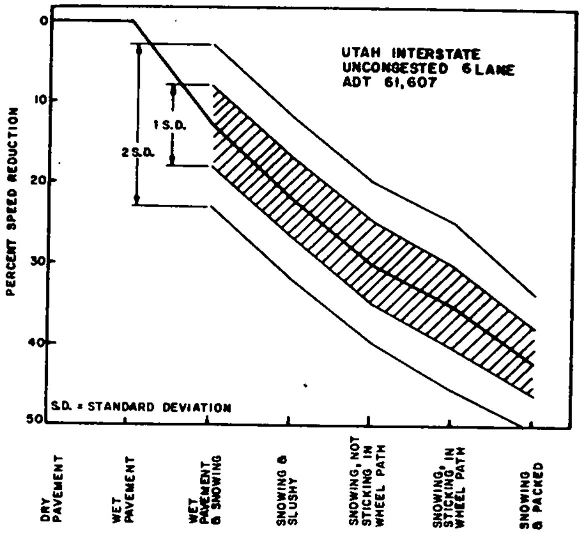
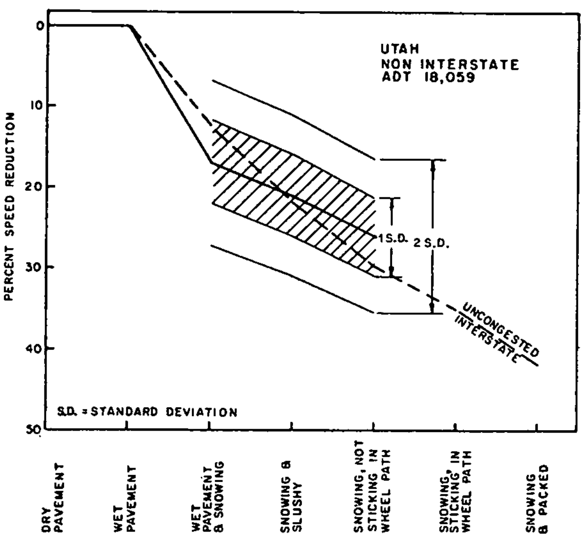


Figure 3. Speed Reduction by Road Surface Condition (Non Interstate)



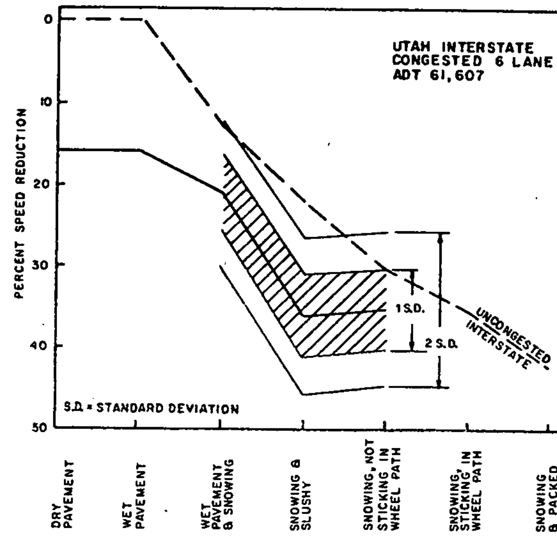
the storm. "The only variable significantly correlating with storm caused changes in traffic volume was normal traffic; no storm characteristics showed a significant correlation with these volume reductions" (4, p. 33).

Modifications in traffic volumes resulting from adverse weather conditions, if not adequately taken into account, can have a substantial impact on evaluations of storm effects. For instance, evaluations of the effects of storms and winter maintenance activities on individual roads in road networks having alternate routes can produce erroneous conclusions unless the shifts in volumes from one route to another are accounted for. Traffic accident rates can be particularly susceptible to the distorting effects of volume changes do to modified road surface conditions. One of the major uses of the data presented in Table 2. was to develop valid accident rate information.

Accidents

Accident records from 1971 to 1973 for the fourteen road segments on which Table 2. is based were obtained. Utilizing the modified volume equations for average snow traffic from that table; and assuming that a wet pavement has no more effect on volume than it does on speed (Table 1); the accident rates for these segments were evaluated. Idaho, Illinois and Utah results are shown in Figures 4, 5, and 6. Minnesota data was not ameniable to the method of analysis and was excluded.

Figure 2. Speed Reduction by Road Surface Condition (Congested Interstate)



Overall accident rates for the three states evaluated are summarized in Figure 4. The data shown there supports the general assumption that accident rates increase with deteriorating road surface conditions. Property damage cost data for the Utah segments was isolated and analyzed. Figure 5. shows these costs (estimated by the investigating officer) for the three road surface conditions. Undoubtedly the under $50 and the $50-100 categories represent only a fraction of the actual accidents that occur in those categories.

Figure 4. Total Accident Rates by State

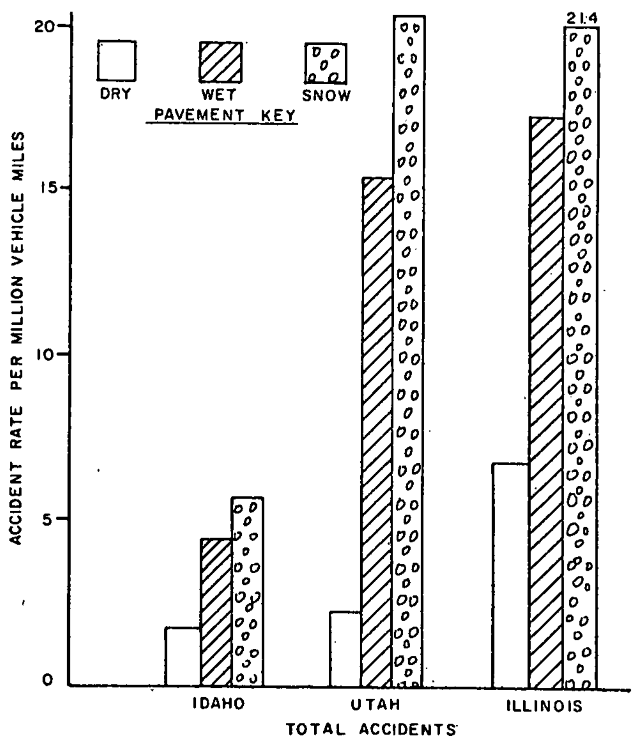


Table 2 Average Modification in Traffic Volume During Storm for Various Highway Types

STATE	ADT (1974)	LANES	PAVEMENT	ROADWAY CHARACTERISTIC	EQUATION (AVERAGE SNOW TRAFFIC) WEEKDAY	EQUATION (AVERAGE SNOW TRAFFIC) WEEKEND	AVERAGE % CHANGE FROM AVNT DURING STORM WEEKDAY	AVERAGE % CHANGE FROM AVNT DURING STORM WEEKEND
INTERSTATE								
UTAH	50,500	6	CONCRETE	URBAN COMMUTER	712+.61(AVNT) (.80)*	153+.94(AVNT) (.88)*	-38 %	-6 %
UTAH	61,100	6	CONCRETE	URBAN COMMUTER				
IDAHO	16,900	4	CONCRETE	RURAL COMMUTER	143+.78(AVNT) (.80)*	-8+.97(AVNT) (.72)*	-21 %	-3 %
MINNESOTA	95,000	8	CONCRETE	URBAN COMMUTER	-122+1.42(AVNT) (.91)*		+42 %	
MINNESOTA	65,000	6	CONCRETE	URBAN COMMUTER	-482+1.09(AVNT) (.72)*		+ 8 %	
ILLINOIS	41,260	6	CONCRETE	URBAN COMMUTER	29+.77(AVNT) (.92)*		-23 %	
ILLINOIS	106,000 (1973)	12	CONCRETE	URBAN COMMUTER	22+.84(AVNT) (.93)*		-16 %	
NON-INTERSTATE								
UTAH	20,400	4	BITUMINOUS	URBAN COMMUTER	1+.95(AVNT) (.99)*	-8+.97(AVNT) (.98)*	- 5 %	- 2 %
UTAH	17,000	4	BITUMINOUS	URBAN COMMUTER				
IDAHO	3,778	2	BITUMINOUS	RURAL COMMUTER	-20+1.12(AVNT) (.99)*	24+.76(AVNT) (.87)*	+11 %	-23 %
MINNESOTA	24,000	4	2 CONCRETE 2 BITUMINOUS	RURAL COMMUTER	202+.77(AVNT) (.65)*		-22 %	

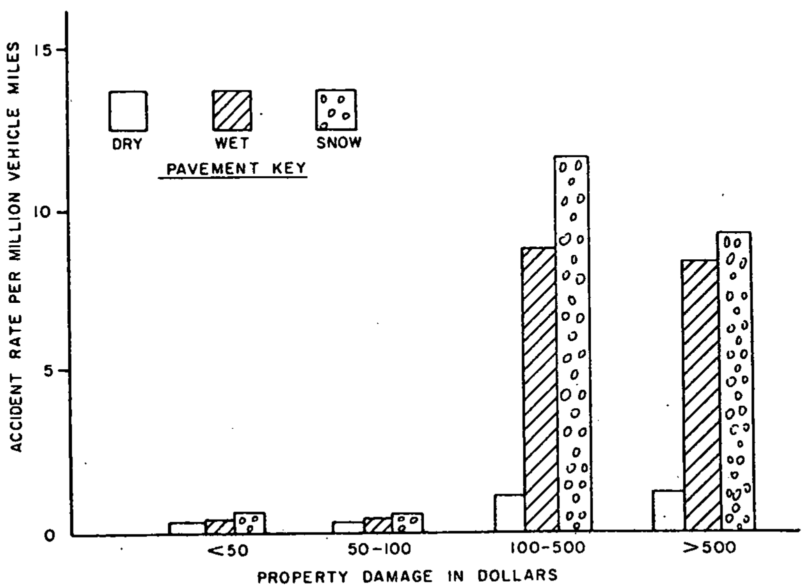
*CORRELATION COEFFICIENT

AVNT = AVERAGE NORMAL TRAFFIC

Nevertheless the substantive element of this figure is the increasing accident cost, in each cost category, as the road surface condition deteriorates. This finding is also in conformance with current expectations of increased property damage costs with deteriorating road surface conditions.

Figure 6. represents a substantial departure from current views; and as such, represents one of the more significant findings of the study. Utah and Illinois injury accident data for their respective segments were analyzed for the three year period. In both states injury accident rates increased with deteriorating pavement conditions. If the data from the Utah and Illinois segments is typical of the snow-belt states then a careful analysis of their data could also yield higher personal injury and, possibly, death rates.

Figure 5. Total Property Damage Accident Rates for Utah

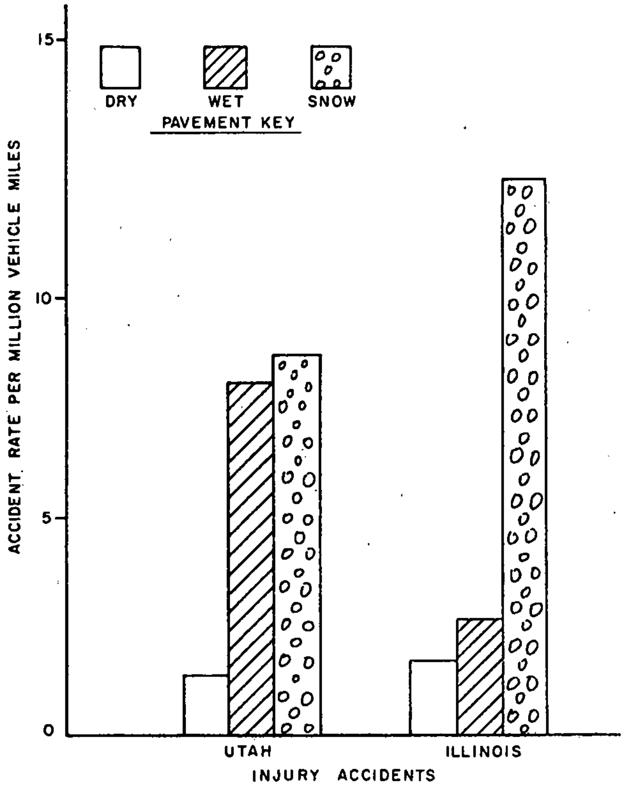


Tardiness.

Tardiness, has been assumed in economic evaluations of snow and ice control to be related to losses in production and/or employee wages. In fact, no attempt to quantify tardiness due to snow storms with respect to such variables as salaried employees versus hourly or contract employees, urban (industrialized) versus rural (self-employed) workers or even tempering snow storm tardiness with normal tardiness rates had been accomplished.

Ninety-one businesses were interviewed by phone or by mail in Utah, Minnesota and Illinois. Included in the interview was a request for information on normal tardiness rates. As a result of this interview Figure 7. was developed. (Both the values assigned to

Figure 6. Total Injury Accident Rates by State



lost wages and the threshold time will vary from industry to industry and from area to area. The values shown are for illustrative purposes only). Figure 7. shows that there is some threshold below which no pay is deducted. The expected value of lost wages per worker can then be developed by Equation 6.

EQ (6)

$$\text{LOST PAY (K)} = \frac{\text{WAGE (K)}}{60} \times \left[\int_{TH(K)}^{\infty} w f_D(w) dw - TH(K)\left(1-F_D(TH(K))\right)\right]$$

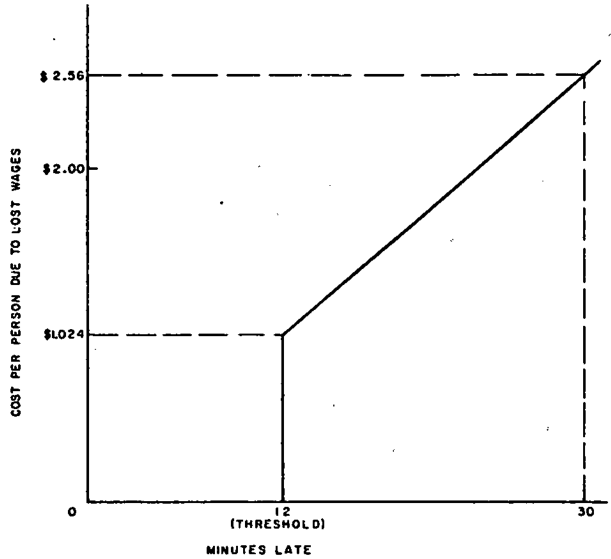
where
WAGE(K) = hourly wage for employees in industry type K
TH(K) = tardiness threshold in industry type K

The total value of lost wages for an industry type K is then given by an expression similar to Equation 5; taking into account the proportion of those who are going to work rather than toward home, and the amount of tardiness that can be attributed to snow conditions.

"Economic forecasts including tardiness in the evaluation should attempt to adjust the gross approximation by the percentage of salaried versus non-salaried workers, percentage of businesses requiring an employee to remain on the job until a replacement arrives, businesses whose goal is such that small time delays do not interrupt total progress and the number of workers whose progress or lack of it does not affect the progress of other people. It is interesting to note from this study investingation (194) that tardiness and absenteeism rates during days of snowy weather were significantly lower than corresponding tardiness and absenteeism rates on a typical Monday or Friday."

"When tardiness results in discernable economic losses, treatment of magnitude of tardy time can be variable depending on income, etc. Values of time delays used by Stanford Research Institute (181) for worker trips (to the worker) may be the best estimate of tardiness values, properly prorated at this time. However, in viewing the macro-economics of the community, a loss to individual workers may not be a real cost, merely a transferred cost in the case of workers remaining on the job until replacements arrive." (2, p. 144)

Figure 7. Lost Wages as a Function of Tardiness



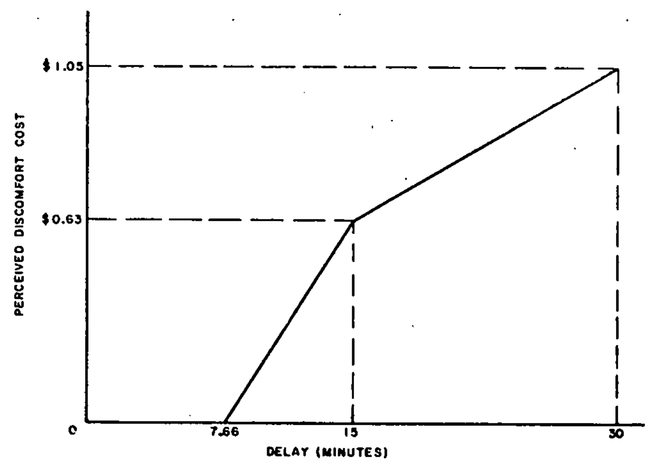
Absenteeism

"Snow-caused absenteeism may create a significant cost in some areas for very large storms. We were, however, unable to separate snow-caused absenteeism from normal absenteeism. Industry often compensates for absenteeism by use of sick leave. It is therefore not clear that snow-caused absenteeism causes a real cost to industry." (3, p. 22)

Comfort and Convenience

Comfort and convenience costs are not direct, measureable economic costs, but their importance cannot be ignored by anyone who must answer to the public. Evaluating these costs is difficult. Thomas and Thompson have developed and appropriate method. Their approach was to determine the amount of money people would pay to avoid a given delay. Figure 8. depicts a typical case. Slopes and threshold values vary with the level of personal income. The values shown in Figure 8. are for annual incomes of from $10,960 to $13,700. (3, p23)

Figure 8. Cost of Personal Discomfort as Percieved by Motorists (Typical Case)



Questionnaire Results

In addition to the ninety-one business interviewed; fifty-three trucking firms were contacted. The following conclusions are the results of these contacts.

Lost Production

Very few of the industries polled indicated a loss in production as a result of inclement weather or snow covered highways. In the case of production line assembly, workers do not usually leave the job until a replacement is available. For non-assembly line production, it is most common for weekly or monthly quotas to be met rather than the daily quotas which would more commonly be affected by snow and ice induced absenteeism. (Although extended cold periods did cause unusual overtime costs in some industries).

Retail Sales

Responses from all of the retail companies indicated that they were aware of sales fluctuations on snow days. However, no company polled had made the effeort to isolate sales during bad weather conditions, and approximately one-half of the responses indicated that most sale losses would be deferred to a later day, thus the quarterly sales index would not be significantly reduced. Sale losses consisting of perishable and impulse items may not be recovered at a later day, but the magnitude of these losses was not known. Of the volume of daily sales, the deferred sales group comprises the vast majority of items sold.

Wholesale Sales

Wholesale suppliers of non-perishable goods generally inventory goods on a quarterly or a demand basis, thus delivery fluctuations on a daily scale as a result of snow did not seem to alter quarterly sales.

Agriculture

Highways which have a traffic composition including perishable products can be affected by snow related highway conditions. Especially susceptible are the daily products such as eggs and milk.

The dairy industries contacted indicated spoilage was not a major problem and only on rare occasions did farmers have to dump their milk due to shipping delays.

Wholesalers of perishable goods reported that produce freezing on trucks may be a problem during bad weather conditions. They did not differentiate between highway conditions or the cold weather as the cause of these losses, nor did they indicate the magnitude of these losses.

Recreational Industries

Recreational industries such as restaurants, theaters, sporting events, etc., fall into the same category as non-deferred sales companies. All recreational industries polled with the exception of skiing and sporting franchises with seasonal ticket sell-outs felt there was a definate decline in business of stormy days. Estimates ranged from 20 to 50 percent reductions on bad weather days. It was not clear whether this business loss was caused by bad weather or by anticipated roadway surface conditions.

Truck Delay

Questionnaires returned from trucking companies polled throughout the United States indicated that no information was available on the magnitude of truck-hours delay as a result of snowy highways. For purposes of snow impact on truck travel, it is assumed from speed measurements that trucks are not significantly affected on rural highways whereas in urban areas trucks are slowed by passenger cars, which are generally influenced by snow.

Public Opinion Poll

The level-of-effort expended on snow and ice control activities is in part determined by public expectations. These expectations have been solidified in the political sphere thru the legislative process and via special interest lobbying. Court action, either by judicial interpetation or through increased case loads and/or increased size of jury settlements represent another form of public pressure for change. The decay of soverign immunity is one indicator for the extent of governmental/judicial response to these pressures. Transportation agencies have responded in a variety of ways. Modification of policies and procedures either to conform with apparent public desires or to protect the agency from punitive actions by the public are the most typical.

If public expectations can be ascertained with some degree of confidence. Then modifications in levels-of-effort can be initiated with some surety as to the expected reaction. Probably more important, additional information as to the reasons for the public's heightened expectations can be used to defuse or ameliorate the backlash resulting from cut-backs in maintenance. The public opinion poll represents an imperfect but viable mechanism for evaluating public expectations. The method has been used extensively and effectively in defining expectations in other areas. As a predictor its potential has yet to be realized by transportation agencies. The following results give some indication of the information that can be obtained and the logic of one evaluative approach. Table 3. summates the high ratings from three separate questions (four for Illinois). The most striking aspect of the table is the consistency of the heirarchical rating. This would have been expected if a single forced-choice question had been used. Where individual roadway types were being rated separately, it was not expected. Decreasing rating with decreasing expenditures would also be expected for freeways and possibly highways. (Toll Roads although included in the freeway column may represent a different connotation to the rater.) That this expectation was substantiated indicates a considerable degree of observational sophistication by drivers. It is highly unlikely that any significant percentage of the samples had raters with comparative winter driving experience in more than two of the states sampled.

The questionnaires were divided into five age groupings (Figure 9). In general, the older the age group, the larger the percentage of that age group ranking the roadway type above standard or excellent. Unfortunately the age groupings were too wide to make definitive suppositions. Never-the-less some generalizations may be appropriate.

Figure 9 Per Cent Rating Winter Maintenance Above Standard or Excellent by Age Group (Total All four States)

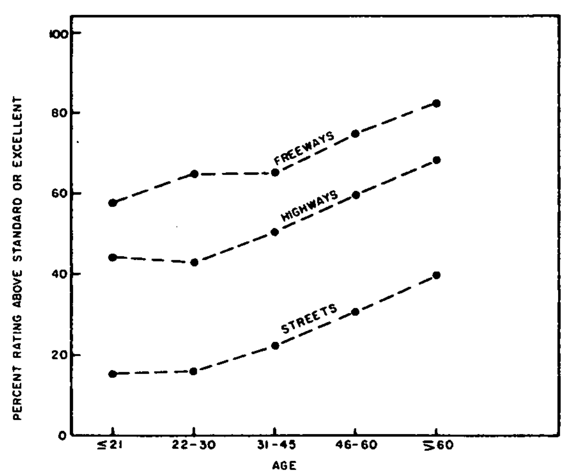


Table 3. Drivers Rating Roadways Above Standard or Excellent

STATE	PERCENT OF DRIVERS RATING ROADWAY TYPE ABOVE STANDARD OR EXCELLENT			PERCENT* OF MAINTENANCE BUDGET EXPENDED ON SNOW CONTROL	SAMPLE SIZE
	FREEWAY	HIGHWAY	STREETS		
MINNESOTA	79.7	61.2	21.8	26.9	1002
UTAH (SUMMER)	71.4	53.5	26.1	23.5	1731
UTAH (WINTER)	66.8	47.9	18.8	23.5	756
IDAHO	60.9	44.9	24.9	19.6	802
ILLINOIS	61.2 TOLL ROADS	44.6	19.8	16.2	1055
	56.5 EXPRESSWAYS				

*AVERAGE PERCENT SPENT FROM 1971 TO 1975 INCLUSIVE (2, P.29)

Figure 9. represents a potential area of concern. It may be that the high ratings, with age, are a result of greater maturity. It seems more likely though that the expectations of the younger drivers are based on the higher levels-of-service initiated in the mid-fifties, expanded, in the sixties, and continued during the seventies. Their expectations, unlike their elders, have not been leavened by the much lower maintenance levels of the Depression, World War II, the post-World War II recession and the Korean War. It is important to remember that when cars were available in the earlier periods, as often as not, chains, in many areas, were a precondition to moving.

The inferred impact of these higher expectations is tied to decreasing real-dollar maintenance budgets and the necessary cut-backs in levels-of-effort/service accompanying these reductions. These cut-backs in combination with the inferred increased expectations of the younger age groups and the movement of these age groups into the bodies politic and judicial may well foreshadow an acceleration in liability actions against all levels of government.

Legal

The NCHRP has published four Research Results Digests (6, 7, 8, 9) in the last two-and-a-half years dealing with governmental liability. Although the documents are of substantial help to the legal entity, as well as being of some help to the administrator, they do not adquately define the trend of the law. They describe the decay of soverign immunity/and give ample illustration to the nature of the changes taking place. What they do not trace adequately is the decay over time.

If the connotations implied in the Public Opinion Poll are valid. Then it is of some importance that this decay be traced and correlated with the expectations of the public. For if these expectations are in fact a principal component of the judicial and legislative forces presently impacting highway agencies; then it can be anticipated that the legal/monetary pressures of the present rather than moderating may well be accelerating.

Vehicle Corrosion

The EPA sponsored a document (10), published in 1976, that asserted that salt caused $2.9 billion annually in damage to the environment. Of that amount $2 billion was attributed to vehicle corrosion. A summation of that document will be published in TRR #647. Following that summation is a discussion (11) that points out the inadequacies of the assumptions and the technical errors that render the vehicle corrosion portion of that EPA assessment invalid.

The automotive industry, in the past, has probably been far more responsible for the damage caused by vehicle corrosion than the highway agencies using deicing salt; although the highway agencies have borne a significantly larger share of the negative publicity. In point of fact, the introduction of reduced sheet metal thickness, prior to the development of an adequate anti-corrosion technology, in the mid-fifties is largely responsible for the high incidence of perforation corrosion beginning then and continuing at a reducing rate into the present. Widely publicized, recent innovations in the steel industry (coil-coating), if fully implemented, will eventually reduce vehicle corrosion damages, do to all causes, to a minimal if not negligible amount.

Structural Deterioration

Structural deterioration represents the largest substantiated indirect cost of snow and ice control. There is no question that salt, deicing or environmental, initiates the depacification of reinforcing steel; although there are a variety of design, construction and loading factors which may hasten the subsequent deterioration of the structure. Salting programs are the principal cause. The State-of-the-Art portion of the study (2) deals with this area in depth.

Discussion

In summary, both highway users and non-highway users incur a number of direct and indirect costs from snow storms and the subsequent snow removal activities. In the case of the highway user the costs of a storm are primarily a result of snow caused delay. The major indirect costs to users and non-users are largely a result of salting activities. Ecological costs, due to salting, represents the one remaining area of substantial uncertainty. With the possible exception of the ecology, both direct and indirect costs are probably not as large as formerly thought.

Accident rates, both property damage and personal injury, are highest for snow-packed roads, lower for wet pavement, and lowest for dry roads. The Utah and Illinois data contradicts the common assumption that personal injury accidents decrease during a storm. If they are typical of the rest of the snow-belt states, then a careful analysis of the other states accident data will quite possibly yield higher personal injury accident rates.

Removal of snow and ice from highway surfaces as rapidily as possible is a valid objective. Its accomplishment will reduce the number and rate of both personal injury and property damage accidents; as well as contributing to a decrease in road-user wage losses and comfort and convenience costs associated with snow-covered highways.

Acknowledgments

Special thanks are due J.E. McBride, Utah Department of Transportation and Bob H. Welch, Transportation Research Board for their assistance. Thanks are also due the co-authors and advisory panel members of the National Pooled Fund Study "Economic Impact of Highway Snow and Ice Control" (DOT-FH-11-8580) for their contributions to this paper.

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Heating Bridge Decks by Electrical Resistance

James H. Havens, W. Vernon Azevedo, Assaf S. Rahal, and Robert C. Deen, Kentucky Department of Transportation

The 9th-Street interchange was designed and constructed with an automated electrical heating system for snow and ice removal. This report describes the heating system, its construction, and initial operation. The heating system was capable of keeping the interchange free of ice and snow accumulation. The average daily slab temperature fell below 0°C (32°F) on only one occasion. The average cost of electrical power for heating the interchange was $1,075 per day.

Design Requirements

The presence of snow or ice on highways, especially at bridges and interchanges, often results in hazardous driving conditions. Conventional snow and ice removal may prove inadequate due to the time lag between ice and snow accumulation and plowing and(or) salting operations. Also, deterioration of concrete in bridge decks is often attributed to the use of deicing chemicals. A number of non-chemical methods of preventing freezing have been investigated. One solution for the control of such conditions is a heating system for bridge decks and pavements capable of melting any snow or ice that might accumulate on the roadway. Various systems of heating pavements using embedded pipes or embedded electrical elements have been tried in the United States, Canada, and Europe. Analyses of these systems have confirmed their ability to remove and prevent the accumulation of snow and ice on bridge decks and pavements *(1)*. However, the installation and operation of these systems is very expensive as compared to the cost of conventional snow removal.

The 9th-Street interchange in Louisville, Kentucky, is subject to extreme conditions due to the use of maximum interstate grades and superelevations, the height of the ramps, and the location near the Ohio River. The major portions of the ramps are elevated, exposing both the top and bottom surfaces of the ramps to wind currents. Conventional snow and ice removal would be undesirable due to potential traffic congestion. Therefore, an automated heating system, with manual override switches, was deemed necessary for this location.

The 9th-Street interchange was first conceived in 1959 *(2)*. Preliminary design began in the early 1960's, and design began in 1964. Hazelet and Erdal of Louisville were the principal consultants. They engaged Bosch and Latour of Cincinnati, Ohio, to design the electrical heating system, controls, and monitors. Design criteria established by the Department are summarized as follows:

1. three independent, parallel 20-watt circuits with variable controlled inputs to provide a total heating capacity of 645.8 watts per m^2 (60 watts per square foot),
2. embedded mineral-insulated cables interrupted at joints and otherwise sectionalized,
3. prevent icing and clogging of deck drains and downpipes,
4. provide building to house controls and monitors,
5. provide TV monitoring throughout,
6. provide ice detectors at strategic points,
7. provide remote-reading temperature sensors and recorders,
8. provide meters and indicators of circuit operation, and
9. provide operating and maintenance manuals and operator training.

The contract for the 9th-Street interchange was awarded April 27, 1973, to the E. Randle Company and the R. R. Dawson Bridge Company. The electrical subcontractor was the Marine Electric Company. The Nelson Electric Company was contracted to manufacture the heating cables. Work began on the project May 17, 1973. The interchange was opened to traffic and the heating system became operational December 3, 1976. The final acceptance of the project by the Department was March 29, 1977. The final costs of the heating system are listed in Table 1.

TABLE 1. HEATING SYSTEM: FINAL COSTS

Electrical Distribution System	$715,345
Roadway Heating and Connectors	720,500
Control Building	204,275
Instrumentation System	168,500
TV System	69,550
Total	$1,878,170

The total project cost was $14,130,645.45.

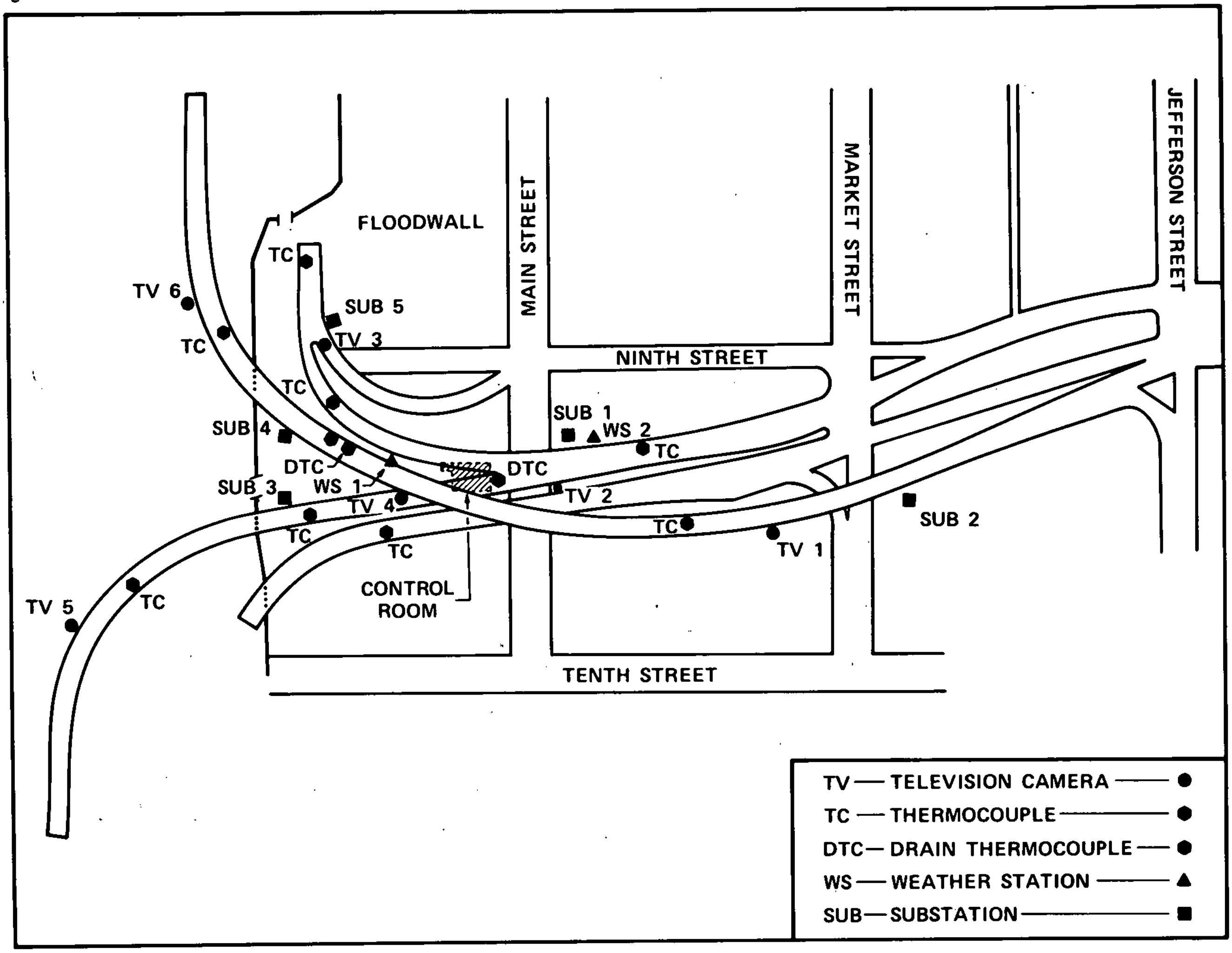
Description of System

The 9th-Street interchange (Figure 1) consists of 1.252.12 m (4,108.0 feet) of welded steel plate girder (continuous, composite) bridge ramps and 353.87 m (1,161 feet) of grade ramps for a total length of 1,605.99 m (5,269.0 feet). The width of the ramps ranges from 6.70 m (22.0 feet) to 15.85 m (52.0 feet). The decks are 229 mm (9 inches) thick while the pavements are 254 mm (10 inches) thick. Class AA concrete (368.1 kg/m^3 (6.6 bags per cubic yard)) was used in both bridge and ramp sections. The total area of heated pavement is 16,713.95 m^2 (174,095 square feet). The bridge ramps can be heated to a maximum of 645.83 watts per m^2 (60 watts per square foot), and the grade ramps can be heated to a maximum of 538.20 watts per m^2 (50 watts per square foot).

All power for the ramp heating system is supplied by a Louisville Gas and Electric (L. G. & E.) underground cable at 13,800 volts, three-phase, ungrounded. There is a 1,200-amp, 500-MVA air-type circuit breaker ahead of the L. G. & E. meter. The main switchgear located in the control building is supplied with 13,200 volts; the remaining power is for auxiliary purposes. The power level is controlled by a motorized, tap-changing-under-load voltage regulator having 32 steps and a range of 2,200 to 13,200 volts. The voltage regulator, positioned behind the control building, may be controlled manually or by automatic response to various sensing devices.

Power from the voltage regulator is distributed through underground electrical ducts to five substations where transformers reduce the adjusted high voltage to low voltage levels which can be utilized by the ramp-heating system. Each substation supplies approximately 2,500 kVA. The maximum secondary voltage at the substations is 480 volts phase to phase and 277

Figure 1. General Facilities and Location.



volts from neutral to ground. Each substation transformer is equipped with two main buses to feed two sections of pavement. Each bus has three panels, each having 12 three-pole, 100-amp breakers. Each panel is protected by a ground-fault interrupter. The secondaries are three-phase, ungrounded, wye-type; each phase returns to neutral. The maximum input to any heater circuit is 270 volts.

Distribution cables (No. 4 wire (5.95 mm)) from the substations extend in conduit (Figure 2) to steel wireway units, termed plinth boxes (Figure 3), on the bridge ramps or concrete hand holes (Figure 4) on the grade ramps. It is here the distribution cables from the substation connect to the cold section of the embedded roadway-heating cables.

Three types of plinth boxes are employed. The first is the plinth-feeder box, i.e., entrance box. The distribution cables connect to the cold sections of the heating cables in this unit. The second type is the plinth-expansion box. Connections are made in this type of box between cold leads of adjacent bridge sections so that a bypass may be made around the expansion joint (Figure 3). The third type is the plinth-termination box where the phase leads are joined together to complete the wye-neutral connection. The same type of arrangement is made in the concrete hand holes for the grade ramps. Both the steel plinth boxes and concrete hand holes are designed so that the cover may be removed for periodic inspection or repair of the various cables.

Cold-section cables leave the plinth boxes through ports and are embedded in the lower plinth and curbing concrete. The connection of the hot and cold sections of each cable is in the concrete below the curb and gutter. The entrance of the cable to the pavement and position of the cold joint prior to the placement of the concrete is shown in Figure 5. The hot sections of the cables extend various distances across the roadway from the entrance box, then turn to run longitudinally for the length of the ramp unit. At the end of the ramp, they turn and exit on the side opposite their entrance. This pattern continues through three or four ramp sections where the cables exit in the termination box and are joined to complete the neutral "wye" connection. At converging bridge or grade sections, the heating cable is joined to a cold section which passes through a sealed construction joint box (Figure 6) to the adjoining pavement and is rejoined to the heating cables.

Cable spacing varies to accommodate the reinforcing rod pattern in the respective units. However, cables are arranged so that each cable is essentially the same length and has the same current for a prevailing voltage, thus assuring uniform heating in the respective units. In addition, phase leads from the three-pole breakers are alternated so that, in the event of a breaker tripout, three separate, 152-mm (6-inch) unheated widths alternating with 305-mm (12-inch) heated widths would occur rather than one 457-mm (18-inch) unheated area.

The heating cables consist of a single copper (No. 16 wire (1.6-mm)) conductor with magnesium oxide (MgO) insulation in a copper sheath. The cold section, 1.83 m (6 feet) at each end of the heating cable, is No. 6 (5.2-mm) copper wire in a copper sheath.

The system is equipped with closed-circuit television so that the effectiveness of the heating system can be monitored visually. Six pan-and-tilt zoom-lense TV cameras are mounted on standards above the plinth. The housings for the cameras are weatherproof and equipped with window wipers. Shielded transmission cable extends from each camera to the control room where the six TV monitors are located.

Two weather stations are also mounted on standards above the plinth. Each is capable of measuring wind speed and direction, outdoor temperature, and humidity; and each is equipped with sunshine, rain, and snow detectors.

The system has eleven thermocouple stations. At each station there are either six or twelve thermocouples. Where six are employed, they are in the drain; where twelve are employed, six are in the gutter area and six are in the centerline of the deck (Figure 7). One of two surface temperature detectors (Figure 8) can be used for modulation of the voltage

Figure 2. Distribution Cables in Conduit.

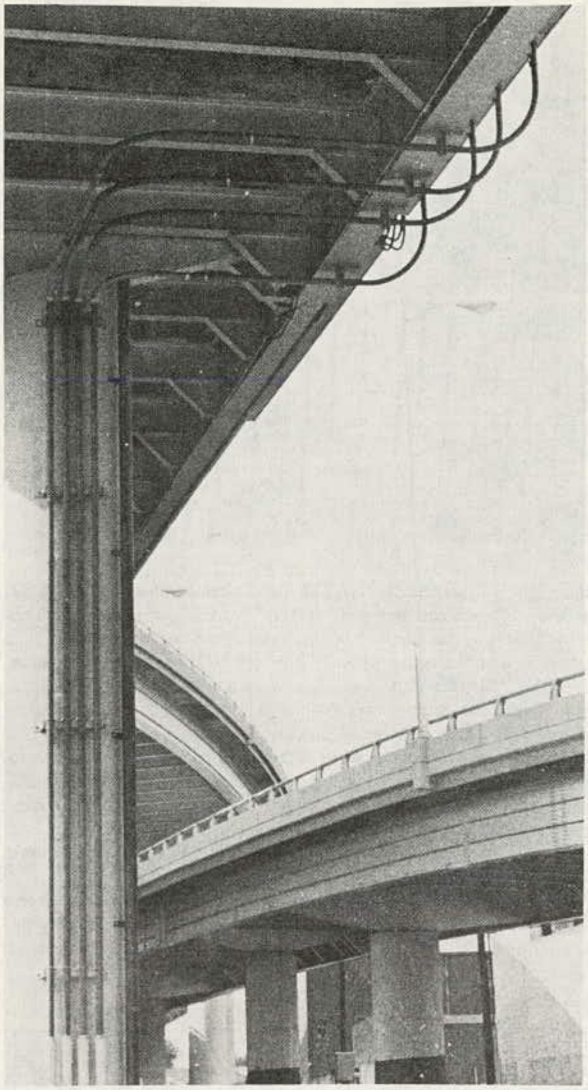


Figure 3. Typical Plinth Box and Expansion Loop at Expansion Joint.

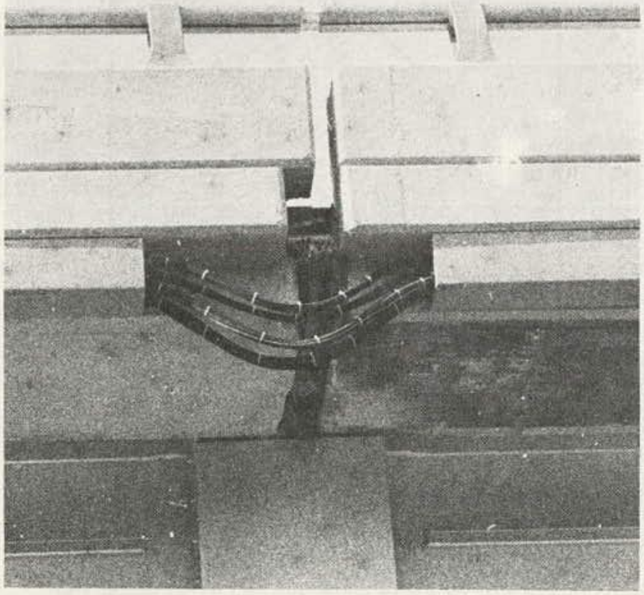


Figure 4. Concrete Hand Holes in Pavement Section.

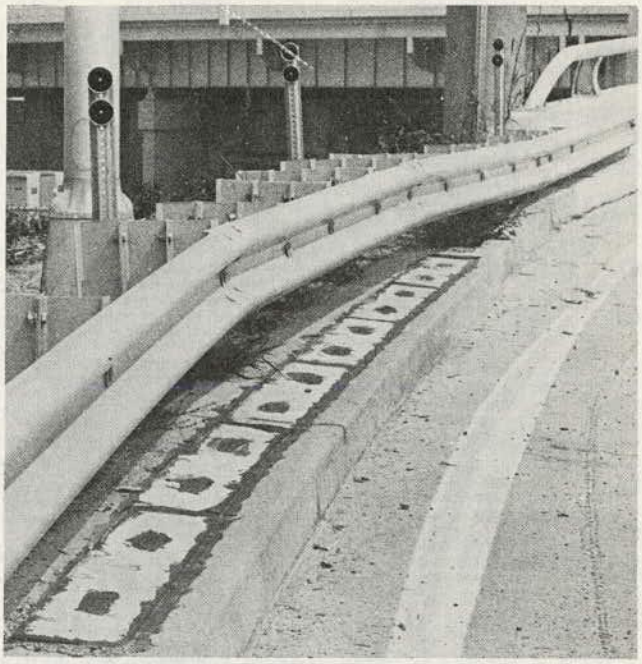
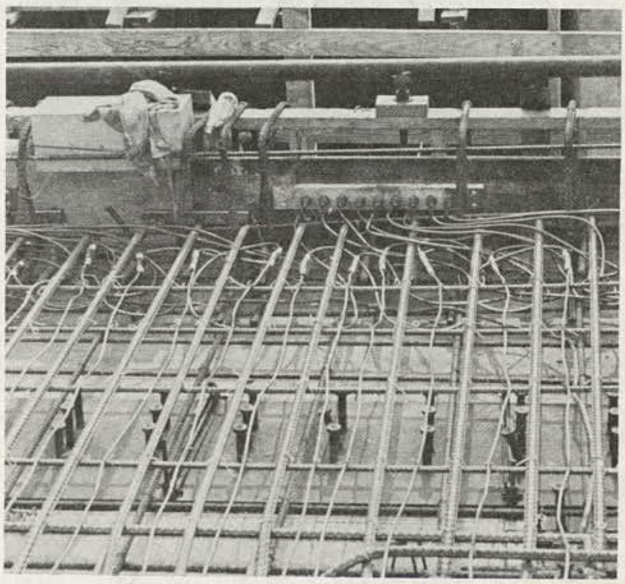


Figure 5. Position of Cold-Section Junction.



regulator.

All drainage troughs and drain pipes are insulated to prevent icing and clogging. The drain troughs are insulated with 16-mm (5/8-inch) foamed plastic and covered with 2-mm (0.08-inch) galvanized steel. The drain pipes are insulated with 25.4-mm (1-inch) fiber glass and covered with a 0.2-mm (0.01-inch) stainless steel jacket.

The control building is located on Main Street under the converging sections of Ramps 1 and 2. It houses the main switchgear, TV monitors, power and weather meters, and the master controller.

The L. G. & E. 13.8-kV service enters in the switchgear room. The power is fed through the main circuit breaker, the main switchgear, and on to the voltage regulator and then runs underground to the various substations. An uninterruptable power supply is also located in the main switchgear room. This 20-unit battery system provides storage of energy for resetting the voltage regulator and the main circuit breaker in the event of a power failure.

The control room houses the six television monitors and various instruments for monitoring the weather and power levels and for adjusting the heating system. The TV monitors, power meters, weather indicators,

Figure 6. Junction Box at Construction Joint.

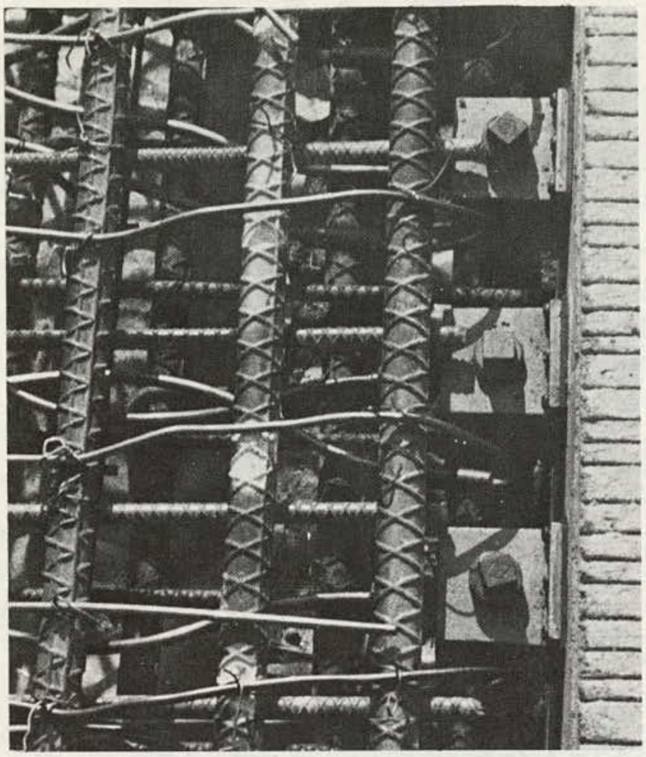
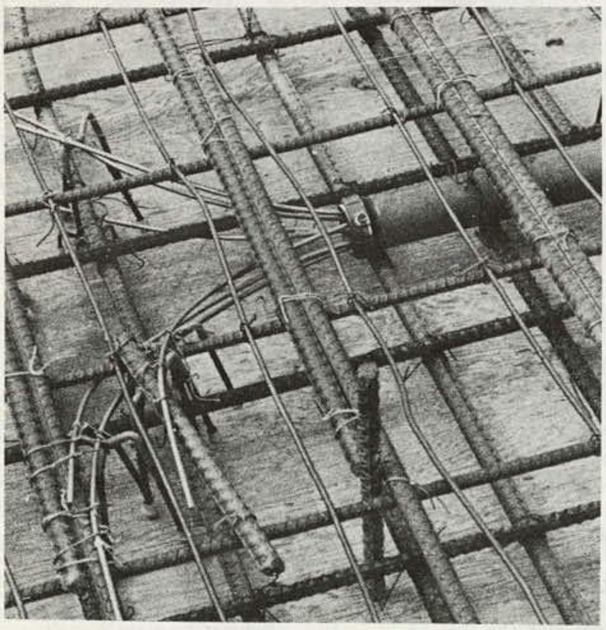


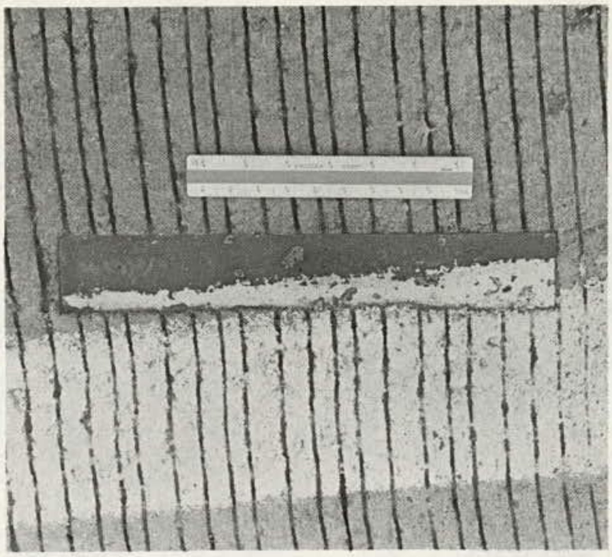
Figure 7. Typical Thermocouple Installation at Centerline of Deck.



and thermocouple monitors allow the operator to stay abreast of current road, weather, and power conditions at the interchange. The annunciator display panel will immediately indicate the location of any problem in the electrical system. Two failsafe systems protect the electrical heating system from overheating. One lowers the voltage regulator when the controlling slab temperature exceeds the set point. The other failsafe trips the main circuit breaker when the outdoor temperature is -8°C (18°F) and the voltage regulator is on Step 33 or when the outdoor temperature is 24°C (75°F) and the voltage regulator is on Step 1.

The master controller is provided to obtain as full an automatic control as possible. The basic concept is to operate the heating system at a low level of heat when the slab temperature goes above a certain set point. As the temperature drops, slab temperature sensors cause the voltage regulator

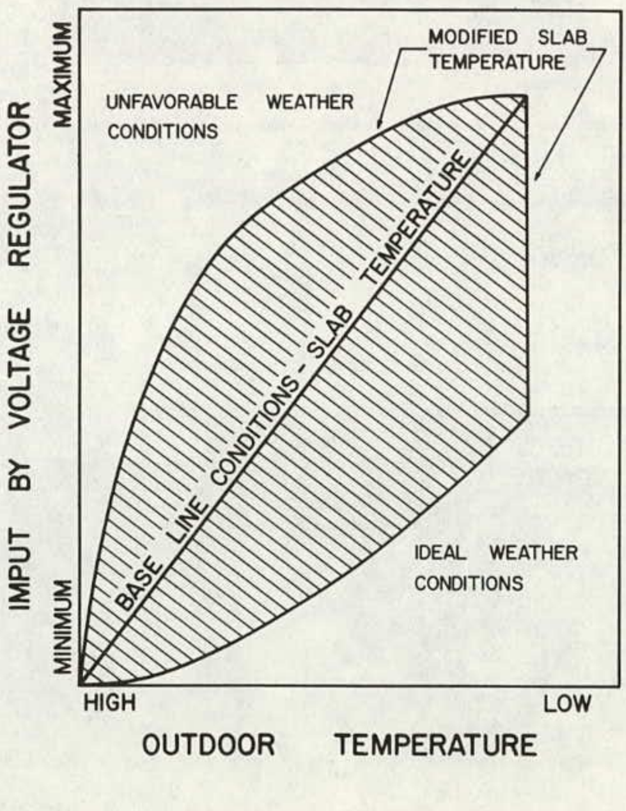
Figure 8. Surface Sensor.



to increase the voltage into the system. As the temperature increases, the voltage level is reduced. However, various weather parameters, such as barometric pressure, rain, snow, humidity, and others, are programmed into the system so that the system actually operates on the probability of snow and ice rather than the detection of snow or ice. An illustration is given in Figure 9. The slab temperature establishes a base-line condition. As the temperature drops, more heat input goes into the slab. The basic straight-line situation is then changed by the weather factor signal modifiers, represented by the cross-hatched areas between the curves. If weather conditions remain ideal, even though the temperature goes very low, a minimum of heating would be required, as shown by the lower portion of the cross-hatched area. If weather conditions are unfavorable, more heat would be required as shown by the upper portion of the cross-hatched area.

There are 11 signal modifiers affecting the modified slab temperature. Eight digital timers on the weather instrumentation console are used by the master controller for timing weather condition changes and duration of

Figure 9. Modified Slab Temperature Conditions.



heating at the various steps. Output of these timers is incorporated into the logic of the master controller to automatically establish the amount of power to be delivered to the heating system.

Signal modifiers and slab set point can be set manually on the system control console. The slab set point is a predetermined slab temperature used by the master controller. If the modified slab temperature as computed by the master controller falls below this set point, the master controller calls for more heat; if the modified slab temperature goes above the set point, the controller reduces the amount of heat to the slab. The console is also equipped with two recorders. The weather factor signal recorder indicates which signal modifiers have been activated by the prevailing weather conditions. The slab temperature for control and composite weather factor signal recorder indicates the actual slab temperature used for control and the modified slab temperature, as computed by the signal modifiers.

Construction

Original design of the heating cables called for the outer sheath to be stainless steel and of a thickness not less than 0.56 mm (22 mils). Cables in the decks were to be tied at 0.91-m (3-foot) intervals with No. 16 (1.6-mm) stainless steel wire. Cables in the pavements were to be clipped to stainless steel mounting strips which were 3.05 m (10 feet) by 25 mm (1 inch). The mounting strips were on 0.91-m (3-foot) intervals, and the clips on the strips were on 140-mm (5 1/2-inch) centers. Due to manufacturing difficulties in drawing the stainless steel covering, a decision was made to use copper-sheathed mineral-insulated cable with a minimum sheath thickness of 0.61 mm (24 mils). This necessitated a means of relieving galvanic action between the copper sheath and the reinforcing steel. To insulate between the copper sheath and the reinforcing steel, the top mat of steel, including the truss bars, in the decks and the entire reinforcing mats in the pavements were epoxy-coated. Copper tie wire replaced the stainless steel tie wire. The stainless steel mounting strips were replaced by 6.4-mm (1/4-inch) solid copper rods on 0.61-m (2-foot) intervals. All chair or bar supports were to be epoxy-coated or of a rustproof material.

Mineral-insulated cable is very rugged, and its use is widespread. It can be hammered almost flat without destroying its operating characteristics; however, it still must be handled and installed with great care. A small cut in the sheath would permit moisture to enter and destroy the electrical insulating properties of the magnesium oxide.

Heating cables were delivered to the job site in pre-cut lengths and with the cold sections attached at the factory. The cables were coiled and packaged in individual cardboard boxes.

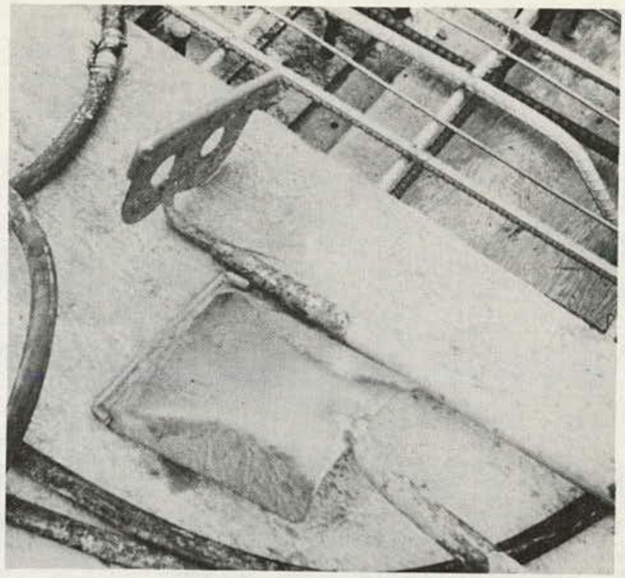
All work, except the concreting, was completed on the decks before cable installation began. Prior to being positioned on the decks, the cables were lubricated with a Dow Corning silicone compound. The lubricant was used to prevent the adherence of the concrete to the surface of the cable. Individual cables were played out from reels and stretched the length of the deck for proper positioning. Heating cables were to be no closer than 38 mm (1 1/2 inches) horizontally to any longitudinal reinforcing bar or no closer than 102 mm (4 inches) to another heating cable or at a distance not greater than 152 mm (6 inches) apart. However, some deviations in this spacing occurred due to variations in cable length as received from the manufacturer. After positioning the cables on the deck, the cables were tied with copper tie wire at 0.91-m (3-foot) intervals. All electrical connections were made according to conventional wiring codes. Plywood walkways were provided for construction workers, preventing damage to the cables prior to the placing of concrete.

Concrete was placed with a crane and bucket. The finishing machine used was a self-propelled, rail-mounted Bidwell finishing machine with a rotating drum, front-mounted auger, and drag-type plate. Concrete was dumped ahead of the finishing machine from approximately 0.46 m (1 1/2 feet) above the heating cables. No apparent damage or displacement of the heating cables occurred as a result of dropping the concrete from this height. The concrete was partially leveled with specially modified shovels and rakes (Figure 10). Tubing was welded to the sharp edges of these tools to prevent damage to the cables. The concrete was vibrated by hand-held portable vibrators. Workmen stood on plywood walkways which were continually backed away as the concreting operation progressed. The concrete was cured in a normal manner.

Each cable assembly was tested for continuity and insulation resistance before, during, and after concreting operations. Each cable assembly was required to measure not less than 200 megohms. Of the 1,800 cables in the system, only one failed during concreting operations.

After 9.14 m (30 feet) of concrete had been placed in Ramp 3, resistance in a cable at the gutterline dropped below the required 200 megohms. As concreting continued, the damaged cable was removed from the fresh concrete and a replacement cable was installed in its place. The replacement cable was tied at irregular intervals with copper wire. The concrete was replaced around the new cable and floated by hand. No revibration of the concrete occurred. The completed interchange is shown in two aerial photos taken December 2, 1977 (Figures 11 and 12).

Figure 10. Specially Modified Shovels and Rakes.



Upon completion of the interchange, the electrical heating system underwent a full-load test to determine the integrity of the system. At a time when the outdoor temperature was predicted to be below -7°C (20°F) for a period of 24 hours or longer, the system was advanced to full load (Step 33) at regular intervals. The system was required to maintain a stabilized condition at this load with all heating cables, power, weather, and recording instruments functioning properly.

Discussion

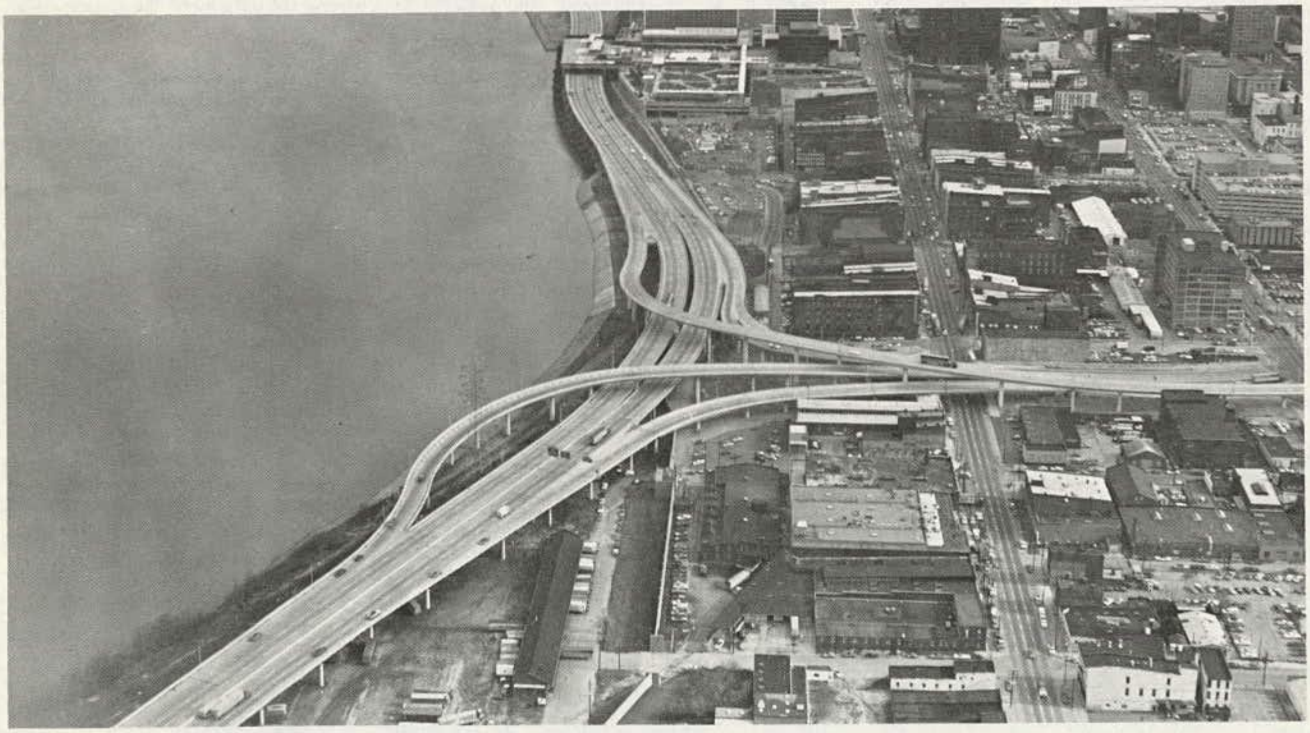
The 9th-Street interchange was opened to traffic December 3, 1976. The initial operating season extended through April 16, 1977. The heating system was in operation at various levels throughout this period.

Monthly weather summaries are listed in Table 2. Figures 13 and 14 compare the average daily slab temperature to the average daily air temperature as recorded at the 9th-Street interchange. The position of the thermocouple used in determining the average slab temperature was at the surface of one of the bridge ramps. On only one occasion, January 10, 1977, during the period December 30, 1976, to April 16, 1977, did the average slab temperature fall below 0°C (32°F). This was the date of the greatest snowfall (198 mm (7.8 inches)) of the winter season. Visual observations throughout this period indicated that both deck and pavement sections were kept free of snow and ice accumulation. Figures 15 and 16 show the transition between heated and non-heated pavements during a period of snow accumulation. Both pictures were taken of the same snowfall. The official ground cover for this day was 127 mm (5 inches) of snow. In Figure 15, note the accumulation of snow on the plinth and curb and patches of snow directly above the roadway drains in the gutterline. These are non-heated areas. Figure 17 is an aerial view of the entire interchange taken on February 2, 1978. The photo clearly shows the difference between heated and non-heated sections during severe cold and snow accumulation.

On January 10, 1977, a short circuit in a plinth box caused a portion of one bridge ramp to be without heat for four days (January 10 through January 13). The largest snowfall of the winter season occurred during this period. However, a combination of adjoining heated pavement and traffic was able to keep this section of pavement clear of ice in the wheel tracks. Inspection of the plinth boxes on this bridge ramp revealed the cause of the short circuit. An apparent buildup of heat within the plinth box had melted the insulation on the cables, thus allowing bare wires to come in contact. The damaged wires (No. 6 (5.2 mm)) were replaced with No. 4 (6.0-mm) wires, and heat was restored to the bridge section. An inspection of all plinth boxes followed, and a decision was made to ventilate all plinth

Figure 11. 9th-Street Interchange, Looking toward River.

Figure 12. 9th-Street Interchange, Looking Upstream.



boxes and separate the cables within the boxes to prevent further damage to the cables from excessive heat. All plinth boxes were opened and have remained open since that date with no further damage occurring. The cost to the Department for repair of the cables was approximately $5,000.

Heating the 9th-Street interchange on the probability of snow appears to be an advantage over other roadway heating systems. Such an approach does not require "catch-up" time after a snowfall to clear a pavement but rather keeps the interchange clear as the snow falls. Figures 18 and 19 show the actual slab temperature compared to the modified slab temperature as computed by the master controller for the period January 1, 1977, to April 16, 1977. The average modified slab temperature is slightly lower than the average actual slab temperature throughout this period because the heating system is based on the probability rather than the actual occurrence of bad weather. In Figures 18 and 19, any average modified slab temperature above 10°C (50°F) is recorded as 13°C (55°F).

A slab set point of 3°C (38°F) was adjudged to be the temperature at which, under normal conditions, the master controller should call for more heat. This allows for a time lag in which the slab may begin to heat as snow and ice conditions approach. The set point was adjusted to as high as 5°C (41°F) by the operator when threatening conditions prevailed.

TABLE 2. MONTHLY WEATHER SUMMARIES

	DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL
High Temperature	18° C	6° C	24° C	28° C	30° C
Low Temperature	-17° C	-25° C	-15° C	-6° C	1° C
Average Temperature	1° C	-7° C	3° C	11° C	16° C
Largest Snowfall/Date	23 mm/12-29-76	198 mm/1-9, 10-77	10 mm/2-19, 20-77	3 mm/3-22-77	20 mm/4-5, 6-77
Greatest Accumulation/Date	25 mm/12-29-76	229 mm/1-11-77	51 mm/2-3-77	Trace/3-22-77	Trace/4-6-77
Total Snowfall	28 mm	498 mm	20 mm	3 mm	20 mm

Note: 1 in. = 25.4 mm; $T_C = (T_F - 32)/1.8$.

Figure 13. Average Temperature Versus Time (January and February).

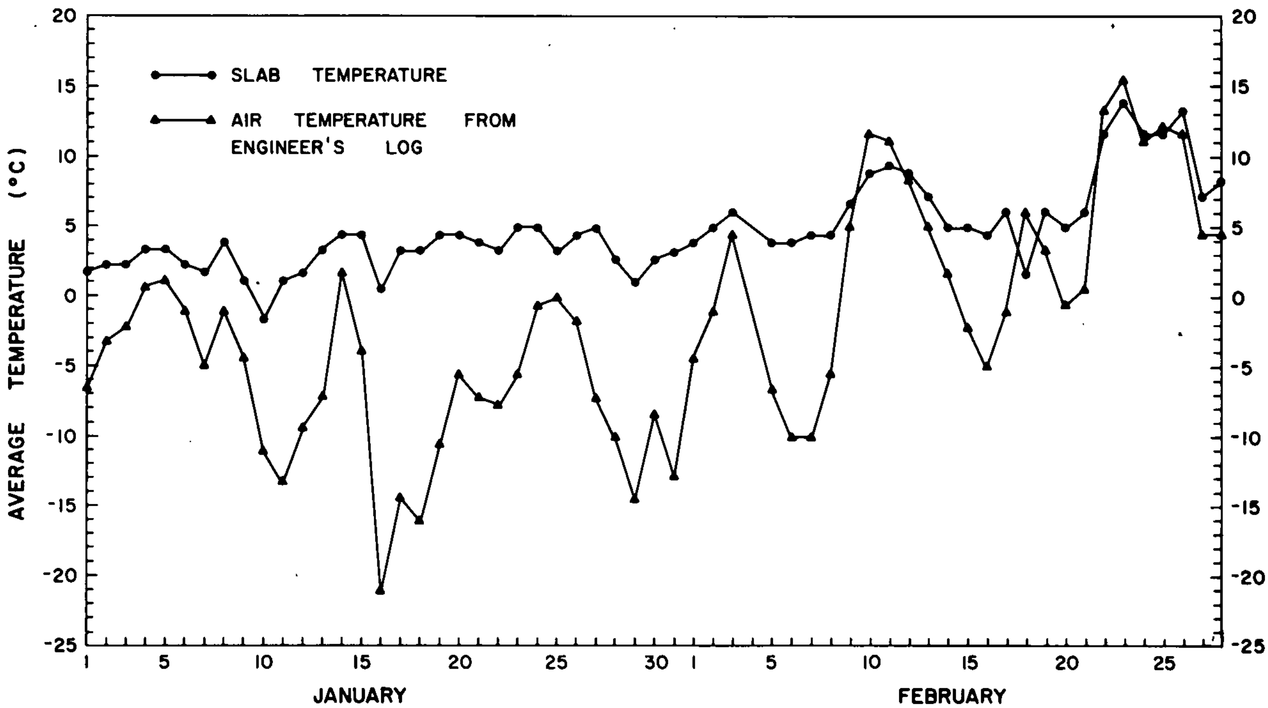


Figure 14. Average Temperature Versus Time (March and April).

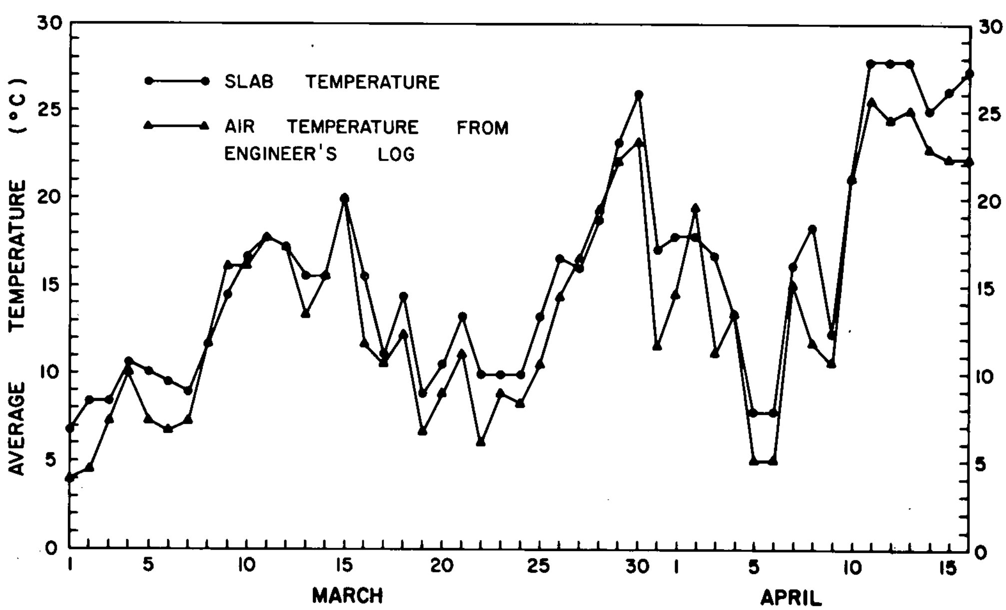


Figure 15. Heated Pavement (January 14, 1977).

Figure 16. Non-Heated Pavement (January 14, 1977).

Although compensation is made by the signal modifiers for rapidly changing weather conditions, the voltage-raise timer must also be adjusted as is the slab set point. Care was exercised in adjusting both the slab set point and the voltage-raise timer as a sudden increase in the voltage could damage the cables or thermally shock the concrete.

It must be noted that the above conditions apply to "automatic operation". The operator may adjust the voltage regulator manually as he deems necessary.

The power usage and costs for the heating system are listed in Table 3. The cost for heating the interchange from December 9, 1976, through April 16, 1977, was \$8.50 per m^2 (\$0.79 per square foot) or \$1,075 per day. These costs do not include labor charges for operators who monitor the interchange 24 hours a day throughout the season. An agreement with the electrical subcontractor for maintenance of the system has been estimated to be \$50,000 per year.

The cost of operating the heating system is dependent on several factors. The weather greatly determines the power required to heat the pavement. January of 1977 had the lowest average temperature for any month dating back to 1872. The 498 mm (19.6 inches) of snow made it the snowiest January since 1918 for the Louisville area. Manual settings of the signal modifiers and the slab set point may also affect the amount of heat input to the slab. The voltage-raise timers affect the power demand by controlling the time allowed the voltage regulator for increasing or decreasing the heat input to the slab. The opinion of the operator, in judging weather conditions and the probability of snow or ice, determines the settings for these instruments.

Some time after April 16, 1977, a longitudinal crack approximately 94 m (310 feet) in length was noted in Ramp 1. Some transverse cracking in this ramp and in Ramp 3 was noted in the fall of 1977. The cracking appears to have had no effect on the integrity of the heating system to the present time.

On October 12, 1977, the heating system was turned on because of the forecast of cold temperatures and snow. It was shot off October 16, 1977. Resistance readings of the heating cables taken October 27-30, 1977,

Figure 17. Aerial View of the 9th-Street Interchange on February 2, 1978, Showing the Distinct Difference between Heated and Non-Heated Sections.

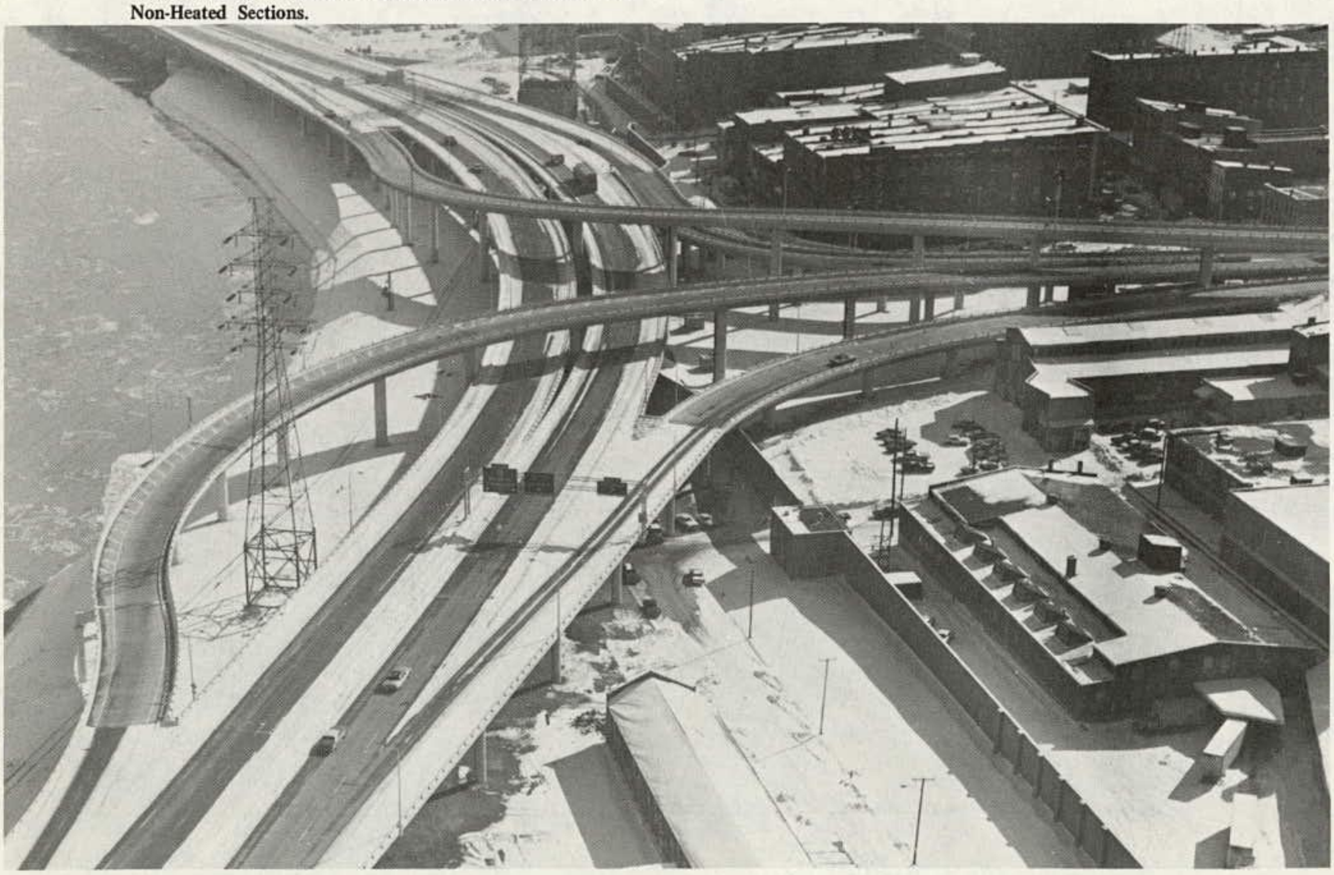


Figure 18. Average Temperature Versus Time (January and February).

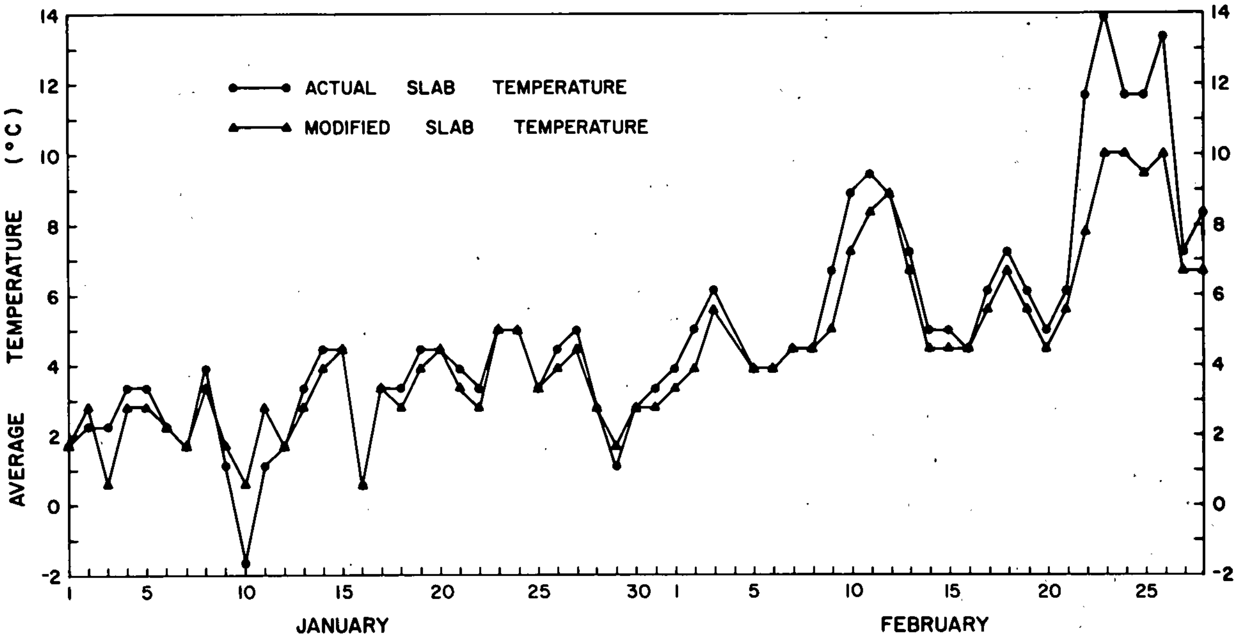


Figure 19. Average Temperature Versus Time (March and April).

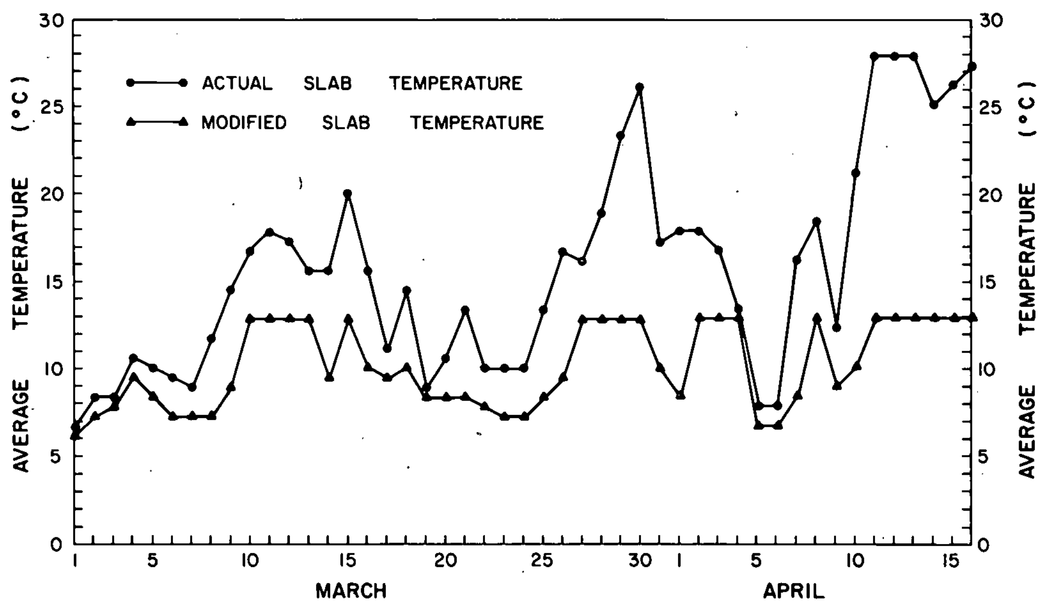


TABLE 3. POWER USAGE AND COSTS

PERIOD	NUMBER OF DAYS	KWH	AVERAGE KWH/DAY	COST	AVERAGE COST/DAY
12-9-76 - 1-10-77	32	2,011,200	62,850	$50,765.62	$1,586.43
1-11-77 - 2-8-77	29	2,505,600	86,400	63,484.30	2,189.11
2-9-77 - 3-10-77	30	648,000	21,600	16,618.09	553.94
3-11-77 - 4-8-77	29	230,400	7,945	5,952.84	205.27
4-9-77 - 5-10-77[a]	8	28,800	3,600	797.36	99.67
12-9-76 - 4-16-77	128	5,424,000	42,375	137,618.21	1,075.14

[a]Heating system turned off 4-16-77; billing cycle through 5-10-77.

showed a decrease, in some instances, attributed to the presence of moisture. On November 1, 1977, the system was turned on to dry the cables; this was earlier than anticipated. The system was kept on thereafter.

On November 25, 1977, Loadcenter 1-A was tripped by the ground-fault interrupter. To restore power, four breakers in three panels of Loadcenter 1-A had to be opened. Upon checking the records, these circuits were found to have low resistances. The cables in these circuits are in the pavement section of Ramp 1. Although the cables from these breakers are adjacent to each other in sections of the pavement, neighboring cables have kept the pavement clear of any snow or ice accumulation (102 mm (4 inches) recorded November 27, 1977) during the first snowstorms of the winter season.

The heating system at the 9th-Street interchange has proven functional; but no economic justification has been attempted. There are no data pertaining to conventional snow removal costs in the Louisville area or to actual maintenance costs of the heating system. Future research efforts will include the monitoring of deck temperatures at various depths and the establishment of definite operational settings for the logic system of master controller.

References

1. Roy Jorgensen and Associates, *Non-Chemical Methods of Snow and Ice Control on Highway Structures,* National Cooperative Highway Research Program, Report 4, Highway Research Board, 1964.
2. Havens, J. H., *Heating the 9th-Street Interchange, Louisville, Kentucky,* Division of Research, Kentucky Department of Transportation, September 1974.

Acknowledgement

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Geothermal Heating of Bridge Decks

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The capability of gravity operated heat pipes to couple geothermal energy to a bridge deck for snow and ice control has been investigated experimentally. A 1.8 x 4.9m (6 x 16 ft.) section of a concrete bridge deck was equipped with 15 heat pipes located on 15 cm (6 in.) centers, 5 cm (2 in.) below the deck surface. The site was heavily instrumented to allow quantitative comparison of the performance of the heated deck, unheated deck and adjacent roadway. One of the major objectives of the project was to provide performance characteristics on the heat pipes for simulation studies. This required additional instrumentation in the deck and in the ground. The power provided by the heat pipes was inadequate to melt the snow as fast as it fell during the most severe storms; however, throughout the 1977-78 winter the surface of the heated portion of the deck was always in better condition than the adjacent roadway. A total of 1.0 x 10^9 joules (9.5 x 10^5 Btu) was delivered to the deck by each pipe at an average rate of 125 w/m^2 (40 Btu/hr-ft.^{2}) during the winter season. It was concluded that heat pipes are an effective means of snow and ice control on bridge decks which should be considered for high risk locations.

Gaugler first introduced the heat pipe in 1944 but it was the reintroduction of the concept by Trefethin (1) in 1962 that stimulated its initial development. Heat pipes have proven to be extremely simple and efficient devices for transferring thermal energy and are therefore used in a wide and growing number of applications. In 1970 Bienert, Pravda, et al. (2) proposed the use of gravity operated heat pipes to transfer low grade energy from the ground beneath runways and highway structures to the surface in order to reduce or possibly prevent their icing.

This idea has been tested by placing gravity operated heat pipes in a small concrete slab at the Fairbank Highway Research Station in McLean, VA (3, 4) and in a 366 m (1200 ft.) long interchange ramp in Oak Hill, WV (5). The purpose of this paper is to report on the preliminary results of the first heat pipe system installed in an elevated highway structure. The overall objective of the project was to generate an empirical data base on the in situ performance of a gravity operated heat pipe system for use in the development of a numerical model to aid in design of these systems.

The design, fabrication, and installation of the heat pipes as well as the instrumentation of the complete system has been described in detail in reference 6. A brief summary is included here to facilitate the interpretation of the experimental data.

Figure 1 depicts a gravity operated heat pipe installed in the bridge deck. The heat pipes are 24.4 m (80 ft.) long and were fabricated from seamless, cold rolled, low carbon steel tubing with an outside diameter of 2.54 cm (1 in.) and a 0.32 cm (1/8 in.) wall thickness. These tubes were evacuated and filled with 0.2 kg (0.45 lbm) of ammonia which is also the condensable fluid that was used in the other two demonstration projects. Over the temperature range that the heat pipes are exposed to, part of the ammonia resides as a liquid in a pool at the bottom of the tube while the remaining ammonia is in the vapor phase filling the rest of the tube. Anytime the deck temperature falls below the temperature of the ground in contact with a heat pipe, the vapor in the deck section condenses and flows towards the bottom of the tube. At the same time, energy is conducted from the ground to the colder heat pipe where it evaporates part of the liquid ammonia. The spring in the evaporator section is used to enhance the area that is wetted by returning condensate. The heat pipe is essentially an isothermal device since the energy is transferred in the form of latent heat of evaporation instead of sensible heat. It is therefore ideally suited for this application where low grade energy is extracted from the ground. Besides its apparent constructional simplicity, this device is self regulating, should have a long lifetime, and could possibly be incorporated as part of the rebar structure.

Figure 2 presents an overview of the experimental site which is a concrete bridge over Sybille Creek, located on State Highway No. 34 in southeastern Wyoming. Twelve standard heat pipes of the type depicted in Figure 1, along with three short electric heat pipes were installed a small section of the bridge deck. Temperature controllers were used to maintain the electrically heated pipes at the same temperature as one of the standard ground heat pipes. The amount of power transferred by the conventional heat pipes was then inferred from a measurement of the electrical power delivered to

Figure 1. Gravity operated heat pipe.

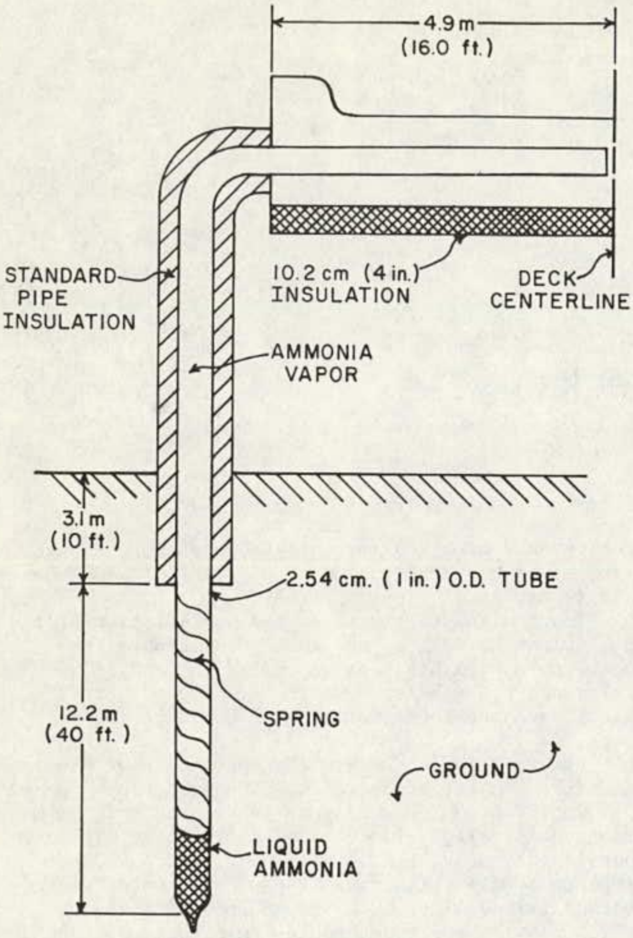
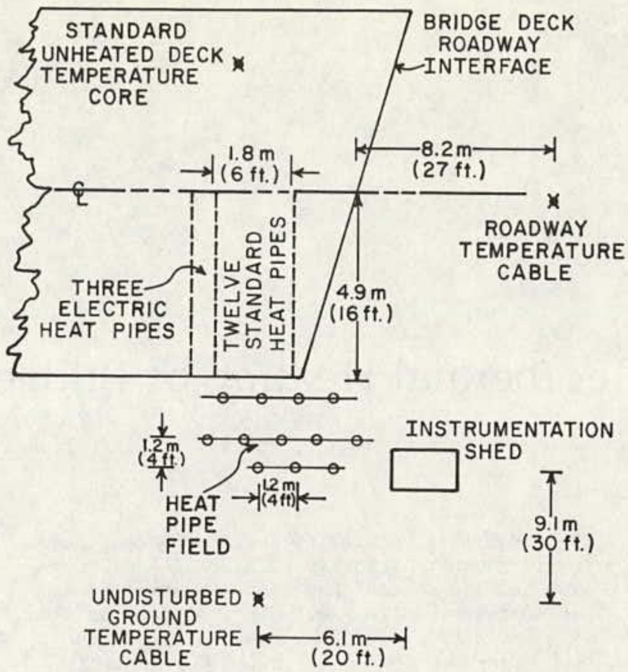
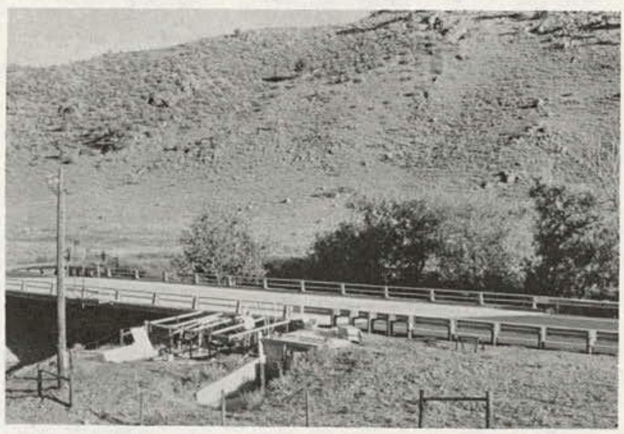


Figure 2. Experimental heat pipe site.





the electric pipes.

Experimental Results

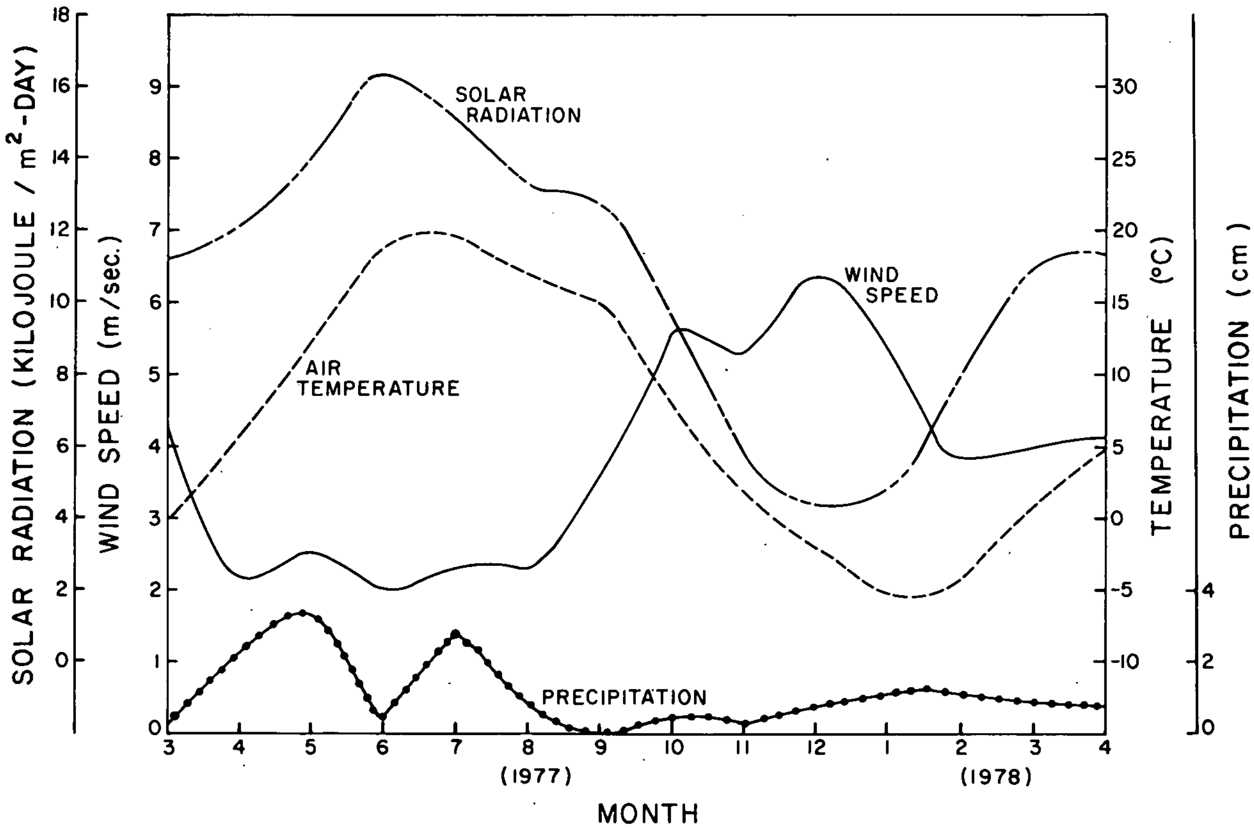
Environmental Data. The environmental parameters that influence the temperature response of a bridge deck were measured at the site and are summarized in Figure 3. This figure presents the monthly average air temperature, solar radiation, wind speed, and precipitation, and indicates that the test site, which is at an elevation of 1817 m (5960 ft.), would present a quite severe test of the gravity operated heat pipe system. The mean ambient temperature is only 6.7°C (44°F). Winter essentially begins in October and can last well into May. Based on this information alone, it could be anticipated that the heat pipes may be completely dormant for only five months of the year.

January was the most forbidding month during the winter. The monthly average air temperature dropped to -5.3°C (22.5°F), the average wind speed climbed to 5.5 m/sec (12.3 mph) and 2.7 cm (1.1 in) water equivalent of snow fell. The degree-days below freezing, which is obtained by integrating the portion of the temperature versus time curve that fell below the freeze line, was 83 degree Centigrade-days for this month. The lowest temperature observed during the winter of 1977-1978 was -26°C (-15°F) on December 9, 1977.

Surface Data. Figure 4 denotes the percentage of the time that the heat pipes operated during each month and also contrasts the monthly average upper surface temperature of the unheated deck with the section that contained the heat pipes. This figure indicates that the heat pipes began to operate in September and did not become completely dormant until June. The heat pipes caused the average surface temperatures of the two sections to begin to differ in October. The temperature difference reached a maximum in January of 5.6°C (10°F) when the heat pipes were operating 89 percent of the time. This breaks down to 79 percent during the day and 100 percent of each night which was found to be a typical day-night ratio (0.8) during the other severe winter months. In terms of monthly averages, the standard deck is shown to be frozen from November through February while the monthly average temperature of the heated deck stays above 1°C (34°F).

The surface conditions of the two deck sections were also recorded through time-lapse photography during the daylight hours (6). An analysis of the

Figure 3. Monthly average environmental parameters.



photographic record from October 10, 1977, through March 15, 1978, indicates that the standard bridge deck was snow packed for 331 hours while the heat pipe section had snow on it approximately 1/3 of this time. A section was considered to be snow covered any time it was covered with more than just very small patches of snow. For instance, the heat pipe section shown on the time-lapse photo taken on November 20, 1977 (Figure 5) was considered to be snow covered even though it had melted away approximately 50 percent of its snow cover. January, the most severe month, accounted for 136 of the 331 hours that the standard bridge deck was snow packed while the heated section was considered to be covered 1/2 of this time.

Mechanical snow removal through the action of traffic and plowing were both minimal at this site. There were many instances under these conditions where the heat pipes did not keep up in terms of melting all the snow as it fell, but were able to maintain the deck surface above freezing. In these cases, the snow formed an insulating layer over a wet surface. The temperature data indicates that the surface temperature of the standard deck was below freezing 242 of the 331 hours that it was snow packed while the heat pipe portion was covered and frozen (failed) only 36 hours.

Since the time-lapse camera was only functional during daylight hours, snowfall or snowpack information during the night was inferred from early morning or late afternoon photographic data. The standard unheated bridge deck entered a night clear and was found the next morning snow packed 21 times, as compared to 14 for the heated deck. Of these events, the standard surface was below freezing 234 hours with the heated deck below freezing only 92 hours.

Unfortunately, not enough of the adjacent roadway fell in the field of view of the camera to allow a determination of its surface conditions during the day. Other visual information is available which implies that the surface condition of the heat pipe section was always better than the roadway in terms of snow pack. This contention is also supported by Table I which tabulates the freezing characteristic of the air, roadway, heat pipe section and the standard bridge section for a 62 day period from January 24 to March 28, 1978. The comparison is limited to only 62 days due to a failure of the surface temperature transducer in the roadway. Table 1 indicates that the standard deck and the adjacent roadway were below freezing approximately the same amount of time while the heat pipe section was frozen only 1/3 of this time. In terms of the severity of the freezes, the heat pipe section had only 1/10 the degree-days below freezing that the standard deck amassed as compared to 3/4 for the roadway. This table also implies that the average temperature during a freeze was -0.9°C (30°F) for the heated bridge section, -2.5°C (27.5°F) for the roadway and -2.9°C (26.8°F) for the standard bridge section. There is no significant difference in the number of freeze-thaw cycles between the heated and unheated sections of the bridge due to the fact that the heat pipe section can hover around freezing. This allows the heat pipe section to go through several short freeze-thaw cycles while the unheated section may only experience a single hard freeze.

Figure 4. Monthly average surface temperatures and percentage of the time the heat pipes are operational.

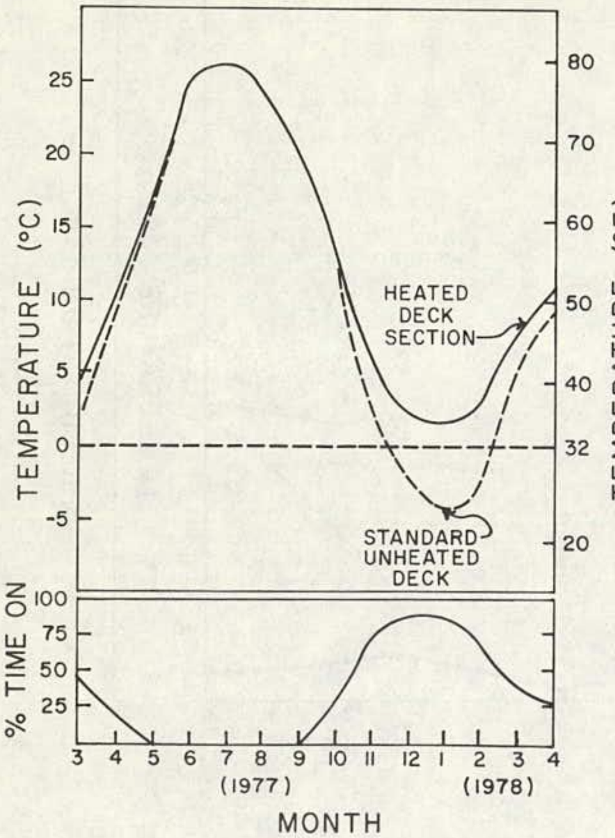
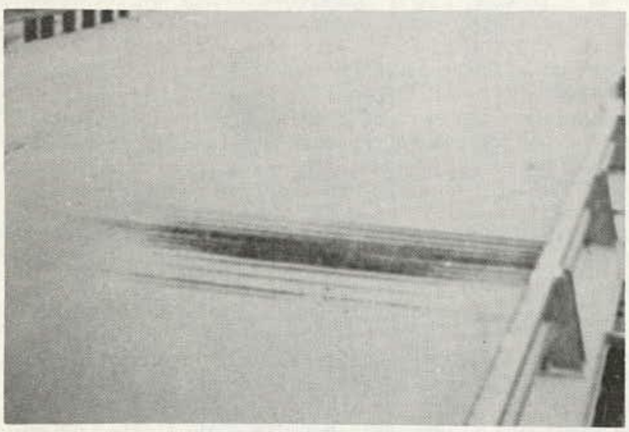


Figure 5. Time-lapse photograph showing entire bridge deck snow packed.



The above discussion reviewed the long term performance of the heat pipe system with respect to surface conditions. Actual thermal response of the heated and unheated bridge deck surfaces and the roadway surface to a typical snow event is shown in Figure 6. The hourly averages for the solar radiation, wind speed, air temperature and the three surface temperatures are plotted for March 14, and March 15, 1978 in Figure 6a. Snowfall began at 10

Table 1. Relative freezing characteristics January 24 through March 28, 1978.

Temperature Transducer	No. of Days Frozen	(°C)-Days Below Freezing	No. of Freeze-Thaw Cycles
Ambient Air	34	121	52
Standard Deck Surface	29	84	28
Roadway Surface	27	62	45
Heated Deck Surface	9	8	25

p.m. on March 14 and continued until 6 a.m. the next morning. A total accumulation of 10.2 cm (4 in.) was observed. The heat pipes came on approximately one hour after the snow began to fall and operated until 10 a.m. the following morning. The heated portion of the deck and the roadway hovered above the freezing point while the standard deck was frozen during the snow event. Figure 6b shows the surface condition at 9 a.m. following the snow fall and indicates that the heat pipe section was totally clear whereas the standard deck and roadway were completely snow packed. Time lapse photographs show that this condition existed at sunrise. The day of March 15 was a clear sunny day as evidenced by the solar radiation data. Since the roadway was not frozen, its snow cover rapidly melted when exposed to the solar radiation following which its surface temperature rose rapidly as did the temperature of the heat pipe section. The difference in the peak temperatures of these two surfaces is due to the variation in their solar absorptivities. The low solar absorbtivity of snow and the fact that the deck was frozen combined in causing the standard deck to remain snow covered. These surface conditions may be contrasted in Figure 6c which was taken around noon. This is a graphic example of preferential icing which is quite common at this site. The standard deck does not clear until the next day. Note that the air temperature drops to -9°C (16°F) the following night which caused both the heat pipe section and the roadway section to drop below freezing. The heat pipes began to operate during this evening at 8 p.m. and ran until 11 a.m. the next day, March 16. This is typical diurnal cycling that is experienced by the heat pipes and emphasizes the importance of solar radiation on the clear deck during daylight hours since the major source of energy may change from geothermal to solar.

This diurnal cycling may be seen in Figure 6a where the periods that the heat pipes were off and on are indicated. Note that in spite of the fact that there is no active control system the pipes tend to operate when additional energy is required. Energy is, in a sense, wasted when the pipes are operating throughout a clear cold night. They do however shut off when the solar heating during the day raises the deck surface temperature above the temperature of the earth at depth. On the other hand if the surface is snow packed it is at or below freezing and the heat pipes function as long

Figure 6. Hourly average surface temperatures and environmental data for the two day period March 14 through March 15, 1978.

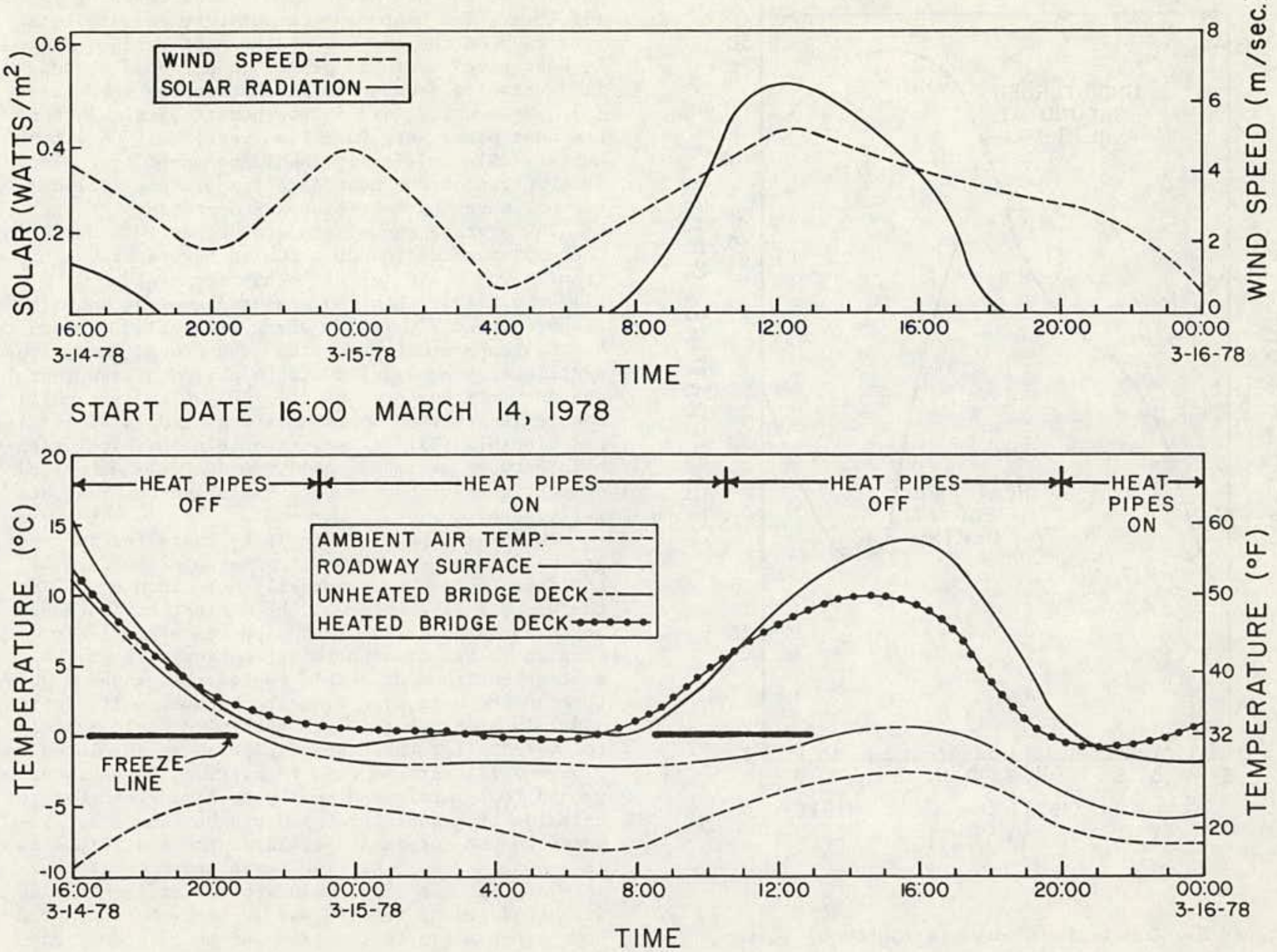


Figure 6a. Surface response and environmental data.

Figure 6b. Surface conditions at 9:00 a.m. - March 15, 1978.

Figure 6c. Surface conditions at noon - March 15, 1978.

Figure 7. Monthly average ground temperature at depth.

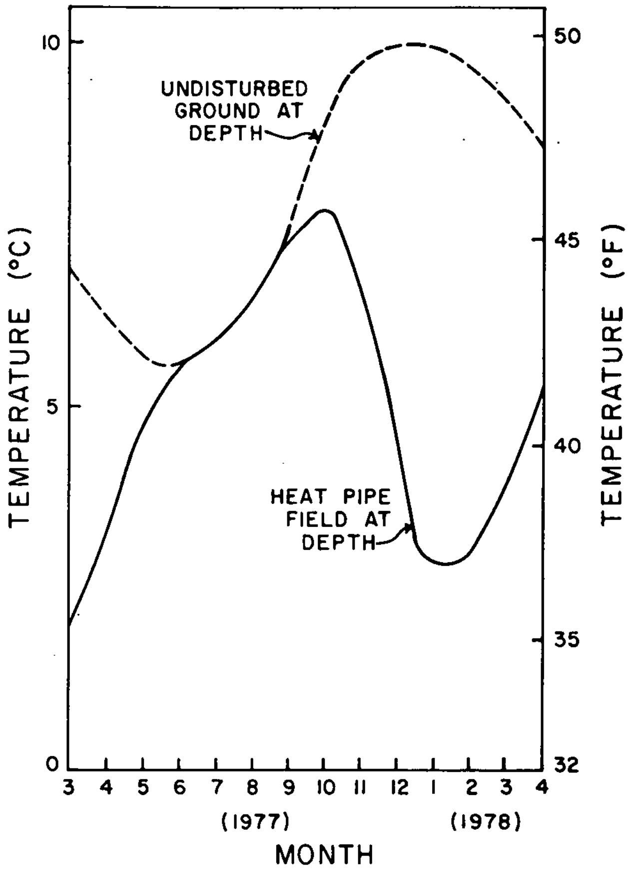
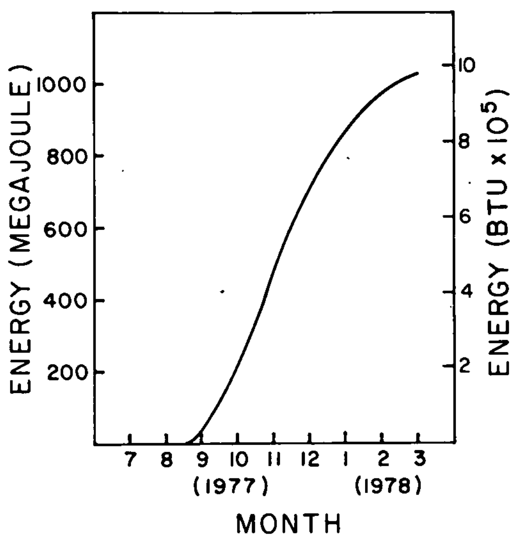


Figure 8. Cumulative energy extracted by a single heat pipe.



as the earth temperature remains above freezing.

Ground Response Data. During the period that the heat pipes are operating, energy is being removed from the earth which leads to a depression of the earth temperature in the neighborhood of the heat pipe. This effect is shown graphically in Figure 7 which compares the monthly average temperature of the undistrubed ground and the temperature on the surface of the heat pipe at a common depth of 16.2m (53 ft.). The heat pipe temperature measurements were made on the surface of the center pipe. Normally heat pipes would be placed in a fanned shaped configuration to reduce the interaction between pipes (5). However, to aid in the numerical simulation, the heat pipes were installed vertically on 4 foot centers (Figure 2). It should be noted that monthly averages of the heat pipe temperature includes periods when the heat pipe was operating.

The average annual temperature at this depth in the undisturbed ground, which is saturated weathered granite was 8.3°C (47°F). This temperature is slightly higher than the measured average annual air temperature 6.7°C (44°F) which is usually assumed to be the temperature at depth. The ground temperature oscillates sinusoidally with a period of one year and an amplitude of 2.6°C (4.7°F) which is significantly larger than amplitudes measured in Minnesota and Virginia (3). A very favorable phase relationship between maximum ground temperatures and periods of peak energy requirements was shown to exist at this depth.

The heat pipes were intially installed in the ground in October, 1976 with the upper portion of the pipe, which was eventually bent into place in the deck, left exposed to the ambient environment until January, 1977. Each pipe was effectively coupled to the atmosphere attempting to heat the ambient environment. This caused the ground temperature in the heat pipe field to be abnormally depressed. In spite of this the heat pipe field rapidly recovered after the exposed pipes were insulated and Figure 7 illustrates this recovery. The undisturbed ground temperature and heat pipe field temperature coincide from June through September which corresponds to the dorminant period of the heat pipes as is shown in Figure 4. The temperature on the surface of the heat pipe begins to depart from the undisturbed ground temperature in September when the heat pipes begin to function and the slope of the heat pipe temperature acutally becomes negative in October. A continuous and nearly constant rate of decrease in the local earth temperature near the heat pipes occurs until February, when recovery is initiated in spite of the fact the heat pipes are operational 70 percent of the time. The heat pipe field appears to repeat the rapid recovery observed at the end of the previous winter. There is no indication that there is a permanent depression in the heat pipe field temperature.

Energy Data. The electric heat pipe control system did not function properly until the end of the winter. The data that was obtained implies that the heat pipe has a constant conductance between the evaporator and condenser section when operating. Using a value of conductance derived from the data a number of performance parameters were calculated.

Figure 8 presents the cumulative energy extracted by each conventional heat pipe for the 1977-78 winter. The heat pipes were operational intermittently 8 months of the year during which time they delivered an average 125 w/m^2 (40 Btu/hr-ft.^{2}) to the deck. It may be seen that over the three month period from October through December the energy delivered per month reached a fairly constant rate of 218 megajoules (2.1 x 10^5Btu). Throughout this period the heat pipes were operating, that is transferring energy to the deck, 63 percent of the time and the average power delivered to the deck when the pipes were operating was 173 w/m^2 (59.6 Btu/hr-ft.^{2}). Referring to Figure 8 it may be seen that the maximum monthly average rate of energy extraction occurred during November, 1977 when 194 w/m^2 (61.4 Btu/hr-ft.^{2}) were provided.

As the winter progressed into January and February, which exhibit the most severe environmental parameters (Figure 3), the rate of energy extraction from the earth decreased despite the fact that the temperature of the undisturbed ground was near maximum and the amount of time that the pipes were operating increased to 80 percent. This is due to the fact that the temperature of the earth proximate to the heat pipes had dropped to an average value on the order of 2°C (35.6°F). This localized temperature decrease leading to a decline in the rate of energy extraction is the major factor in heat pipe system design since it influences both the energy and power which can be extracted.

All of the power values quoted are based on averages using that portion of the time during which the heat pipes were operating, regardless of power output, for an entire month. The values are not indicative of the peak power delivered by the heat pipes and due to the fact that the electric heat pipe controllers were not functional during the early part of the winter no estimate of the peak power can be given.

The monthly average values of power quoted above may be contrasted with short term averages obtained for the two periods, indicated on Figure 6a, when the heat pipes were operating. A maximum power of 134 w/m^2 (43 Btu/hr-ft.^{2}) and an average power of 100 w/m^2 (32 Btu/hr-ft.^{2}) were obtained.

Conclusions

The heat pipes have been in operation for 18 months and performance of the system has been continuously monitored for more than one year. A data base has been generated which can be used to refine computer simulations of the thermal response of gravity operated heat pipe systems.

The experimental program has demonstrated that a geothermal heat pipe system can be effective in prevention of preferential icing between a bridge deck and the adjacent roadway. All of the data taken indicates that preferential icing of the heated portion of the deck relative to the roadway was completely eliminated. In fact, for purposes of eliminating preferential icing the capacity of the heating system could be significantly reduced, for example, by increasing the center to center pipe spacing in the deck in future installations.

Throughout the 1977-78 winter season there were only 36 daylight hours when the surface of the concrete deck over the heat pipes was both snow packed and below freezing. The system did not provide sufficient power to keep the surface completely clear during the most severe snow storms, however, there were no situations where the accumulation of snow on the heat pipe field exceeded 5cm (2 in.) in depth. The total energy provided by the system during the winter was almost 50 times greater than required for a Class III design in Cheyenne, WY (7). Since no estimate of the peak power provided can be made it is not possible to assess the system in this respect.

One of the dominant questions which persists with respect to design of large scale heat pipe systems is whether the earth temperature in the heat pipe field becomes permanently depressed. In spite of the fact that the field recovered very rapidly during the spring for this project, the relatively small field employed precludes any general conclusions in this regard.

The portion of the deck incorporating the heat pipes was intentionally selected adjacent to an abutment wall in order that the pipes would be located in a relatively rigid portion of the deck. In addition this location allowed the pipes to enter the deck through its side below the curbing. These design features minimized the problems associated with incorporating the pipes in the deck during the construction of the bridge and also minimized mechanical problems associated such as flexure and differential expansion. These as well as a variety of other significant problems associated with the design of a practical deck heating system were not addressed in this study.

The project has demonstrated that geothermal heating of bridge decks can be an effective means of ameliorating adverse environmental effects on elevated structures even in severe environments. Future studies addressed at decreasing system costs and practical problems associated with large scale system integration are warranted.

Acknowledgements

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Physical Alternatives to Chemicals for Highway Deicing

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The objectives of this 3-year study are to use data from the literature supplemented by analyses to identify and evaluate physical alternatives for deicing highways and to improve the evaluation of the most promising alternatives with the results from laboratory and field tests so that implementable and developable alternatives will be determined. A total of 21 alternative physical deicing concepts were identified, evaluated and screened for their potential usefulness in the three steps necessary for successful deicing. These steps are: (1) the prevention, reduction or elimination of the bond to the pavement; (2) the breaking and dislodgment of the snow/ice; and (3) the removal of the snow/ice from the traveled way. Up to five alternative physical deicing concepts have been identified for potential laboratory testing. The first set of recommended laboratory tests will investigate the effectiveness of various ice cutting edges.

With very few exceptions it is the current practice of highway (and street) departments to use chloride salts, either with or without plowing, for the removal of snow and ice from the traveled way. In most climates the chloride salts are effective and they are relatively inexpensive. However, the chloride salts may cause vehicles to rust, increase portland cement concrete scaling, lead to pavement spalling from corroded reinforcing, damage steel bridge structures and pollute water resources.

What is now needed is a practical and economical physical system of highway deicing that will substitute for or minimize the use of sodium chloride, calcium chloride, or other chemicals and will not adversely affect the physical integrity and utility of the highway itself or adversely affect the environment.

Overview of Study

Midwest Research Institute is currently conducting a study of physical systems of highway deicing for the Federal Highway Administration entitled, "Physical Alternatives to Chemicals for Highway Deicing." The objectives of this 3-year study are twofold: to use data from the literature supplemented by analyses to identify and evaluate physical alternatives for deicing highways; and to improve the evaluation of the most promising alternatives with the results from laboratory and field tests so that implementable alternatives and developable alternatives will be determined.

In the study we will identify, analyze, evaluate, and test physical alternatives to chemicals for highway deicing. Although the scope of alternatives includes those which prevent the accumulation of snow and ice on the pavement, the majority of effort is being devoted to alternatives which remove snow/ice from the pavement. Also, we are including unpacked snow in the scope and in the evaluations, although the emphasis is on traffic packed snow and ice.

The pavement related alternatives are being limited to those which involve surface treatments, surface dressings, or at the most, a thin overlay. In a similar vein we are restricting our attention to alternatives which are compatible with current highway structures, cross-sections, pavement designs, and principal pavement materials. Alternatives which use fossil fuels to melt the snow and ice are not being considered. However, consideration has been given to the employment of heat or fuels derived from waste or obtained from inexhaustible sources.

The scope also includes evaluations of processes which have previously been discarded as a sole mechanism for deicing, but may be satisfactory for one step in a multistep procedure.

The study is composed of three steps which are oriented towards the development of a highway deicing method which is feasible and practical, and does not employ either chemicals or extensive consumption of exhaustable fuels for melting. In the first step, the pertinent literature was reviewed and critically evaluated. Also within this step the concepts for ice and snow removal methods were developed, evaluated and initially screened. The screening process employed a ranking scheme to select the most promising concepts for laboratory testing.

Laboratory tests are being employed in the second step to supply needed information. These test results will be combined with the information assembled in the first step to arrive at improved evaluations and the selection of the most promising concept(s) for field testing.

The field tests will be conducted in the third step. The field test results will be added to previously assembled information and used to make final evaluations. The final evaluations will provide the basis for recommendations of deicing methods which can be implemented with current technology, as well as those methods which have desirable characteristics but require development of improved technology or equipment.

A parallel investigation was undertaken to examine the possibilities of using waste materials and/or inexhaustable energy sources for application to highway deicing. The evaluations of waste utilizations and inexhaustable energy sources were carried through the first step or conceptual evaluation.

The balance of this paper presents a summary of the results from the first step of the study--the development of concepts for physical alternatives to chemicals for highway deicing. This summary is basically taken from the first interim report to FHWA on the study (1).

Literature Searches

Extensive literature searches, using both computerized and manual data bases, were employed to locate information pertinent to the conceptualization and evaluation of physical alternatives to chemicals for highway deicing. The areas searched included:

1. Previously tested or suggested methods for release and removal of snow and ice.
2. The scientific and technological fundamentals associated with potential methods.
3. The potential for usable energy from waste materials and inexhaustible sources.
4. The technology and economics of current ice and snow removal practices.

The pertinent literature found was reviewed, evaluated, and used for the development of physical concepts. A description is given in a recent report (1) of the literature sources used; the literature search areas investigated that are directly related to ice and snow removal, and the literature searches conducted in other areas to provide supplemental information for evaluating the physical concepts.

In order to conceive and evaluate physical alternatives for deicing, it was necessary to know and employ the mechanical properties of ice and snow. An overview of the solid state physics of ice, including a discussion of the related material characteristics of ice and snow, and a summary of their engineering properties, was prepared and is presented in a recent report (1).

Physical Concepts Investigated

The selection of concepts for physical deicing methods was guided by a consideration of the four separate steps which generally are required of any successful and desirable method to produce a bare pavement. The first step is the removal of low strength snow. Low strength snow is still granular or has metamorphosed into a solid with very low strength. This material can be removed with plows or blowers--a process that is part of current technology and practice. This technology and practice has been examined for improvements; however, it is usually successful except in extreme climates or storms. (In some cases, say with freezing rain, there may be no low strength snow to remove.)

With the low strength snow removed the remaining material on the pavement will usually have significant mechanical strength. The remaining material may be solid ice in the case of freezing rain, but more frequently it is a lower density ice formed from snow or sleet by traffic action and natural agents of metamorphosis. The removal of the packed snow/ice is the major problem and, for examination of concepts it is convenient to consider separately the three steps that will usually be required. They are: (1) prevent, reduce, or eliminate the bond to the pavement; (2) break and dislodge the snow/ice; and (3) remove the snow/ice from the traveled way. These latter three steps were examined separately with the recognition that compatibility is required for the complete deicing process. Also, it was recognized that some candidate methods and equipment may perform more than one step.

A total of 21 alternative physical deicing concepts were identified and evaluated for their potential usefulness in the latter three steps. The concepts examined for the debonding step included release agents, various methods of delivering energy to provide temporary melting at the pavement-ice interface, and agents to reduce the ice strength at the pavement surface. The concepts investigated for the breaking and dislodging step included tire loads, mechanical devices producing steady or impact stresses, jets of liquid or gas, mechanical waves (ultrasonics), variable electromagnetic fields, gas introduction at the pavement surface, and a heated plow blade. The concepts examined for the removal step included blade action, plow blades with jets, sweeper action, rotary action, and traffic action.

Evaluation Considerations

Information extracted from the literature, mathematical and descriptive models and engineering judgment were used to help evaluate the candidate deicing processes for their technical and operational feasibility, and their economic and environmental acceptability. Seven models were developed during the study. These models pertain to: (1) the mechanical properties of snow; (2) a winter maintenance district; (3) temporary melting; (4) electromagnetic microwaves in the ice/snow-water-pavement system; (5) fracture in ice and snow; (6) mechanical waves in the ice-pavement system; and (7) heated snow plow blades. Additional details about the models developed appear in a recent report (1).

Major Findings

The major findings are presented under each of the three steps that are considered necessary for successful and desirable deicing. They are: (1) prevent, reduce or eliminate the bond to the pavement; (2) break and dislodge the ice/snow; and (3) remove the ice/snow fragments from the traveled way. These steps and the findings emphasize the deicing problem associated with the 7.5 cm (3.0 in.) or less of ice or snow next to the pavement that has acquired some mechanical strength. Current practice with plows and snow blowers can remove deposits above 7.5 cm (3.0 in.). Less attention is devoted to the deicing of unbonded, dry, granular precipitates that are typically associated with newly fallen snow, snow pellets, or sleet and hail.

There are also major findings concerning mechanical properties of snow and ice. These findings are presented with the steps where they are important.

Bond Prevention, Reduction or Elimination

The bond between ice/snow and the pavement is due to both intermolecular forces and to mechanical interlocking of asperities. Bond prevention, reduction, or elimination is necessary for ice and ultimately for frozen precipitates that acquire mechanical strength and a bond to the pavement through traffic action and natural metamorphic processes. The step is essential since the strength of the bond to the pavement is nearly equal to the ultimate strength in the ice/snow.

Concepts for bond prevention, reduction, or elimination fall into three categories: (1) bond prevention through the use of release agents on the pavement surface; (2) bond elimination through temporary melting at this ice/snow-pavement interface; and (3) bond reduction through strength reduction in the ice/snow at the pavement surface. The major findings of these three concepts are now summarized.

Release Agents. Release agents are used on the pavement surface to reduce the intermolecular forces between ice and pavement. Some mechanical interlocking may remain even with ideal release agents.

Some of the most definitive data in this area were developed in a project conducted by Ball Brothers Research Corporation for the Environmental Protection Agency. Their major procedures and findings are:

- Hydrophobicity is an important correlate of effectiveness. (It was the only major correlate used by Ball Brothers in their screening process for effectiveness.)
- Effective agents also need to be at least 10,000 Å (or one micron) thick to reduce the strong dipole forces between ice and pavement.
- Effective agents should have low water solubility.
- Adverse findings were that: the effective release agents reduce skid resistance, lane closures of 1 to 3 hr are required for curing, flammable solvents are released in current application procedures, and the coatings are largely worn off by 150,000 to 300,000 vehicle passages (1 to 2 months at the test sites).

The literature on tire-pavement interactions was searched for fundamentals related to this question. However, the data and relations found do not show if there is an irremediable connection between release agent effectiveness and reduced skid resistance.

The need exists for additional information about release agents before the final evaluation of them can be concluded. Most importantly, the available data do not confirm hydrophobicity as the only important correlate of agent effectiveness. Also, the tensile strengths of bonds are not available and the relations between texture and bond strengths are not quantified.

Since wear off is a problem for release agents it would be desirable to incorporate the agent in the pavement or some constituent of the pavement, and induce it to migrate to the surface as needed. In several fields of technology, there is extensive knowledge about the migration of gases, liquids, and solids in porous media. However, it does not appear possible to transfer this knowledge directly to the current problem for the purpose of making feasibility estimates.

Temporary Melting at the Ice/Snow-Pavement Interface. This concept envisions heat supplied for a very short time at the ice-pavement interface to temporarily melt a very thin layer of ice there. A melt thickness of two microns (0.00008 in.) would be sufficient to eliminate intermolecular forces between ice and pavement. The procedure for breaking and dislodging would then be performed before the melt refroze. The findings here are based on results from a computerized model.

Ideally, if the heat supplied went exclusively into melting ice, a six micron melt could be provided in a 2.7 m (9-ft) lane width at 24 km/hr (15 mph) with a heating power input of slightly over 45 hp. At -1°C (30°F) with accountability for heat losses, the power requirement jumps to 95 hp and the melt refreezes completely in 0.7 sec.

If the ice-pavement temperature at the interface falls below freezing the power requirements increase primarily because of additional losses of heat into the adjacent pavement and ice. (There is some increase even in the idealized case.) The power requirements and the time until refreezing are listed in Table 1.

Table 1. Heat power requirements and times until refrozen (power for one lane at 24 km/hr (15 mph)

Initial Temperature (°C)	Melt Thickness (microns)	Heat Power (hp)	Time Until Refrozen (sec)
-1	6.67	95	0.710
-10	14.41	505	0.205
-20	10.19	817	0.115
-30	10.23	1,124	0.100

Table 1 is based on efficient geometric and temporal introduction of heat. The heat is introduced within 1 mm of the interface and at each point on the lane in a time period of 1/40 to 1/20 of a sec. Heat introduced more than 1 mm from the interface is for the most part ineffective in producing temporary melt, however, it does delay refreezing.

The temporary melting process is unaffected by boundaries and ambient conditions remote from the ice-pavement interface. However, these boundaries and ambient conditions are important for their influence on the initial temperature of the interface.

The large power requirements at subfreezing temperatures reduces the desirability of temporary melting for bond reduction. The process may be applicable in special cases where the temperature is usually not far below freezing. Temporary melting may also be feasible if breaking and dislodging can be accomplished with just a fraction of the ice debonded.

Energy Delivery for Temporary Melting. Five methods for delivering the energy for temporary melting have been considered. They are: electric current in the surface course (fixed site), induced current in the surface coarse, induced current at the interface, microwave electromagnetic radiation, and visual range electromagnetic radiation.

Electric Current in the Surface Course at Fixed Sites. This could be supplied by direct connections to a power source. A very thin top layer of a conductive asphalt would introduce heat there. However, there would be long heat paths from the asphalt to exposed aggregate surfaces. Consequently a long heat input period would be required to cause melting at the aggregate surface. Heat losses into the pavement would thereby be increased.

Induced Currents in the Surface Course. This could be used for temporary melting. This process could be employed from a moving vehicle. An electrical conductive surface course is again required and the undesirable aspects of the heat introduction geometrics apply. In addition the processing vehicle must carry an engine generator set, a high frequency generator and a coil or coils to induce the eddy currents in the pavement. The power efficiency measured from engine output shaft to induced currents in the pavement is estimated as 28%. This estimate does not include effects of losses in undesired eddy currents that may be introduced in surface water or in wet snow.

Induced Currents at the Ice-Pavement Interface. This possibility is suggested by reports that conductivity at the interface is higher than in embedded ice volumes. The conductivity of the interface region was not quantified in the literature.

This process remains as a possibility but it is suspect because a layer of higher than normal electrical conductivity in ice at the interface is likely to be very thin and it may not compete effectively with other eddy current circuits where heating is not desired.

Microwave Electromagnetic Radiation. This radiation can be used to deliver energy for temporary melting. It would be ideal to have the radiation pass through the ice/snow without absorption but be absorbed in the very top of the pavement. Ice has very low absorptivity in the 10^9 to 10^{10} Hertz frequency range used for industrial heating processes. Unfortunately, pavements also have relatively low absorptivity in this frequency range. To prevent absorption at great depths a reflector of chopped wire or metallized film is required under the pavement surface. The chopped wire would reflect about 90% of the radiation incident on it; the metallized film could reflect almost 100%. A microwave cavity would be required on the applicator to receive and return the power reflected from the reflector and from the air-ice and ice-pavement interfaces.

A plane wave model was used to solve for the destination of microwave power directed downward in an 8.0 cm (3.0 in.) thick ice layer. The microwave reflector, 1.0 cm (0.4 in.) under the surface of the asphaltic concrete, was located as close to the surface as permitted by large aggregate. Results are shown in Table 2.

The water layer, with high absorption, still receives only a fraction of 1% of the power delivered because the layer is very thin. Of the power absorbed in the pavement, only that absorbed in the top 0.1 cm (0.04 in.) would be effective for temporary melting. Consequently, of the power delivered only 2.18 to 2.43% would be effective for temporary melting. If the reflector were 100% effective 4.0 to 5.0% of the power delivered would be effective for temporary melting.

Table 2. Microwave power destinations (reflector 90% efficient)

Power	Condition: No Water at Interface	Condition: 1.0 Micron of Water at Interface
Fraction reflected to applicator	0.81	0.89
Fraction delivered	0.19	0.11
Destinations of delivered power (by percent)	**No Water at Interface**	**1.0 Micron of Water at Interface**
Lost through reflector	65.3%	58.7%
Absorbed in ice	10.4%	19.2%
Absorbed in water	0%	0.3%
Absorbed in 1 cm pavement (above reflector)	24.3%	21.8%

The efficiency from engine output shaft to microwaves in the ice is about 25%. Consequently, overall efficiency will be low and in the range of 0.5% to 1.25%. A very small part of the losses are in microwave leakage at the applicator-ice interface where they constitute a potential health hazard which can be minimized through applicator design.

Visual Range Electromagnetic Radiation. This radiation can be used to deliver energy to the pavement surface. This concept has been attempted in the field by others, but with little success because radiation from heat lamps and flood lamps is strongly absorbed by the ice/snow. However, there is a narrow frequency range near the wavelength of 0.40 microns (e.g., ultraviolet to violet), where both ice and water are very transparent; only 0.25% of the power would be absorbed in passage through 8 cm (3.0 in.) of ice. Part of the radition incident on the pavement would be reflected but the radiation entering the pavement would be absorbed in a desirably small depth.

With 8 cm (3.0 in.) of compacted snow the radiation would be scattered by tne numerous ice-air interfaces and the effective path length to the pavement would increase. Some radiation would be lost by side scattering and some would be returned to the applicator where it should be reflected by highly polished silvered surfaces.

Mercury vapor lights are a potential source for the radiation. Their efficiency is about 10%. When other losses are considered the overall efficiency from an engine output shaft to power delivered for temporary melting is estimated as about 4%.

Bond Reduction by Electrolysis. Two concepts employing electrolysis were considered. First, electrolysis was considered as a supplement to temporary melting to form gas bubbles in the water film and reduce the work subsequently required to dislodge the ice. However, calculations indicate that the work required to break the water seal would be acceptably small without the introduction of bubbles.

In the second concept electrolysis in solid ice would be used to reduce its strength at the interface. There are suggestions that ion numbers and ion mobility are above average at the ice-pavement interface. The ions are also associated with imperfections in the ice crystal structure. The number and local concentrations of ions might be increased and the strength of ice at the interface might be affected by electrolysis in the solid. Data to evaluate this possibility were not found.

Gases Released at the Ice-Pavement Interface. Gases released at the ice-pavement interface could reduce ice strength in either of two ways. Firstly, the presence of bubble inclusions would reduce ice strength. However, this process would not be effective on the major problem of compacted snow. Also, chemical reactions to produce the gas generally will be fastest at high temperatures and in the presence of water rather than ice.

The strength of ice at the interface can also be affected by the introduction of gases that combine with the water molecule to add imperfections in the crystal structure of ice. Hydrogen fluoride (HF) is known to have a pronounced effect. A concentration of 0.03 ppm in ice reduces its yield strength almost 50%. HF can be formed by reacting fluorspar (CaF_2) with weak acids and should readily enter and migrate through ice because it is small and has a structure similar to that of water. Ammonia (NH_3) also affects the mechanical properties of ice, but it is reported to toughen ice.

The influences of HF and NH_3 on ice properties are reported in the literature. It is possible, but not certain, that these effects can be used to weaken the ice at the ice/snow-pavement interface.

Hydrogen fluoride is a highly corrosive and dangerous gas. It is considered here as an agent only because it would be formed on the pavement by chemical reaction and initial estimates of the quantities released appear acceptable. However, the gas-producing chemical reaction, like most reactions, will tend to proceed most rapidly at high temperatures, when the gas is not needed or wanted.

Combined Processes for Bond Prevention, Reduction or Elimination. Combined processes are considered for potential synergistic effects and for the possibility that equipment, materials, or procedures might economically or conveniently provide two processes. The possibility of synergestic effects cannot be excluded but no basis for expecting them has been established. A candidate combination is: release agents with strength influencing impurities. In this case the impurity might be formed from a carrier in the agent. The practical problem with combinations is the likelihood of requiring more numerous materials, equipments and costs.

Breaking and Dislodging of the Ice/Snow Layer

Freshly fallen dry snow has insignificant mechanical strength. Metamorphic processes and particularly the compression due to traffic action increase both the bonds between ice particles and the density of the snow. Its mechanical strength and elastic modulus increase rapidly when the density rises above 0.4 g/cc.

Compacted snow and ice respond to low strain rates by creeping but behave like brittle solids and can be fractured by rapidly imposed strains. Most methods for breaking and dislodging will impose high strain rates that cause the brittle material response.

The method used should form large rather than small fragments, since energy must be supplied for each unit area of fracture surface formed.

Fractures propagate in a material when the elastic energy in the vicinity of the crack tip is sufficient. Solutions of fracture models using ice as a material show that fractures can be driven in ice by wedge-like tools. However, the elastic strain is insufficient to open the crack enough to admit even a very sharp narrow angle wedge. As a result a practical wedge will crush ice/snow at the sides of the fracture or will induce subsiduary fractures running to the side.

For breaking and dislodging, consideration has been given to: stresses under a tire footprint, mechanical devices, jets of gas or liquids, mechanical waves, variable electromagnetic fields, gas formation by electrolysis at the interface, and a heated plow blade.

Stresses Under a Tire Footprint. Tire footprints impose both compressive and shear stresses, with the compressive stresses dominating. The stresses are neither uniform or concentrated. The distribution is probably not condusive to inducing fractures.

It appears that the conditions when tires are most likely to fracture snow occur when the snow is still yielding under the footprint and the tire-snow interface is channel shaped rather than flat.

Mechanical Devices Producing Steady or Impact Stresses. A variety of mechanical devices have been developed and used to break and dislodge snow and ice from road surfaces. The devices can be classified into six general types: (1) blade or displacement plows; (2) rotary plows; (3) pure blowers; (4) power brooms; (5) combined devices; and (6) specialized devices for removing compacted snow and ice. Almost all of the mechanical devices now in common use are based on long established practices, and fundamental research on the units appears to be somewhat neglected.

The most commonly used device is the blade or displacement plow. These units are the least expensive devices to operate and generally are the most satisfactory for highway use. In practice, these plows are generally operated in contact with the pavement. They are particularly effective at producing a nearly bare pavement when the ice-pavement bond has been partially weakened or broken. The devices will leave a thin ice/snow layer if the bond has not been reduced.

Rotary plows are designed to clear roads of deep snow falls. Most states have found that rotary plows are too expensive and slow for general snow removal. However, they are effective at removing age-hardened snow that has built up to considerable height. Rotary plows generally cannot produce a bare pavement and will leave a several inch layer of ice/snow especially, if the bond has not been reduced.

Pure blowers are not considered well suited for highway deicing because of the noise level produced by their power units.

Power brooms cannot break or dislodge hard packed snow or ice from the pavement. They can, however, be used to pick up small amounts (less than 5.1 to 7.6 cm [2 to 3 in.]) of loose snow that has been broken from the pavement by some other mechanism.

A number of combined devices have been built and used with varying degrees of success by state highway agencies to fill specific needs. Quantitative performance data are generally unavailable.

A variety of units have been built with some form of rolling, pressure cutting edges. A common problem has been damage to the pavement or to the edges. This configuration has potential merit especially if it can be used where the pavement-ice bond has been reduced or eliminated.

Jets of Gas or Liquids. Gas jets have been tested in conjunction with a standard plow blade. A hand pushed model was successful; a full scale device was not. The difference in results may be due to differences in the orifice geometrics and to the sensitivity to forward speed which this type of device should have.

A hot gas jet has been tested to drill or cut ice. The jet merely melts the ice, which makes it a very expensive process. (By contrast, high temperature jets used on rock cause successive fractures due to extreme temperature gradients.)

Continuous Liquid Jets. Water jets driven by very high pressures 210 to 630 kgs/cm^2 (3,000 to 9,000 psi) are used to cut ice. However, power requirements are high. As an example, a 200 hp pump could supply water to make vertical cuts in 7.5 cm (3.0 in.) ice on 15.0 cm (6.0 in.) centers in one lane with an advance rate of 0.73 m/min (2.4 ft/min). It is not certain if the ice would break favorably when the jet reached the interface. Also, the pavement would be jeopardized by a jet with this erosive capability.

Percussive or Cavitating Liquid Jets. Liquid jets with modulated streams have been used to fracture rock. These liquid jets break up into small packets that impact a target surface individually for enhanced erosion and fracturing effects. The individual impacts set up mechanical waves that cause fractures in rock that is subject to fracture in tension.

These jets may be capable of fracturing previously debonded ice. Compacted snow would have a greater tendency to yield and erode. The jets would jeopardize pavement surfaces and leave residual water to freeze.

Unsteady Gas Dynamics. An internal combustion compressor that employed gas dynamics rather than moving parts was known to be under development in the 1940's and 1950's. References to this device were sought but not located. It may be applicable in situations where a high capacity compressor is needed for only a few hours per year.

Unsteady gas dynamics may also be used to provide impact forces on the ice/snow for breaking and dislodging. These forces could be applied by gas dynamics preferably with shock or detonation waves. No data were found that deal with shaping of shock or detonation waves to provide a point or line impact on a target surface. A related field, explosive shaped charges, provides some guidance although it deals with much more energetic products of detonation than are needed or wanted here.

Mechanical Waves (Ultrasonics). Mechanical waves can be used to induce fractures at a weakened bond between ice and pavement. It is necessary that the waves produce tension stresses at the interface with sufficient magnitude and for a sufficient time to propagate the fracture.

With the exception of vacuum devices all means for applying forces to the exposed upper surface of the ice/snow deliver compressive stresses so that a compression wave is generated at the ice/snow surface and travels down through the ice to the pavement where 50 to 85% of the wave amplitude is reflected back as a compression wave. When the upward traveling compression wave arrives at the ice/snow upper surface it will be almost totally reflected as a tension wave if the surface is free. The tension wave will travel down to the ice-pavement interface and, while being partly reflected, will place the ice there in tension.

Desirable characteristics for an effective wave driving force can be estimated together with the energy and power delivered. The force magnitude should produce the maximum attainable compressive stress $\sigma_{c_{max}}$ in the ice/snow. The force should be applied for the time Δt_{max} which ends when the compressive reflection begins to arrive at the surface. This time depends on the ice/snow properties and the ice/snow depth. The energy and power delivered also depend on the ice/snow properties and depth. The characteristics are shown in Table 3.

Table 3. Characteristics of maximum wave input

Material	Max Time Δt_{max} Per in. of Depth (sec/in.)	$\sigma_{c_{max}}$ (psi)	Energy Per Unit Area Per Unit Thickness (lb in.)/(in^2 in.)	Horsepower Per Unit Thickness to Process One Lane at 15 mph (24 km/hr) (hp/in.)
Glaze Ice	15.0×10^{-6}	710	0.8993	3.88
Compacted Snow	32.1×10^{-6}	140	0.2613	1.13

One pound = 0.4536 kilograms; one inch = 2.5400 centimeters.

The energy and power are for a single wave delivered and do not include losses associated with delivery of force to the ice/snow.

The energy and the power requirements are seen to be reasonable. The time interval requirements, Δt_{max}, are small (in the ultrasonic range). To estimate success in fracturing the bond requires a model that includes the bond strength and other boundary conditions.

Variable Electromagnetic Fields. Electromagnetic forming is one of several high energy (high rate) forming processes presently in use. A force is imposed between a work coil and an electrically conductive work piece (in this case the ice/snow) when condensors are discharged through the work coil. With typical work coil geometrics a downward force would be imposed on the ice/snow under the coil. Modified work coils might produce some horizontal force components in the ice/snow and associated tension stresses.

Fairly expensive equipment is required for the process and in most present applications the repeat rate is not sufficiently high for deicing. The efficiency and utility of this process needs to be evaluated using a model that includes the rather low electrical conductivity of ice/snow.

Gas Formation by Electrolysis at the Ice/Snow to Pavement Interface. The use of electrolysis as a bond reducing mechanism was discussed previously. Here, however, the process is conceived for dislodging and breaking, and is a follow on to temporary melting or other bond reducing processes. An estimate of energy and power requirements was based on producing sufficient gas to uniformly lift a thin layer of ice/snow 0.63 cm (0.25 in.). For this requirement, 775 hp is needed to produce the necessary gas by electrolysis to process one lane at 24 km/hr (15 mph).

Heated Plow Blade. It has been suggested by others that a heated plow blade would be effective for removing ice/snow close to the pavement. It is known that only very small amounts of ice or snow can be melted with energy expenditures that are within reason. Consequently, this concept was configured to make best use of the energy for melting. Just the leading edge of the plow blade is heated with the idea that a small indentation melted there repeatedly in the ice would continuously initiate the fracture close to the pavement surface and prevent the blade from riding up on an inclined surface of ice.

An elementary model was solved and showed that the plow blade tip should be at 770°C (1400°F) in order to process at 31 cm/sec (1.0 ft/sec). The model assumed water adjacent to the blade tip. However, the required blade temperature would cause boiling, which would reduce the heat transfer rate. It is concluded that a heated blade tip cannot be used to control and favorably direct the fractures in ice/snow produced by the blade assembly.

Removal of the Ice/Snow From the Traveled Way

This step is assumed to deal most frequently with the removal of fragments of ice or compacted snow loose on the pavement. This is the most likely situation after applying a successful process for breaking and dislodging. The density of the fragments will lie in the range of 0.4 to 0.9 g/cc (25 to 56 lb/ft^3). The size of the fragments will depend on the thickness of the ice/snow layer and characteristics of the process for breaking and dislodging. The thickness dimension should not exceed 7.5 cm (3 in.) and will probably be less in most cases.

Conceivably, the removal step could be performed by the same vehicle that produces the breaking and dislodging. There may be a penalty if removal is delayed since vehicle passages may rebond some material to the pavement.

The majority of the processes and equipment in use are not intended to remove even loose fragments down to bare pavement. This section discusses the major findings concerning the various concepts available for the removal of the ice/snow from the traveled way: blade action, plow blades with jets, sweeper action, rotary blowers, and traffic action.

Blade Action. The displacement plow is one of the least expensive devices to operate and is generally the most satisfactory for the removal of ice and snow from the highway when the ice-pavement bond has been weakened or broken by some other process. The fundamental mechanisms of snow plowing are understood qualitatively, but they are not sufficiently developed theoretically to allow a snow plow blade to be designed from fundamental considerations.

Improvements in the performance of some existing blades might be made by coating the blades with a material to reduce the frictional forces between the blade surface and the snow. For the material coating to be effective, it would need to be inexpensive and durable.

Plow Blade with Air Jets. The current practice of operating blades in contact with the pavement can produce pavement damage. To eliminate this destructive contact, it has been suggested that blades be designed to deliver a low pressure, high volume air stream to lift the snow off the pavement so that the plow blade mold board can push it away.

A small scale model test of a plow blade with air jets has been conducted by others and the results showed promise. Based upon these results, full scale tests were conducted. The full size prototype did not clear the pavement any better than a standard plow blade and, in fact, left wet, uncompacted snow of the same depth as the height of the blade above the pavement. The reason for the prototype failure may be the processing rates or the characteristics of the ice/snow. In any event, the contrasting results need investigation before definite conclusions can be drawn from the data.

The effectiveness of this removal concept for snow with some mechanical strength depends upon the availability of an exposed edge of the ice/snow layer. The process is vulnerable to the loss of an exposed edge, so that the removal would cease when a particularly strong or well bonded snow layer was encountered. The jet or some part of the jet span is also vulnerable to blockage.

Sweeper Action. Two types of sweepers have been considered for the removal of ice/snow: (1) conventional street sweepers; and (2) towed cylindrical sweepers. Both devices brush the pavement to get the debris (or, in this case, the broken and dislodged ice/snow) moving in the direction of the brush and then flick it towards the collection point.

Standard street sweepers have been adapted from their intended uses into devices for the removal of snow and ice that has been loosened from the pavement surface. The adaptations replace the soft fiber or synthetic brushes with stiff high tensile steel wire. The converted sweepers have generally been found to be undesirable for all except minor snow removal tasks such as removing snow and ice blocking catch basin inlets.

Towed cylindrical sweepers are used primarily by airports to clear runways of snow and ice. The sweepers cannot remove snow that has become packed by traffic action. However, they can remove hard packed snow or ice that has been debonded, dislodged and broken from the pavement and also small amounts, 5 to 7.5 cm (2 to 3 in.), of light snow. Some carryover of snow almost always occurs. The carryover must be removed before it becomes packed by traffic action.

Because of these limitations, the cylindrical sweepers are used as a part of a system. Usually the sweeper is towed by a plow that can reduce the depth of the snow to a level that the sweeper can handle. However, there is a lack of useful data about the sweeper dynamics that tends to cause misinterpretations of the sweepers potential as a snow removal device. It may be useful as a component that, with moderate damage to the pavement, can displace ice/snow that has been dislodged and broken.

Rotary Blowers. There are two basic types of rotary blowers currently in use: single element and two element snowblowers. Hybrid snowblowers utilize components of both snowblowing and non-snowblowing devices.

Rotary blowers have very limited uses; but they are indispensable in removing very large depths of high density snow. The units have several unsatisfactory characteristics: they must leave a 5 to 10 cm (2 to 4 in.) layer of snow next to the pavement surface to prevent damage to the blower and pavement; they operate at very slow forward speeds; and they are very expensive compared to conventional snow plows.

Only simple estimates concerning the power and energy requirements of rotary blowers exist. However, these estimates are difficult to use because of the lack of data needed to evaluate some of the variables.

Traffic Action. No qualitative or quantitative information could be found in the literature on the removal of ice/snow from the traveled way through traffic action. Engineering judgment combined with personal observations can be used to gain insight into the possible effects of traffic action. Some beneficial effects of traffic action on the ice/snow removal process can be anticipated for the cases of dry snow, slush and possibly broken and dislodged snow fragments on the pavement.

Combined Processes for Bond Reduction, Breaking and Dislodging and Removal of Ice/Snow from the Traveled Way. Combined processes are considered for potential beneficial effects. To illustrate this point, there are two kinds of beneficial interactions that can arise from combinations: (1) the breaking and dislodging process may accelerate or position the ice/snow fragments favorably for the removal step; and (2) it may be possible and economical to perform two steps with the same device. An example of a device designed to accomplish two steps--breaking/dislodging and removing--is the plow blade.

More examples of possible combinations will be considered through the project.

Rating and Screening of Concepts

A rating system was developed to compare the different physical alternatives to chemicals for highway deicing and to select the most feasible alternatives--those with the greatest potential for successful use under typical highway conditions--for further evaluation. The objective of the rating system was to rate each physical alternative in five categories: (1) technical feasibility; (2) operational feasibility--maintenance operations; (3) operational feasibility--traffic operations and safety; (4) economic acceptability; and (5) environmental acceptability. Each concept was rated not only according to each of these categories, but also on an overall basis using the average of the category ratings. The rating system has been initially applied to evaluate and compare the various concepts for physical alternatives in the three steps necessary for successful and desirable deicing. No attempt was made to combine the rating results for the individual steps into a rating for the overall deicing process.

The results of the application of the rating system are described in a recent report (1) and are summarized in Table 4. Two types of ratings are given in Table 4 for each category and overall rating: unadjusted and adjusted ratings. The unadjusted ratings are the best available measure of the feasibility/acceptability of a concept, based on the rating for each category factor and its relative importance. The adjusted ratings are always less than or equal to their respective unadjusted ratings, and incorporate the reliability of the factor ratings. The difference between the unadjusted and adjusted ratings is a measure of the uncertainty in the category and overall rating that may be eliminated through further analysis and experimentation. The ratings given in Table 4 will be modified as the project moves into the laboratory and field evaluation phases.

Table 4. Initial rating of concepts for alternative physical deicing methods

Concept	Category Rating Values[a/]											
	Technical Feasibility		Operational Feasibility Maintenance Operations		Operational Feasibility Traffic Operations and Safety		Economic Acceptability		Environmental Acceptability		Overall Rating Values[a/] (Average)	
Step 1: Prevention, Reduction, or Elimination of Adhesive Bond of Ice to Pavement												
* Release agents on pavement surface	9.25	7.45	6.82	3.90	3.67	1.78	6.16	0.66	8.40	3.40	6.86	3.44
* Gas releasing agents in surface course	8.00	4.23	6.56	3.16	4.33	0.43	7.48	0.76	7.60	1.48	6.79	2.01
* Release agents in surface course	6.50	3.88	6.21	3.16	3.67	0.56	6.16	0.75	7.20	2.64	5.95	2.20
* Temporary melting at interface with energy delivered by:												
. Current in surface course	3.75	2.38	5.57	1.82	4.33	0.83	4.78	0.48	8.80	0.88	5.45	1.28
. Visual range electromagnetic radiation	3.50	1.05	5.24	0.52	4.33	0.43	4.15	0.41	6.80	0.68	4.80	0.62
. Microwave electromagnetic radiation	3.00	0.96	4.92	0.57	4.33	0.43	3.73	0.37	6.80	0.68	4.56	0.60
. Induced current at the interface	2.50	0.48	4.68	0.48	4.33	0.43	4.90	0.49	6.40	0.64	4.56	0.50
. Induced current in surface course	2.50	0.58	4.68	0.48	4.33	0.43	4.69	0.61	6.40	0.64	4.52	0.55
* Gas formation at the interface by electrolysis	2.50	0.26	6.10	0.63	4.33	0.43	4.99	0.50	8.80	0.88	5.34	0.54
Step 2: Breaking and Dislodging of the Ice/Snow Layer												
* Mechanical devices producing steady or impact stresses	8.25	6.08	5.71	2.61	5.56	3.69	4.46	0.44	7.20	0.72	6.24	2.71
* Mechanical waves (ultrasonic)	5.25	1.13	5.86	0.65	7.74	0.77	2.67	0.26	6.80	0.68	5.66	0.70
* Stresses under tire passages	5.50	1.05	5.23	1.65	3.54	1.58	7.07	0.72	6.00	2.40	5.47	1.48
* Variable electromagnetic fields	3.00	0.36	4.63	0.47	6.76	0.67	1.78	0.18	6.80	0.68	4.59	0.47
* Gas formations by electrolysis at ice/snow-to-pavement interface	2.75	0.43	4.35	0.45	6.76	0.67	1.78	0.18	6.80	0.68	4.49	0.48
* Heated plow blades	3.00	0.36	3.91	0.53	5.74	0.91	1.89	0.21	6.80	0.68	4.27	0.54
* Jets of gas or liquids driven by compressors and pumps	3.00	0.46	3.48	0.43	4.30	0.87	2.68	0.27	5.60	0.56	3.81	0.52
Step 3: Removal of the Ice/Snow From the Traveled Way												
* Blade action	9.50	9.05	5.58	4.20	5.18	3.99	6.7[illegible]	5.52	7.60	7.60	6.92	6.07
* Rotary blowers	7.50	7.25	5.25	4.59	5.74	4.59	3.48	2.48	7.20	7.20	5.83	5.22
* Plow blades with air jets	7.00	3.30	5.58	0.87	4.64	0.93	4.89	0.49	6.20	0.62	5.66	1.24
* Traffic action	5.50	1.05	5.23	1.65	3.54	1.58	7.07	0.72	6.00	2.40	5.47	1.48
* Sweeper action	5.50	4.70	4.92	3.44	5.56	3.34	4.53	1.50	6.40	4.12	5.38	3.42

a/ Numbers appearing in left column of each category are unadjusted rating values; adjusted rating values appear in right column of each category.

All category and overall ratings for each concept are on a scale of 0 to 10, where 10 is the most desirable rating and 0 is the least desirable rating. The range of the overall ratings in Table 4 goes from 3.81 (unadjusted) and 0.52 (adjusted) for the concept of jets of gas or liquids driven by compressors and pumps up to 6.92 (unadjusted) and 6.07 (adjusted) for the concept of blade action.

The alternatives listed in Table 4 are rank ordered within each of the three individual steps in the ice and snow control process according to decreasing values of the unadjusted overall rating. A decision, based upon engineering judgment, was made to divide the 21 concepts according to the magnitude of the unadjusted overall rating into three classes: 0.0 to 5.49, 5.50 to 5.99, and 6.00 to 10.00. A concept with an unadjusted overall rating value from 6.00 to 10.00 has a high potential as a physical alternative and is recommended for further investigation through laboratory testing and/or analytical studies. A value in the range of 5.50 to 5.99 means the concept has some merit as a physical alternative, but it also has some questionable features that might make it unacceptable. Those concepts receiving an unadjusted overall rating value between 5.50 and 5.99 are recommended for further investigation, but only after those with a value between 6.00 and 10.00 have been investigated and only if time and funds permit. Finally, an unadjusted overall rating value in the range 0.0 to 5.49 means the concept is unacceptable as a physical alternative at this time and will not be investigated further.

Most of the concepts initially considered for deicing have unadjusted overall rating values in the range of 0.0 to 5.49. The large number of low ratings is due to evaluations that cover several important aspects including: excessive power requirements, bulk and size of equipment required, low efficiency, high costs, safety, and potential damage to the environment, including the pavement. Four of the concepts have unadjusted overall rating values in the range of 5.50 to 5.99: release agents in the surface course, mechanical waves (ultrasonics), rotary blowers, and plow blades with air jets. These concepts are considered as candidates for potential improvement.

Four closely rated concepts are located in the upper class: release agents on the pavement surface, gas-releasing agents in the surface course, mechanical devices producing steady or impact stresses, and blade action. With some exceptions, these last concepts generally also have higher unadjusted category ratings compared with those category ratings for other concepts within the respective deicing steps. These four concepts have the most potential of all the concepts considered for physical alternatives to chemicals for deicing highways.

Direction of Laboratory Investigation

The direction of the laboratory investigation is being guided by the results of the rating and screening of the 21 concepts and by the interests of the FHWA. Up to five alternative physical deicing concepts have been selected for potential laboratory testing, depending upon time and funds. They are:

- Mechanical devices producing steady stresses.
- Release agents on the pavement surface.
- Mechanical devices producing impact stresses.
- Mechanical waves (ultrasonics).
- Ice strength-reducing agents in the surface course.

The last concept listed is mentioned for completeness only. It is unlikely that it will be tested in the laboratory investigation. However, the decision to further examine this concept will be made later in the study and will be based upon the results of an ongoing study of ice-adhesion. Blade action is another concept that received a high rating value. This concept was not included in the above list because it does not need further laboratory testing at this time.

The laboratory tests will be conducted in an evolutionary manner, starting with mechanical devices producing steady stresses. The first set of recommended laboratory experiments will deal with a single disc making multiple passes on three types of pavement specimens (smooth portland cement mortar, dense graded and open graded asphalt) with glare ice. Subsequent tests to be conducted will be based upon the findings of these first tests. Possible additional follow on tests of the first concept might involve:

- A single wobble disc.
- A single angled cutting edge.
- An array of discs.
- A simulation of a Minnesota ice crusher.
- The devices acting on compacted snow.

These and later tests will employ both dense and open graded asphalt pavement specimens.

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On Performance of a Two Stage Rotary Snow Blower

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We manufactured two types of augers, a screw and rake type auger and a ribbon screw type auger to further improve the performance of the two stage rotary snow blower that is now considered as the most effective remover in view of the diversified nature of snow in Japan. After installing each of them on a base machine actually used, we examined the performance characteristics while changing revolutions and snow nature. We also prepared two blowers (four-blade blower and five-blade blower) to examine their difference. The results of the test are summarized as follows: (1) 3-element ribbon screw type auger was superior to 2-element screw and rake type auger in general performance. (2) Snow removing performance considerably depends on the combination between blower and auger circumferential speed. Maximum snow removing capacity (t/h) is got at such a combination as the blower speed is low, while the auger speed is high in order to increase the capacity of snow gathering. Blower high speed is provided to get the distance of snow ejection. In this case, low auger speed produces better result. (3) The 4-blade blower was superior in performance to the 5-blade blower. This, however, depends on the volumetric capacity margin of the blower housing.

Circumstances of Snow Removal from Roads in Japan

Japan is world-famous for its heavy snowfall. As compared with other snowy countries in Europe and America, it is located in low latitudes lying from north to south. The nature of snow, therefore, is diverse because the weather condition varies from one region to another. In Japan, cold and snowy provinces account for 60% of the whole country where about one fourth of the total population live. It is, therefore, very important to provide proper policy to protect roads from snow and ice and to remove snow from roads to ensure smooth traffic in the winter season in such provinces for industrial promotion and stabilization of the people's livelihood.

Mechanization of snow removal from roads in Japan first started in 1945. In those days, however, only few machines were used and method was immature. As the demand for snow removal grew year after year, studies of methods, improvement of domestic machines, and proto-type manufacturing and research were gradually promoted. Thanks to the Japanese Government's financial aid started from 1957, various projects against snow have been actively promoted in snowy provinces. As a consequence, social and economic activities in the winter season have been remarkably progressed. However, we will not be fully satisfied until we attain social and economic activities in the same level throughout a year by constructing ALL WEATHERED ROADS in the entire area.

The nature of snow is various as it falls, and changes in complexity as it lies on the ground under influence of local weather and traffic conditions. Therefore, we must remove snow with the nature varying in fresh snow, lying snow, removed snow, and snowdrift under various road conditions requiring different methods, such as the road structure and traffic volume. So that many kinds of machines are necessary to cope with any circumstance conceivable.

Classification of Snow Removing Machines

Snow removing machines are various in their structure, applications, and sizes. They are categorized into four types below.

1. Snow plough
2. Rotary snow blower
3. Snow loader
4. Others

A snow plough is used to remove fresh snow with rapidity, a rotary snow blower to remove snow pushed aside to road shoulder as well as in air fields and railroads, and a snow loader to load snow to a dump truck in narrow roads. These machines have been continuously improved in structure and performance. Meanwhile, rapid expansion of traffic volume in recent years brings about a demand for high efficiency in snow removal. Large-sized high-speed snow removing machines (max. 800 HP class) have been developed to satisfy the demand. Also pressed snow removers to improve the removed snow quality and small-sized machines (100 HP class) for sidewalks have been developed and successfully utilized.

In Japan in such a background, the typical snow removing machine in use is a two-stage rotary snow blower with a 200 to 300 HP engine. It has only one engine and the snow removing mechanism is mechanically driven.

General Description of Test

Specifications of Test Machine

Model NR652S rotary snow blower was selected as the base machine for the test. The machine is driven by one engine and adopts 2-way system in which the vehicle is driven hydrostatically during snow removal operation requiring constant low speed and backing. During travelling, it is mechanically driven as general vehicles. The snow removing system consists of two stages; the auger and blower. Figure 1 shows the appearance of the test machine.

1. Model Rotary Snow Blower model NR652S
2. Performance

Max. snow removing capacity (based on JIS D6509 Test Code of Vehicles with Rotary Snow Blower)	1700 t/h
Max. snow removing width	2600 mm
Max. snow removing height	1800 mm

Snow ejection distance;

Speed range	1	2	3
Snow ejection distance (m)	18	27	35

Running speed;

For operation

Speed range	1	2	3
Forward & backward (Km/h)	0-5	0-10	0-17

For travelling

Speed range		1	2	3
Forward	(Km/h)	22	30	40
Backward	(Km/h)	0-5	0-10	0-17

Figure 1. Appearance of the test machine.

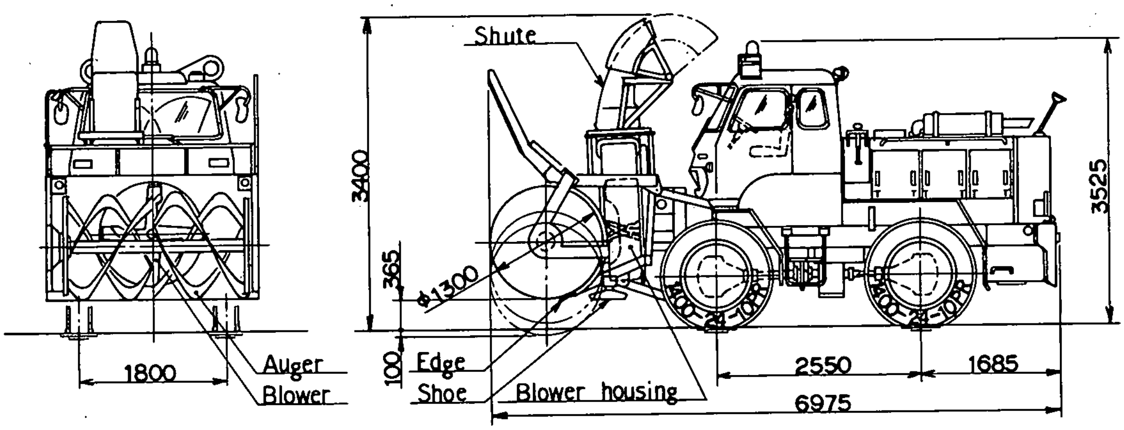
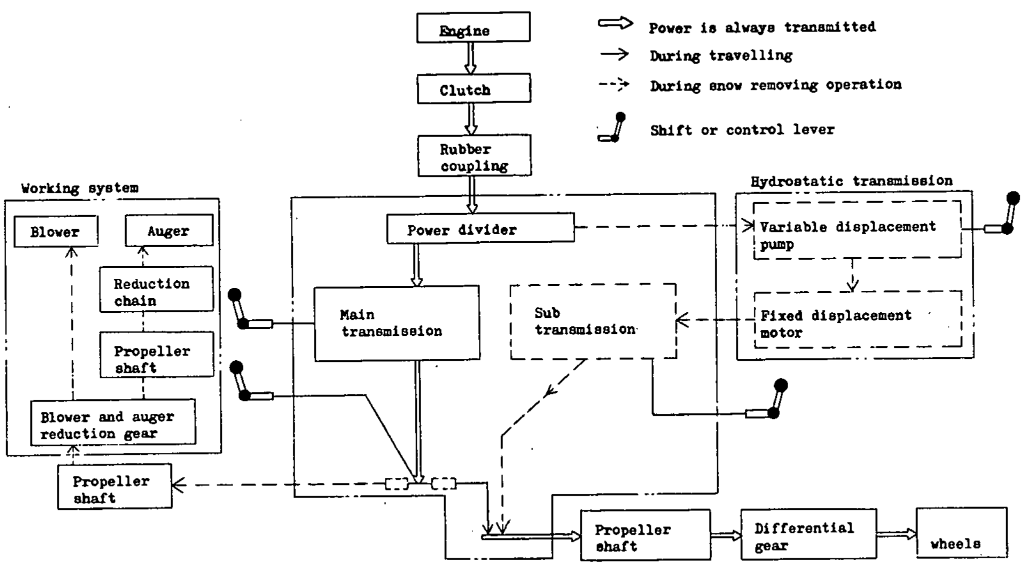


Figure 2. Power transmission flowchart of the test machine.



3. Main dimensions

Overall length	6,975 mm
Overall width	2,600 mm
Overall height	3,525 mm
Minimum ground clearance	300 mm
Weight	
Overall weight (including 2 crew-members)	12,600 kg
Front axle	6,450 kg
Rear axle	6,150 kg
Weight of vehicle	9,540 kg
Weight of snow removing unit	2,950 kg
Crew	2 members

4. Power transmission

Power transmission flowchart is shown in Figure 2.

5. Vehicle

Type Front wheel steering, one rear engine

Engine Nissan Diesel Engine model RD8T

Rated number of revolutions 2200 rpm

Rated output 260 HP

Max. torque 106.5 kgm at 1400 rpm

Drive system All - wheel drive (4x4)

6. Snow removing system

Type Two - stage type

Auger;

Type	Number of screw element	Screw lead (mm)
Screw and rake type	2	1040
Ribbon screw type	3	1700

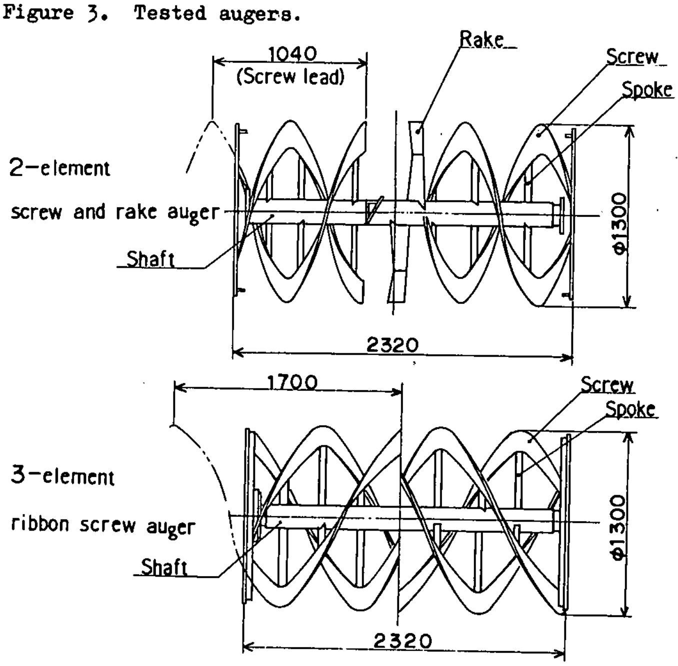
Auger revolution speed (with engine revolving at 2200 rpm) ;

For the test, two auger revolution speeds (High and Low) were provided by changing auger driving chain sprokets.

Speed range		1	2	3
rpm (circumferential speed m/s)	H	96 (6.56)	129 (8.79)	171 (11.7)
	L	128 (8.75)	172 (11.7)	228 (15.6)

Two types of tested auger are shown in Figure 3.

Figure 3. Tested augers.



Blower;

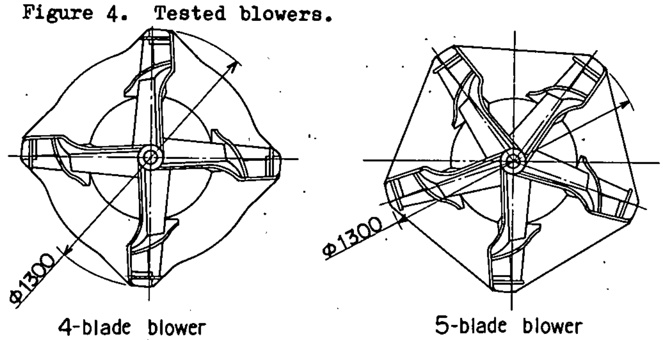
Type	Outside diameter (mm)	Depth (mm)
4-blade blower	1300	500
5-blade blower	1300	500

Blower revolution speed (with engine revolving at 2200 rpm) ;

Speed range	1	2	3
rpm (circumferential speed m/s	213 (14.5)	285 (19.4)	387 (25.7)

Two types of tested blower are shown in Figure 4.

Figure 4. Tested blowers.



Test Method

Table 1. Test period and site

Period	Test site	Nature of snow	Snow density (g/cm3)	Snow removing height (cm)
Jan. 11 - 12, '77	Nagaoka	Coarse snow - settled snow	0.36	70 - 90
Jan. 16 - 17, '77	Yamato	Settled snow	0.27	130 - 150
Feb. 9 - 16, '77	Sapporo	New snow	0.22 - 0.30	70 - 80
Mar. 13 - 16, '77	Yamato	Coarse snow - settled snow	0.45	170 - 200

Table 2. Measuring items and instruments.

No.	Measuring items	Instruments
1	Overall torque for working system	Torque meter (Strain gauge type) — Dynamic strain gauge — Graphic meter
2	Auger torque	
3	Number of revolution of propeller shaft for working system	Torque meter (Strain gauge type); Non contact switch
4	Oil pressure of hydrostatic transmission	Pressure gauge (Strain gauge type)
5	Snow density	500 cc Samler, Spring balancer
6	Snow temperature	Thermometer
7	Snow hardness	KINOSHITA'S hardness gauge
8	Time	Stop watch
9	Snow ejection destance	Tape measure
10	Snow removing height	Tape measure, Pole

Test Items.

Blower Performance Test. For each of 4-blade and 5-blade blowers, observed the snow suction and discharge status while measuring the removed snow quantity.

Auger Performance Test. For each of 2-element screw and rake type auger and 3-element ribbon screw type auger, measured the removed snow quantities at H-range and L-range auger speeds.

Horsepower Measurement. Blower horsepower, auger horsepower, and running horsepower were measured with respect to each test.

Snow Quality Measurement (Hardness and Density). Hardness of snow was measured with Kinoshita's Hardness Gauge which is outlined below.

A thin circular metal C (area S cm^2) is put on the surface of snow, the hardness of which is to be measured. Rod A with a cylinder B at its bottom end is set vertically on the plate C and cylindrical weight W (m kg) with a hole through the center, is dropped from height (h cm) onto B along road A, an impulsive force is applied to snow producing a depression of the snow surface (d cm).

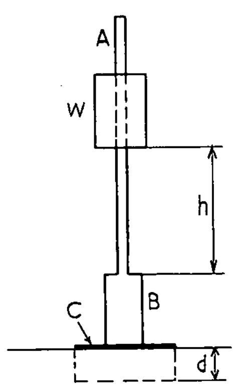


Figure 5. Kinoshita's hardness gauge

The average resistance F (kg) which the snow exerts to C is given by

$$F = m(1 + h/d) + M$$

where M is the sum of the weight of A and C.
The hardness of snow(Hkg/cm^2) can be defined by

$$H = F / S$$

$$H = 1 / S(m(1+h/d) + M)$$

Circular plates of different diameters are prepared to apply wide range of snow hardness, and to apply to hard packed snow, slender cylindrical pieces (basal area S cm^2) are attached to the cylinder B instead of plate C.

Measurement of Closs Section Area of Snow in front of The Machine.

Combinations. Sites with natural snow cover were selected for the test. Each test item was repeated for following combinations.

Table 3. Combinations.

Auger type	Auger speed range	Blower type	Snow removing width
2-element Screw and rake type	High	4-blade	Full (2.6m)
3-element Ribbon screw type	Low	5-blade	Quarter (0.65m)

Test Results and Comments

The total number of measurements throughout the test added up to 290. The results and comments are given below.

Blower Performance Rate L_B (t/HP. h)

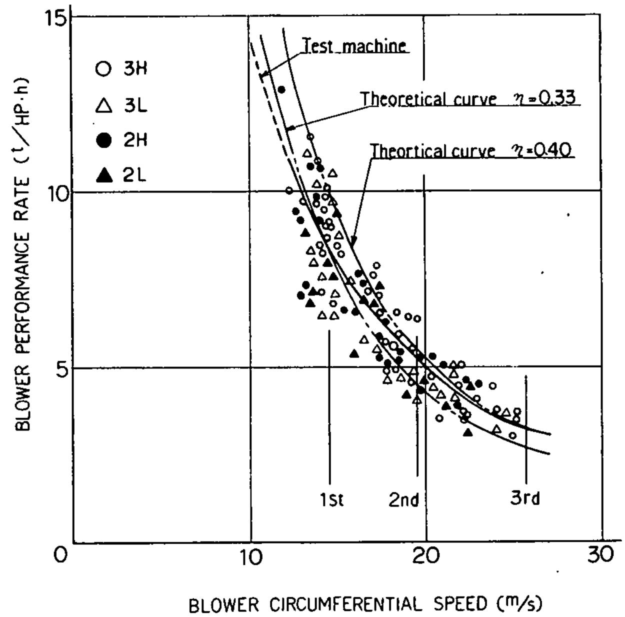
L_B is the gross weight of snow ejected by the blower in an hour per one horsepower. Theoretical L_B is given by the following formula.

$$L_B = \frac{540g}{V_B^2} \times \eta$$

g: gravitational acceleration
V_B: blower circumferential speed
η : blower volumetric efficiency

Fig. 6 shows the relationships between blower performance rate L_B and blower circumferential speed V_B. The value of η in the above formula, therefore, is estimated to be 0.33 - 0.40.

Figure 6. Relation between blower performance rate and blower circumferential speed.



Overall Snow Removing Performance Rate Lo (t/HP.h)

Lo is the gross weight of snow removed by the working system (blower and auger) in an hour per one horsepower.
Figure 7 shows the relationships between Lo and V_B.

1. As a general tendency, in the 1st speed range where V_B is low, Lo is in proportion to the auger speed while in the 3rd speed range where V_B is high, Lo is in reverse proportion to the auger speed. In the 2nd speed range, the difference caused by auger speed difference is minimum. The work efficiencies of different combinations are as follows:

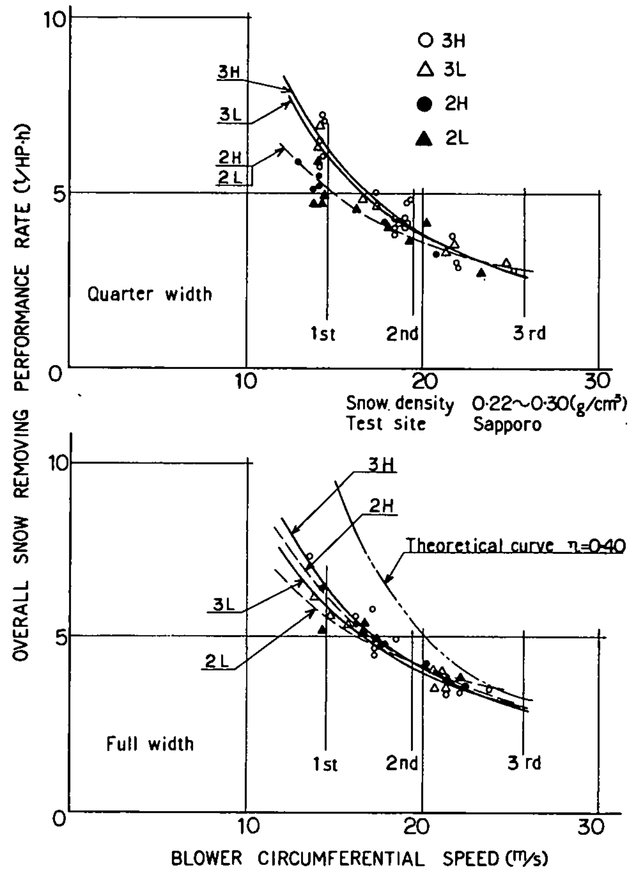
3H > 3L ≈ 2H∼2L (descending order)

2. Snow removing performance rate Lo in quarter width as compared with the same in full width operation.

Blower speed range	Quarter width/full width 3H	2H
1	0.98	0.85
2	0.95	0.88
3	0.92	0.85

The above table shows that under high-speed revolution the snow removing performance of the 3-element ribbon screw auger drops only 2-8% in quarter width snow removing operation as compared with full width operation.

Figure 7. Relation between overall snow removing performance rate and blower circumferential speed.



Relationship between Blower Performance Rate L_B and Overall Snow Removing Performance Rate Lo

Lo shows similar tendency for different snow density. L_B/Lo calculated from the data in Fig. 7 (for 3H in full width operation) are as follows:

1st blower speed range $L_B/Lo = \frac{8.50}{6.45} = 1.32$

2nd blower speed range $L_B/Lo = \frac{5.30}{4.20} = 1.26$

3rd blower speed range $L_B/Lo = \frac{3.25}{2.85} = 1.14$

L_B/Lo for values of L_B given by theoretical formula

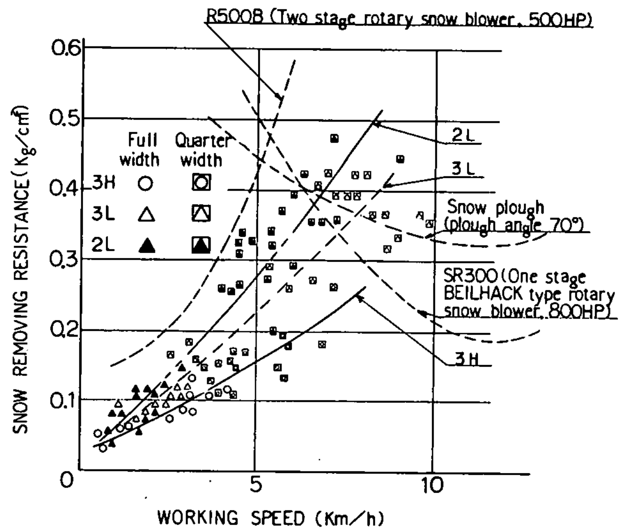
$$L_B = \frac{540g}{V_B^2} \times \eta \quad (\eta = 0.33 - 0.40)$$

decreases as blower circumferential speed increases.

Snow Removing Resistance R (kg/cm^2) and Working Speed U (Km/h)

Snow removing resistance R is given as reaction force (tyre tangential force) per cross section area of snow removed. Figure 8 shows the relationships between R and U. The general tendency of the test machine is different from that of SR-300 (one stage BEILHACK type rotary snow blower, 800HP). It resembles that of R500B (two stage rotary snow blower, 500HP) except that snow removing resistance tends to staylower. The resistance R is largest in 3H followed with 3L and 2L in this order. It decreases as the number of screw elements and auger speed increase. R in two stage type increases as the working speed increases while in BEILHACK type it decreases and reaches the minimum at the working speed of 12 km/h.

Figure 8. Relation between snow removing resistance and working speed.



Maximum Snow Removing Capacity

Table 4 shows such values among the measured data that are considered to be obtained in reasonable operation status. The specified maximum snow removing capacity of the machine is 1700 t/h at snow density of $\rho = 0.3$.
As the result of our test, the machine recorded over 1700 t/h in full width operation with 4-blade blower and 3-element ribbon screw type auger at high speed revolution and over 1500 t/h in quarter width operation under the same conditions. (Snow density ρ was 0.27 - 0.30)

Comparison between 4-blade Blower and 5-blade Blower

Visual observation of flying snow at the blower housing outlet told that the 5-blade blower performance is slightly more continuous. As to the snow removing capacity, however the 5-blade blower was a little inferior. In 3H operation, the snow removing capacity with the 4-blade blower as against the same with the 5-blade blower is as shown below.

Blower speed range	Full width	Quarter width
1	$\frac{1770}{1718} = 1.03$	$\frac{1523}{1268} = 1.20$
2	$\frac{1395}{1184} = 1.18$	$\frac{1177}{1055} = 1.12$
3	$\frac{872}{814} = 1.07$	$\frac{922}{686} = 1.34$

The 4-blade blower increases the snow removing capacity by about 16% in average.
The ratio of total blade volumes is:

$$\frac{\text{5-blades}}{\text{4-blades}} = \frac{0.0978\ (m^3)}{0.0869\ (m^3)} = 1.125$$

The ratio of total voids in blower housing is:

$$\frac{\text{Voids of 5-blade blower}}{\text{Voids of 4-blade blower}} = \frac{0.462\ (m^3)}{0.473\ (m^3)} = 0.98$$

The total voids in the 5-blade blower are only 2% less.
The increase of blade volume of 12.5% in the 5-blade blower is considered to be the cause of reduction of the snow removing capacity.

Table 4. Data of maximum snow removing capacity of the test machine.

Blower type	Combination of auger type and auger speed range	Snow density (g/cm³)	Test site	Snow removing capacity (t/h)					
				Full width (2.6m)			Quarter width (0.65m)		
				1st	2nd	3rd	1st	2nd	3rd
4-blade	2L	0.26	Sapporo	1542	1221	868	1242	897	621
		0.28	Yamato	1126	1070	774	1080	1029	710
		0.36	Nagaoka	1521	1057	823	1154	1031	
	2H	0.22	Sapporo	1639	1230	765	1514	1093	715
		0.36	Nagaoka	1632	1121	674	1128	1169	
	3L	0.26	Sapporo	1872	1276	840	1201	1089	839
		0.28	Yamato	1471	1147	800	1251	942	641
	3H	0.27 - 0.30	Sapporo	1770	1395	872	1523	1177	922
		0.28	Yamato	1419	1112	840	1475	1130	857
5-blade	2H	0.44	Yamato	1595	1232	766	1480	1043	794
	3H	0.26	Sapporo	1718	1184	814	1268	1055	686
		0.45	Yamato	1605	1251	851	1447	1077	747

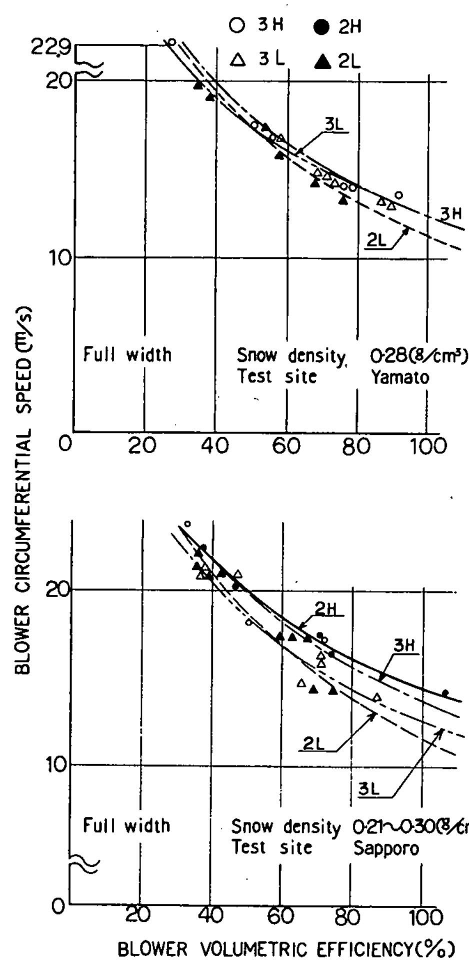
Blower Volumetric Efficiency η_B

η_B refers to the ratio of actual snow removing capacity to the full blower displacement for a unit hour. Figure 9 shows the relationships between blower volumetric efficiency η_B and blower circumferential speed V_B.

1. Slower V_B produces higher η_B. As V_B increases, η_B decreases because the snow drawn into the blower is accelerated before it reaches the depth of the blower. High circumferential speed, however, is necessary in actual operation.

2. As a general tendency, η_B is higher in high auger speed range (H range) than in low range (L range). The ratio of blower circumferential speed V_B to auger circumferential speed V_A is 1.66 in high auger speed range, and is 2.21 in low auger speed range. Thus, matching of V_B and V_A is better in high auger speed range.

Figure 9. Relation between blower circumferential speed and blower volumetric efficiency.



Running Horsepower Psr (HP)

Figure 10 shows the relationships between running horsepower. Psr is smaller in high auger speed range than in low range. 3-element ribbon screw type auger results in less Psr than 2-element screw rake type auger.
The following sequence shows the descending order of Psr for different combinations.

2L > 3L ≈ 2H > 3H

Relationships between Psr and U are as follows:

2L	HP ≒ 7.0 U
3L	HP ≒ 6.2 U
2H	HP ≒ 5.5 U
3H	HP ≒ 4.5 U

Ratio between different augers are:

$$\frac{2L}{3L} = \frac{7.0U}{6.2U} = 1.13$$

1.17 in average

$$\frac{2H}{3H} = \frac{5.5U}{4.5U} = 1.22$$

Ratio between different speedsare:

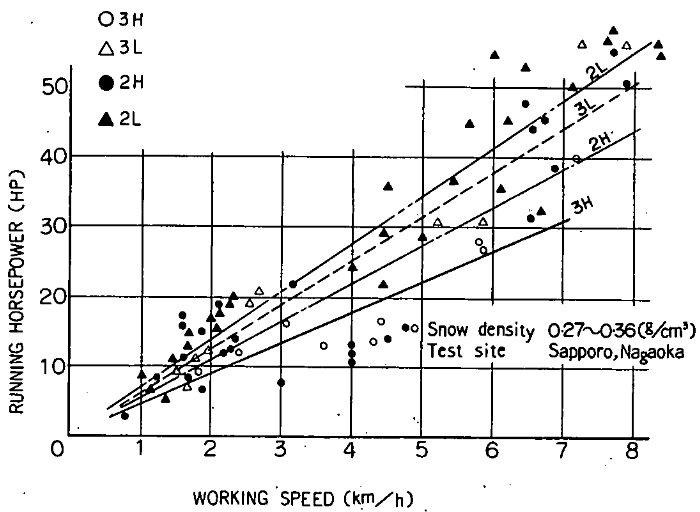
$$\frac{2L}{2H} = \frac{7.0U}{5.5U} = 1.27$$

1.33 in average

$$\frac{3L}{3H} = \frac{6.2U}{4.5U} = 1.38$$

Therefore, Psr is more affected by auger speed than by auger types.

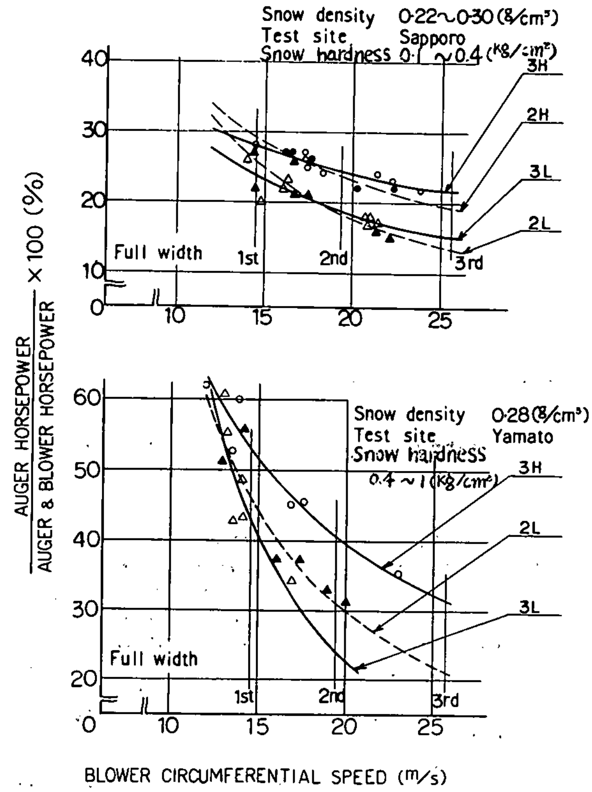
Figure 10. Relation between running horsepower and working speed.



Distribution of Working Horsepower

Figure 11 shows the horsepower distribution between the blower and auger. Although the fresh snow (ρ = 0.22 - 0.30) at Sapporo and settled snow(ρ = 0.28) at Yamato are almost equal in density, power consumption at Yamato is larger than at Sapporo. The ratio of auger power consumption to overall power comsumption is also larger at Yamato. These are considered to be caused by the difference in the nature of snow than by the auger type or speed.

Figure 11. Horsepower distribution between blower and auger.



Reference

Seiich Kinoshita. The Hardness of Snow(1). Institute of Low Temperature Science, Hokkaido University, Japan. Series A 19 1960, pp 119-134.

Airborne Snow Concentration and Visibility

J. R. Stallabrass, National Research Council of Canada

Little information is available on the probability distribution of the mass concentration of snow in the atmosphere. Such a deficiency became apparent as the result of engine malfunctions in helicopters while flying in falling snow. To help rectify this deficiency and so provide data for the meaningful design and testing of aircraft engine intake systems for operation in snow, a program was initiated to measure the snow mass content of the air. In conjunction with the measurements of snow concentration various other meteorological parameters were measured. It was found that the snow concentration may be estimated from the visibility with reasonable accuracy, thus offering the hope that concentration statistics may be derived for any location where climatological data on visibility are available. This is currently being tested using climatological data for Ottawa.

Other papers in this Symposium deal with problems or investigations of snow either on the ground or within a metre or so above it, i.e. blowing snow. This paper addresses itself to the mass concentration of snow in the atmosphere at greater heights and in the absence of blowing snow, although it is likely that the demonstrated relationship between mass concentration and visibility should apply equally to blowing snow as to falling snow.

Little interest in a detailed knowledge of the mass concentration of snow in the atmosphere was evinced until a few years ago when certain helicopters were found to develop engine malfunctions when flying in snow (1). Until then, aircraft flight through snow had presented few problems because the dry snow crystals did not adhere to the surfaces on which they impinged; however, the helicopters in question had rather sinuous engine intakes where snow accumulations could occur, particularly where stray heat warmed the intake wall. The subsequent release of these snow accumulations frequently resulted in engine flameout and, in a few instances, in serious crashes. It was evident that in order to permit the meaningful design and qualification testing of aircraft engine intake systems, a quantitative knowledge of the snow mass concentration in the air was needed.

A knowledge of the snow concentration also has applications where it is necessary to know the snow mass flux under circumstances where the horizontal component of the flux is significant relative to the vertical flux (precipitation rate), whether that horizontal flux is due to movement of an object (such as a surface vehicle or aircraft), the induction of air and snow into an air intake system (such as that of a stationary gas turbine installation), or as a result of wind action (such as the accumulation of wet snow on transmission lines or communication antennae).

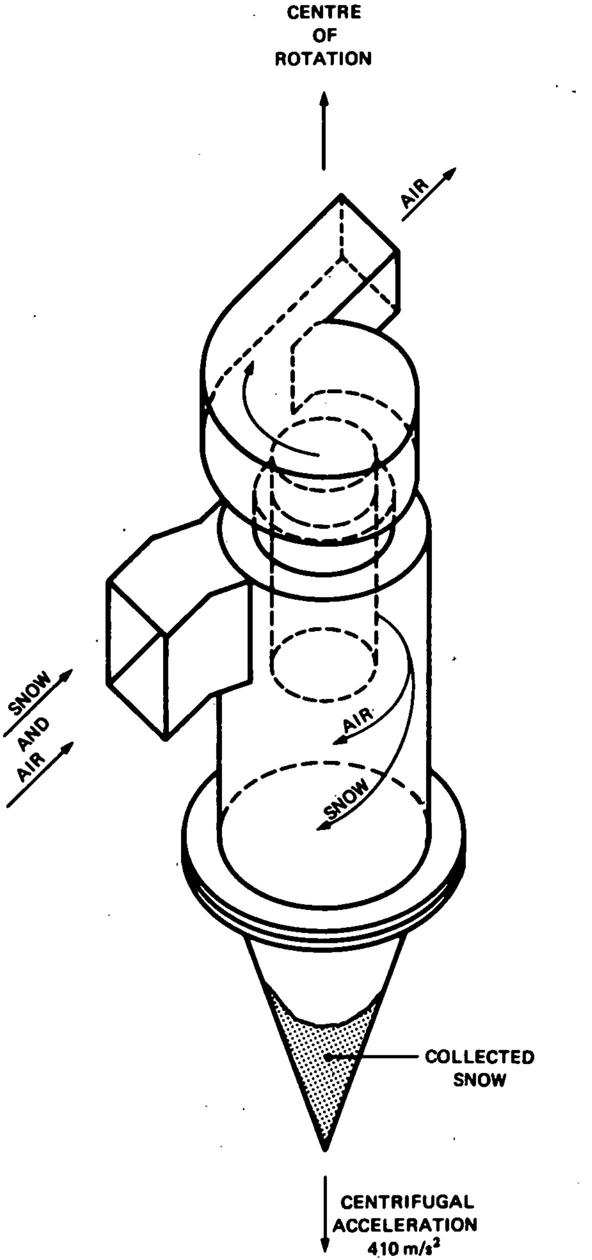
In theory, the snow mass concentration can be derived from the precipitation rate, but to do this a knowledge of the fall velocities of the spectrum of snow particles comprising the snowfall is required. Since these may vary by as much as an order of magnitude depending on snow crystal size and type (2,3,4), it is clear that a detailed knowledge of the characteristics of the particular snowfall would be required. Add to this the uncertainty of measurement of snow precipitation rate, particularly under conditions of even moderate winds, and also the fact that precipitation rates are usually reported as, at best, one-hour, and more usually, six-hour averages, it is clear that the use of precipitation rate to derive mass concentration statistics for snow is rather marginal.

In present weather observing practice, snow intensity is normally defined in a very qualitative way in terms of visibility, thus providing no indication of mass concentration. Thus it was concluded that an independent and direct means of measuring snow mass concentration was required to derive reliable concentration probabilities. Further, it was felt that if a correlation could be found to exist between the measured concentration and some routinely measured meteorological parameters, either alone or in combination, the prevailing snow concentration could be derived without resort to specialized measuring equipment, and concentration probabilities could be derived for any locality where meteorological records were available.

Methods of Measurements

The basic approach used to measure snow concentration was to sample a known volume of the atmos-

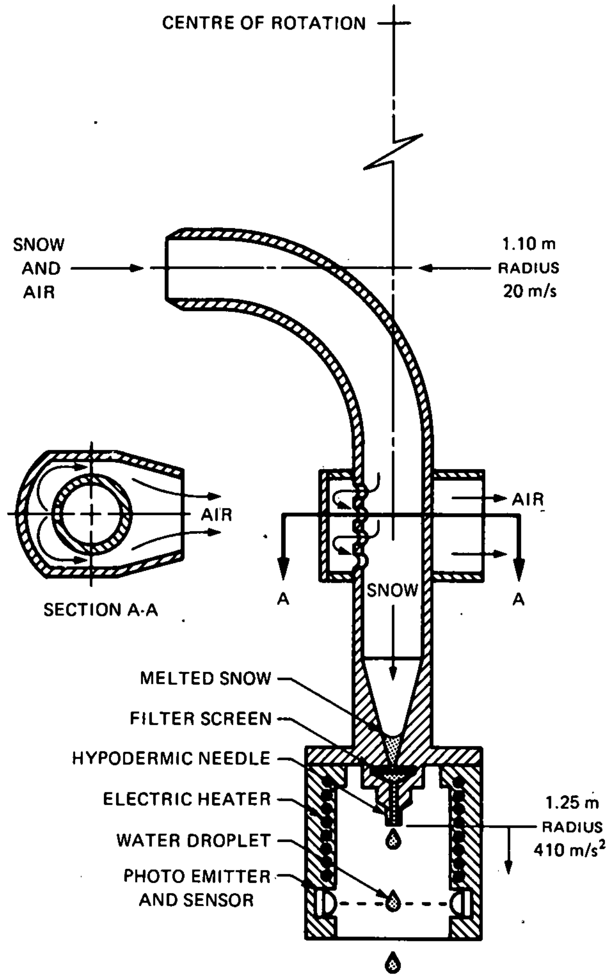
Figure 1. Cyclone separator used for manual measurement of snow mass concentration.



phere and to separate from it the snow for measurement of its mass. The apparatus consisted of a sampling device mounted at the end of an arm rotating in a horizontal plane at sufficient height above the surrounding surface as to be unaffected by blowing snow.

The type of sampling device used for the bulk of the data was a cyclone separator (Figure 1) mounted with its axis aligned with the radial arm. Flow through the device ensured high catch efficiency while both cyclone and centrifugal action ensured efficient separation of the snow from the air with little chance of particle re-entrainment in the exhausting air. The separated snow was retained in the device and weighed after a given collection period (in the order of 2 to 6 minutes depending largely on intensity), so giving a measure of the average concentration during that period.

Figure 2. Automatic sampler used for snow mass concentration measurement.



In addition an automatic snow sampler has been under development and was put into use for the first time in early 1977 for evaluation against the cyclone device. Mounted on the opposite arm to the cyclone, it collects snow in a simplified form of inertial separator (Figure 2). The collected snow is melted and allowed to flow through a hypodermic needle under the influence of the centrifugal acceleration. The resulting droplet stream is monitored photoelectrically and the pulses so generated are counted over a given time period (~1 minute) to obtain the snow concentration. Using the drop size data of Harkins and Brown (5), the resulting performance was found to be in close agreement with the concentration measurements provided by the cyclone device.

Simultaneously with the snow concentration measurements the following associated measurements were made adjacent to the snow sampling site:

1. Air temperature.
2. Dew point.
3. Wind speed and direction.
4. Observed visibility.
5. Precipitation rate.
6. Output of a Videograph back-scatter visibility meter.
7. Snow crystal type and estimate of size.

Table 1. Snow type categories.

Type Category	Designation	Description	Magono and Lee Classification
1	P	Plates and Broad Branched Crystals	Pla, Plb, Plc, P7a
2	D	Dendritic and Stellar Crystals	Pld, Ple, Plf, P2a, P2b, P2c, P2d, P7b, CPlb
3	RD	Rimed Plates and Dendrites	Rlc, Rld, R2a, R2b, R3a
4	G	Graupel	R3b, R3c, R4a, R4b, R4c
5	N	Needles, etc.	Nla, Nlb, Nlc, Nld, Nle, N2a, N2b, N2c
6	RN	Rimed Needles	Rla, Rlb
7	C	Columns, Bullets, etc.	Clb, Clc, Cld, Cle, Clf, C2a, C2b, CPla, CP2a
8	S	Multiple Capped Columns, Side Plane Assemblages, etc.	CPlc, S1, S2, S3
9	I	Miscellaneous, including Broken Crystals, etc.	I1, I2, I3a, I3b, I4

Items 1, 2, 3, 5 and 6 above were recorded on a digital data acquisition system at discrete intervals. The sampling interval was normally one minute when manual snow concentration measurements were being made, and 10 minutes during automatic operation.

The reference points for the observed visibility estimates were mostly tall buildings lying largely in the quadrant between west and south from the sampling site. This directionality may have contributed some scatter or bias to any relationships involving visibility whenever the snow intensity was variable.

The heated precipitation gauge used proved unreliable in its original form, but now, after considerable modification, consistent operation has been achieved. This instrument provides a signal for each 0.2 mm of water collected.

Snow crystal type was observed by allowing a number of crystals or flakes to fall onto a velvet covered board. The snow crystal classification scheme of Magono and Lee (6) was used in recording crystal type. However, for the purposes of correlating the data, many of these types were grouped together reducing the number of individual categories to 9, as shown in Table 1. In most cases a variety of crystal types co-existed, but one type usually predominated; the snowfall was then categorized according to the predominant type. Where it was impossible to assign a predominant type, the sample was included in the miscellaneous (I) type.

Relationship between Concentration and Visibility

Multiple regression analysis techniques were applied to the snow concentration and the other measured quantities, but apart from a highly significant correlation between concentration and visibility (and Videograph reading), no other significant influences were discernible. It was thought that, since the basic visibility (in the absence of snow) was dependent to a large extent on relative humidity, the introduction of this parameter into regression would help to resolve some of the scatter of data points, particularly in the low concentration/high visibility region which can be most affected by the effects of haze. However, it was found that the relative humidity was itself influenced by the concentration and hence was not an independent variable that could properly be taken into regression.

Except for some cases of very small ice crystals (<0.5 mm) no systematic effect due to crystal size was discernible. It is likely that any effect due to size was masked by variations in crystal form and by uncertainties in measurement, particularly those due to directional and time variations in concentration and visibility during the sample.

Physical reasoning suggests that the relation between snow concentration and visibility should conform to a log-log relationship, the coefficient in which should be about -1.33. Figure 3, which shows all the points measured by the manual snow

Figure 3. Data plot of manual snow mass concentration measurements against observed visibility for all snow types, and showing regression line $\log_{10}C = 3.315 - 1.286 \log_{10}V$. 832 Data points.

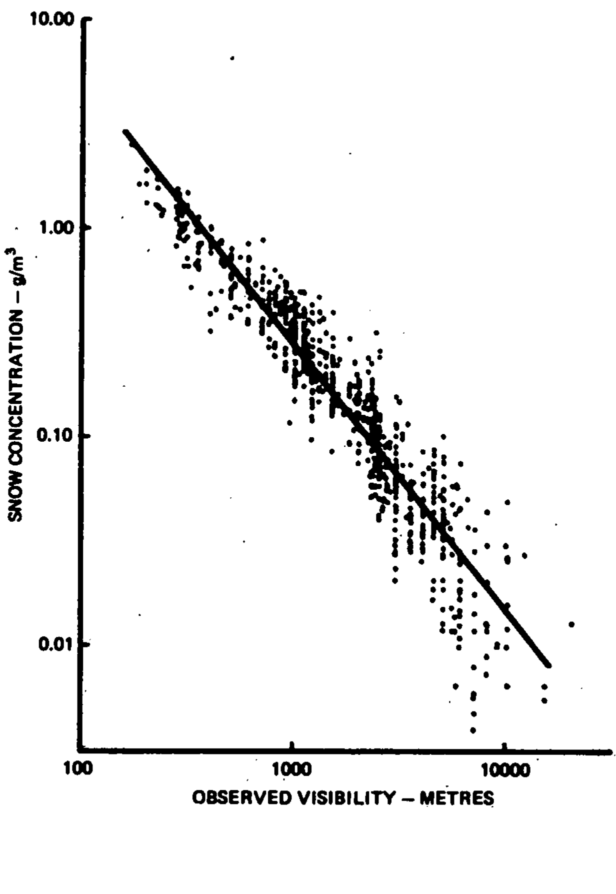


Table 2. Regression results, $\log_{10}$ concentration vs $\log_{10}$ visibility, for various snow types and groups of types.

Snow Types	No. of Samples	Regression Equation	Correlation Coefficient	Std. Error of Estimate
All	832	$\text{Log}_{10}C = 3.315 - 1.286 \log_{10}V$	-0.943	0.174
1,7 & 8	312	$\text{Log}_{10}C = 3.579 - 1.367 \log_{10}V$	-0.954	0.130
3,4 & 6	310	$\text{Log}_{10}C = 3.069 - 1.202 \log_{10}V$	-0.949	0.173
2	77	$\text{Log}_{10}C = 4.130 - 1.564 \log_{10}V$	-0.930	0.171
5	6	$\text{Log}_{10}C = 2.292 - 1.022 \log_{10}V$	-0.972	0.114
9	127	$\text{Log}_{10}C = 3.258 - 1.264 \log_{10}V$	-0.930	0.209

sampler over a period of seven winters, indicates that the regression equation

$$\text{Log}_{10}C = 3.315 - 1.286 \log_{10}V$$
$$\text{or} \quad C = 2100\ V^{-1.29}$$

(where the mass concentration C is in g/m^3 and the visibility V is in metres) does in fact represent the measured data reasonably well, but with some slight overestimation at low concentrations where the effects of haze become more predominant.

In general it was found that individual snow types gave better correlation and/or lower standard error of the estimate than when all the data for all snow types was consolidated. Some of the individual snow types had similar regression equations and could be grouped together with little effect on the regression statistics. Hence types 1, 7 and 8 (i.e. plates and broad branched crystals, columns and bullets, and side plane assemblages, etc.) could be treated together as a group, and so could all the rimed types (i.e. types 3, 4 and 6). The regression equations for these two groups and for the remaining individual snow types are shown in Table 2.

It is clear from these results that the differing light scattering characteristics of different snow crystal types do, as expected, have an effect on the visibility. However, other modifying influences, which are difficult to identify or isolate, appear to be as significant as the crystal form in causing variation in the observed visibility for a given snow mass concentration. Such influences may include the crystal size distribution in the snowfall or the presence of other crystal types along with the predominant type. In none of the correlations was there any marked indication that the aggregation of individual snow crystals into snowflakes had any consistent effect, although it is possible that the generally poorer correlation exhibited by the stellar and dendritic type crystals (the type most commonly forming flakes) may have resulted in part from this cause.

A marked difference in the concentration-visibility relationship between unrimed and rimed snow of the same type (i.e. types 2 and 3) was evident. Two factors are probably operative, the added mass relative to the crystal dimensions resulting from the accreted rime, and the modification of the basic hexagonal form of the crystal and the resulting effect on scattering characteristics. In spite of this, the degree of riming (i.e. from snow crystals with a few frozen droplets to graupel) did not appear to have any consistent effect.

Relation between Concentration and Videograph Output

The Videograph backscatter meter measures the amount of light scattered from a projector beam back into a photosensitive receiver placed alongside the projector. The amount of scattered light entering the receiver depends on the number and nature of the light scattering elements in the beam. Thus the possibility existed that the instrument would prove useful in providing a measure of the mass concentration of snow in the atmosphere. Accordingly mean values of the Videograph output current were recorded for all snow concentration samplings. Various functional relationships between the measured snow concentration and the Videograph output were attempted in regression analysis, and the one found to give the highest correlation coefficient and the lowest standard error of the estimate was found to be a log-log relationship.

Two Videograph instruments have been used at different times during these measurements; the first one was of a batch built for the Canadian Coast Guard as a fog warning device, while the one that has been in use for the last two winters is of more recent manufacture and has the same intrinsic calibration as instruments supplied to the Canadian Atmospheric Environment Service for visibility measurement at remote automatic meteorological stations. Since the calibrations of the two instruments differ slightly, only the data taken with the latter instrument is presented here. This data is shown in Figure 4, and its regression equation was found to be

$$\text{Log}_{10}C = 0.143 + 4.648 \log_{10}I_v$$
$$\text{or} \quad C = 1.39\ I_v^{4.65}$$

(where the mass concentration C is in g/m^3 and the Videograph output current I_v is in mA).

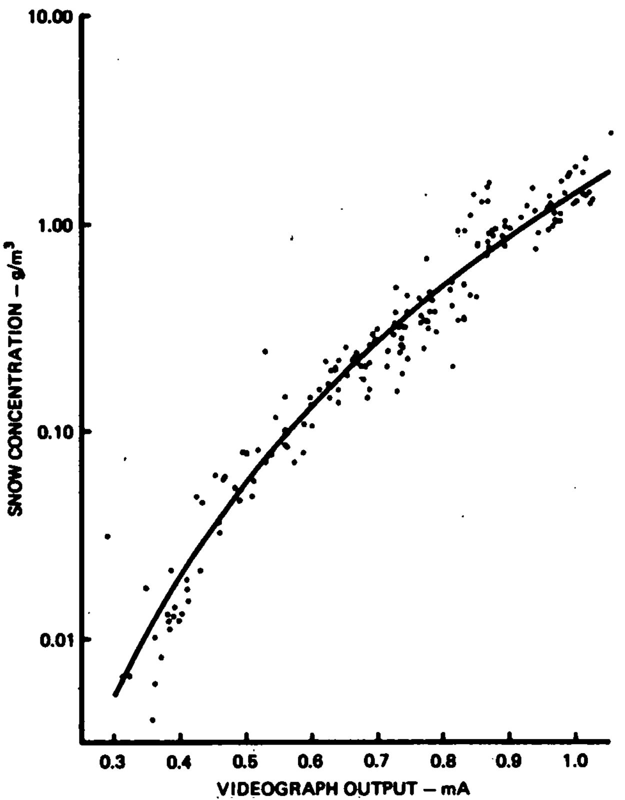
Like the visibility results, rather better correlation is obtained by considering individual snow types; however, less differentiation between the various types was observed, so that all the unrimed types with the exception of type 1 (i.e. plates) could be treated as one group (no observation of type 5, unrimed needles, was made in the last two winters), while the rimed types (3, 4 & 6) formed another group. The regression results for these two groups and for type 1 snow are presented in Table 3.

The regression results for the unrimed group (i.e. types 2, 7, 8 and 9) differed little from that for all the snow types combined. However, type 1 snow (hexagonal plates) exhibited a lower Videograph output for a given mass concentration than other types, while the rimed types gave a slightly higher output. Both type 1 and the rimed snow group showed extremely good correlation.

Table 3. Regression results, $\log_{10}$ concentration vs $\log_{10}$ Videograph output current, for various snow types and groups of types.

Snow Types	No. of Samples	Regression Equation	Correlation Coefficient	Std. Error of Estimate
All	176	$\log_{10}C = 0.143 + 4.648 \log_{10}I_v$	0.970	0.154
1	17	$\log_{10}C = 0.347 + 4.880 \log_{10}I_v$	0.982	0.059
2,7,8 & 9	94	$\log_{10}C = 0.152 + 4.614 \log_{10}I_v$	0.968	0.153
3,4 & 6	65	$\log_{10}C = 0.093 + 4.773 \log_{10}I_v$	0.988	0.110

Figure 4. Data plot of manual snow mass concentration measurements against Videograph output current for all snow types, and showing regression line $\log_{10}C = 0.143 + 4.648 \log_{10}I_v$. 176 Data points.



Liou (7) suggests that back-scattering from randomly oriented ice needles and columns is small, while plates and irregular types of crystals have strong backscattering returns. However, these results indicate that plates have a smaller backscatter than the other snow types. This is undoubtedly because plates tend to fall flat rather than with random orientation, so that only their edges are presented to the Videograph beam, thus resulting in low backscatter relative to their overall size. Rimed crystals, conversely, give a larger backscatter than their unrimed counterparts, probably because orientation effects are less critical.

Rather less scatter is evident in the Videograph results at low snow concentrations than is the case with observed visibility (c.f. Figures 3 and 4). This would seem to be because the Videograph senses the backscatter from the near field only, and is therefore not so sensitive to the effects that haze has on visibility when longer visual paths are involved.

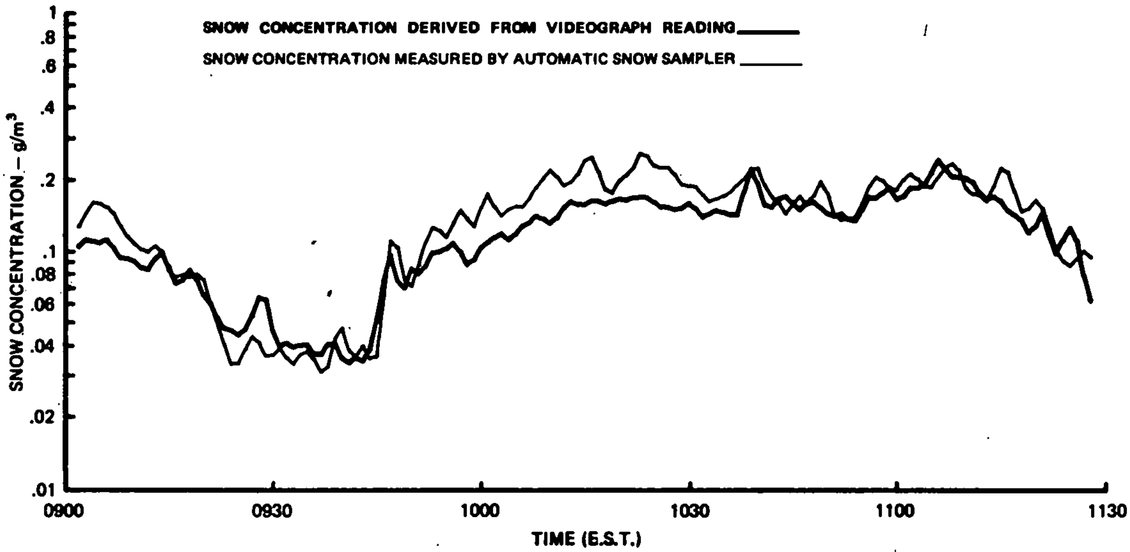
It is evident from these results that a backscatter visibility meter is a useful device for estimating snow concentration. This is demonstrated further by Figures 5 and 6 which compare the snow concentration as deduced from the Videograph output with that measured by the automatic snow sampler. Figure 5 shows a 2½-hour segment of a snowstorm during which samplings were made each minute. A three-point smoothing has been applied to this data since the Videograph readings were instantaneous values, while the snow sampler readings were the average snow concentration over a 50-second period between Videograph samples. Figure 6 shows the complete history of a snowstorm of 16 hours duration. In this case samplings were made every 10 minutes, the automatic snow sampler readings being the 50-second average immediately following the instantaneous Videograph reading. This data is unsmoothed. Both examples show good prediction by the Videograph of the snow mass concentration, with predicted values lying within approximately a factor of 2 of the measured concentration.

Relation between Concentration and Air Temperature

In Figure 7 the temperature dependence of the mass concentration is shown in the form of a scatter plot, using only data from the manual snow sampler. Until last winter, no discernible relationship between maximum snow concentration and surface air temperature was evident; however, some extremely high concentrations at temperatures between -2°C and -4°C that were recorded last winter now suggest an increasing mass concentration with increasing surface temperature. Such a relationship is perhaps not entirely to be expected since the temperature at ground level may bear little relationship to that at those levels at which formation and growth of the snow crystals took place. The great variation of crystal types falling concurrently on many occasions, the frequent complex crystal forms, and the occurrence of riming all attest to the variations in temperature and saturation of the air encountered by the snow particles during their lifetime.

Figure 7 suggests that there is perhaps a bimodal relationship between maximum concentration and temperature, with maxima at about -12°C and -3°C. The snow types contributing to the peak at about -12°C were rimed dendrites, rimed needles and miscellaneous rimed particles, while those responsible for the mode at about -3°C were plates, rimed dendrites, graupel, miscellaneous rimed particles, and to a lesser degree, side plane assemblages. The peak values at both peaks occurred with snow particles that could not be uniquely typed and

Figure 5. Comparison between snow mass concentration derived from Videograph output and that measured by automatic snow sampler. Portion of storm of 22 February 1977 sampled at 1-minute intervals.



hence were included in the miscellaneous category, although in both cases the particles were rimed. The total number of observations in each temperature range suggest that the frequency of occurrence of snow events increases with temperature up to a maximum in the temperature range of -2°C to -4°C. Over one half of the observations (and hence, we may assume, over one half of the time that snow occurs) are within the temperature range 0 to -8°C.

Probability Distribution of Snow Concentration

The cumulative distribution curve of 758 discrete snow concentration measurements made over a period of six winters is shown as curve (a) in Figure 8. This curve shows that the mean of the measurements was about 0.15 g/m^3, while a concentration of 1.0 g/m^3 was exceeded by about 5% of the measurements.

It had been hoped that these measurements might represent a reasonably random sampling of all snow events during this period; however, it must be conceded that the frequency of sampling during heavy snowfalls tended to be greater than during lighter, less significant events. Thus it may be assumed that curve (a) is biassed to heavier concentrations than those of a true random distribution.

The correlation that has been shown to exist between snow concentration and visibility provides another tool for deriving probability distributions of snow concentration at any location for which climatological records are available. The probability distribution has been derived in this way for Ottawa by converting to equivalent snow concentration the hourly visibility readings during reported snowfall for the 20-year period 1955-1974. This is shown as curve (b) in Figure 8. All obser-

Figure 6. Comparison between snow mass concentration derived from Videograph output and that measured by automatic snow sampler. Storm of 20-21 January 1978 sampled at 10-minute intervals.

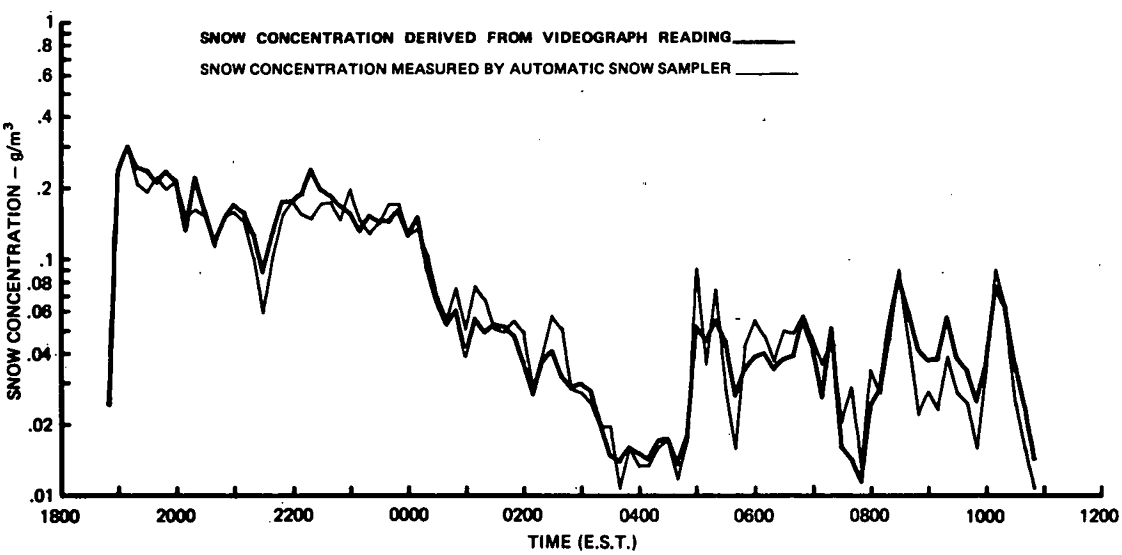
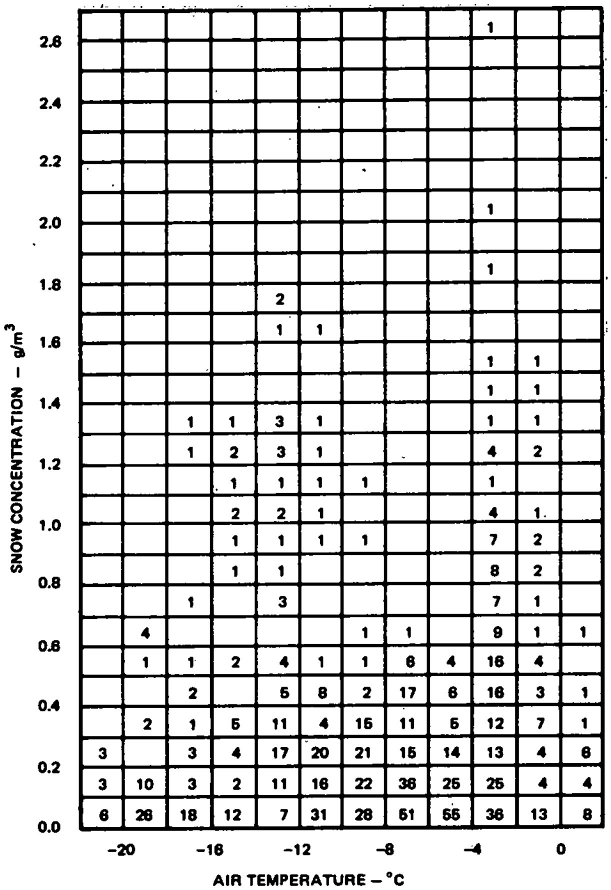


Figure 7. Plot showing number of observations within a given interval (0.1 g/m^3) of snow concentration for each 2°C interval of air temperature. Total number of observations = 851.



vations of greater than 8 km were grouped into one sample class, so that a tentative continuation of the curve to higher visibilities is shown as a broken line in the figure. Clearly a considerable discrepancy exists between the two curves.

With the introduction of the automatic snow sampler into service, performing a sample every ten minutes during all snowfall events, another means of verifying the probability distribution has become available. To date only five storms have been fully analysed, and, although they hardly comprise a representative sample, their concentration distribution is nevertheless presented as curve (c) in Figure 8. This seems to reinforce the belief that curve (a) overestimates the frequency of higher concentrations, while at the same time suggesting that curve (b) might overestimate the frequency of lower concentrations. Only continued data from the automatic sampler over a number of winters will resolve this and decide the usefulness of climatological visibility data for deriving the snow concentration distribution.

General Observations

The maximum snow concentration measured during this work was 2.66 g/m^3 which was an average value over a 3-minute sampling period. Three snow crystal types were identified but no one was judged predominant so the sample was classed in the Miscellaneous category. The three snow types were rimed columns (R1b), densely rimed stellar crystals (R2b), and rimed broken branches (I3b). Crystal sizes were about 2 to 3 mm with some aggregates of about 5 mm. Visibility at this concentration was 170 metres and the temperature -2.5°C.

The second peak value, occurring at -12.7°C, was 1.73 g/m^3 and was a 4-minute average value. This sample was also placed in the Miscellaneous category, but comprised rimed needles (R1a), densely rimed plates (R2a), and multiple capped columns (CP1c). Crystal sizes were about 2 to 3 mm but with no aggregation into flakes. Visibility was 200 metres. It is of interest to note that on this occasion the mass concentration continuously exceeded a value of 1 g/m^3 for a period of 1.5 hours. Further analysis, particularly of the automatic snow sampler data, will be necessary to derive some duration statistics for various concentrations.

It is also of interest that, throughout this work, approximately 50% of all samples comprised rimed snow crystals, which implies that on about half of all occasions when snowfall is occurring at the ground there is some level aloft where mixed cloud conditions of supercooled water droplets and ice crystals may be encountered. The significance of such mixed conditions to aircraft icing is currently under investigation.

Conclusions

Of the various meteorological parameters normally recorded, visibility provides the most reliable measure of the atmospheric snow mass concentration. The concentration, in g/m^3, is given to within a factor of 2 by the relation

$$C = 2100\ V^{-1.29}$$

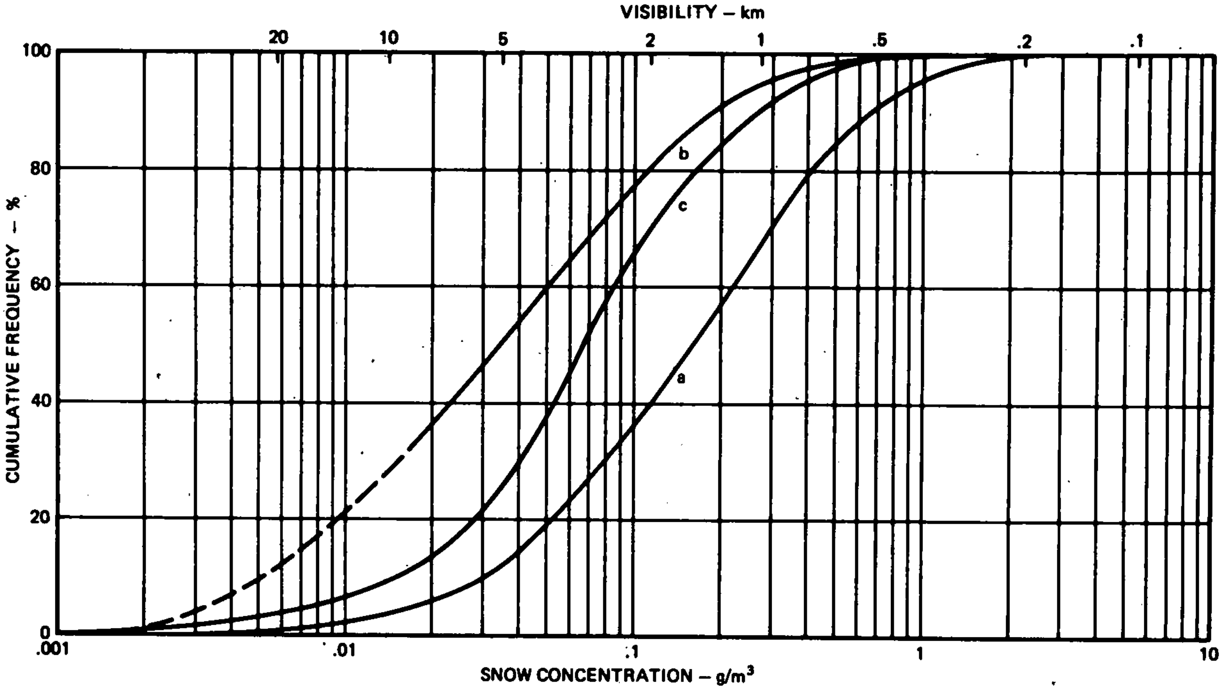
where the visibility, V, is measured in metres.

A backscatter visibility meter, such as the Videograph, was found to provide an excellent means for estimating the prevailing snow concentration. The output meter of such a device may be scaled in terms of snow concentration to provide a direct readout.

The maximum snow mass concentration so far recorded at Ottawa is 2.66 g/m^3, and concentrations in excess of 1 g/m^3 have been recorded for periods of up to 1.5 hours.

Two probability distribution curves for Ottawa, one derived from actual snow concentration measurements, and the other from visibility records, show some considerable discrepancy; in particular the measured concentration results show a higher probability of higher concentrations. It is expected, though, that the discrepancy will be resolved by forthcoming results from the automatic snow sampler. Should the results from the visibility data be confirmed, then concentration probability data may be derived for any location where climatological records are available.

Figure 8. Cumulative distribution curves of snow concentration for Ottawa: (a) from N.R.C. discrete snow concentration measurements, 1971-77; (b) as derived from diurnal frequencies of reported visibility in combination with snow for the 20-year period 1955-74 at Ottawa International Airport, using the relation $C = 2100\ V^{-1.29}$; (c) from 5 snowstorms monitored by N.R.C. automatic snow sampler, 1978.



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Measuring Visibility in Blowing Snow

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An electronic system that monitors visibility in blowing snow has been developed by the USDA Forest Service, in cooperation with the Wyoming Highway Department. The sensor for blowing snow is a photoelectric particle counter that produces a voltage pulse for each snow particle which passes through a 3 by 25 mm area normal to the wind. The sensor's pulse train is electronically processed to give voltages proportional to five-second averages of particle frequency and diameter. These voltages are combined with the signal from an anemometer in an analog computer which stimulates visual range according to the equation, $V = 5U/FX^2$ where V is the visual range in meters, U is windspeed in meters per second, F is the particle frequency in number per second through a 1 cm^2 area, and X is the particle diameter in centimeters. Field calibration was accomplished by comparison with closed circuit television recording of visual range targets during drifting. The correspondence between theory and observed visual range was very satisfactory, and two such systems are now in use for traffic control in Wyoming, having proved reliable and useful during three winters.

The Phenomenon

Becoming lost in a blizzard is one hazard that still threatens winter travelers in the Great Plains and western United States. To most, such an experience is certainly frightening, and for some, it has been fatal. This paper describes an electronic system developed by the USDA Forest Service, in cooperation with the Wyoming State Highway Department, to help travelers avoid being stranded in blowing snow storms, and to improve the safety of transportation under drifting conditions. The system consists of an anemometer, a blowing snow sensor, and a specialized analog computer designed to combine signals from the sensors according to an equation for visual range.

Some pertinent features of the blowing snow phenomenon are included to help the reader follow the assumptions in the development of a visibility equation. A description of the blowing snow sensor follows that derivation, and then the design of the electronic analog is presented. The procedure and results of field calibrating the system are explained, and an example of the strip chart record leads to a discussion of the usefulness and application of the system.

Blowing Snow Particles

Much of the quantitative information about blowing snow has been written by scientists studying the mass balance of water in Antarctica. Their measurements, and data obtained with the sensor described in this paper, show that particles of drifting snow are usually much smaller than the original precipitation crystals. The reduction apparently takes place by the crystal shattering, being abraded, and sublimated, during wind transport. At heights 50 to 100 cm above the surface, mean particle diameters are close to 100 μm. The distribution of size is skewed toward smaller diameters, so that log-normal or two-parameter gamma functions provide useful approximations (1). Mean size increases exponentially nearer the surface, approaching values of 200 μm at levels between 5 and 10 cm above the surface. At a given height, mean size increases with windspeed, once the threshold speed for wind transport is exceeded, but the function is conservative. Particle frequency, the number per second passing through a unit area normal to the wind direction, increases as a much higher power of windspeed, and also decreases exponentially with height, like particle size. Because of this strong vertical gradient in the density of blowing snow, truckers and snowplow operators usually enjoy better visibility than car drivers and patrolmen in the same drifting conditions.

Mean particle velocity at any height is equal to the mean wind velocity, except perhaps within a centimeter of the surface. Since particle frequency is such a strong function of wind velocity, natural wind gustiness produces a very large variation in particle frequency with time. At the 50 cm level, for example, particle frequency may increase from a few hundred to greater than 5,000 particles per second per square centimeter in less than 10 seconds. Careful consideration of averaging times is essential to assure that any measure of visual range approximates the ability of the human eye to form a persistent image with such rapid changes in visibility.

A Visual Range Equation

Liljequist (2) reports visibility in blowing snow and corresponding windspeed observed at Maudheim, in the Antarctic. Assuming constant particle size distributions, he argued that visibility is inversely proportional to the density of drifting snow. Data to test his hypothesis are provided by Budd, et al. (3), who show that visual range, V (m) is well predicted by $V = 100/n$, where n is drift density (in gm/m^3) at 2 m. These measurements were also made in Antarctica, at Byrd station.

The theory of visibility is covered completely by Middleton (4) and specifically for blowing snow by Mellor (5). Dr. R. D. Tabler first drew my attention to the derivation that follows (6). Attenuation of visible light by blowing snow should be proportional to the projected area of the transported particles, since particle diameters are large compared to the light wave lengths. If N represents the number of particles per cubic centimeter in the air stream, then for spherical particles of uniform diameter, the sum ϕ of all particle cross sections in this volume is

$$\phi = N\pi X^2/4 \qquad (1)$$

where X denotes the particle diameter (in centimeters).

Contrast C is defined as the difference in luminance between objects and background luminance, and liminal contrast C_e is that threshold value below which an observer cannot discern object against background. Contrast is reduced by blowing snow as an exponential function of distance and ϕ, the total cross section per unit volume. The threshold defines the observer's maximum visual range as

$$V = -\frac{\ln C_e}{\phi} \qquad (2)$$

Values of C_e are usually between 0.01 and 0.03, as determined by experiment. Assuming the mid-range value, $C_e = 0.02$, and substituting (1) in (2), the visual range for uniform spherical particles is estimated by

$$V = 5/(NX^2) \qquad (3)$$

If F denotes the number of particles per square centimeters area passing across the sight path each second, then $F = NU$, assuming the particles move with mean windspeed, U (cm/sec). Therefore, visual range in blowing snow might be estimated by

$$V = 5U/FX^2 \qquad (4)$$

where V is in meters if windspeed is in meters per second. The following assumptions have led to this greatly simplified equation:

a. the principles of geometric optics apply; particles are large enough that absorption of light may be neglected,

b. particles are spheres, all of the same diameter, and

c. wind velocity is equal to particle velocity and perpendicular to the sight path.

The first assumption seems to meet most conditions in blowing snow quite well, and should not lead to errors. Assuming that blowing snow particles are spheres instead of smoothed, but still irregular ice grains, is not likely to lead to much error either, because we wish to approximate scattering cross section, and it is quite possible to choose a diameter that will lead to the proper sum of projected areas. By the same argument, we should be able to minimize any error that is caused by approximating the scattering cross section of a skewed distribution of particle sizes with the areas of an equal number of uniform particles. However, the assumed diameter should be somewhat larger than the mean of the distribution. Measurements show that mean particle speed closely approximates mean windspeed. Since the particle number concentration in the sight path, which is computed by $N = F/U$, is the same regardless of wind direction, the equation (4) should apply even with oblique winds. Implicit in the derivation is an assumption that averaging times for all factors are properly choosen. As already noted, such an assumption is required by the physiological nature of the definition for visual range.

Comparison with Antarctic Data

If visibility is related to drift density, as in the empirical result, $V = 100/n$, then visual range must vary inversely as the cube of diameter, whereas (4) predicts an inverse variation according to diameter squared. Mellor (5) concludes from this contradiction that particle size must be nearly constant, as Liljequist had assumed. However, another explanation was suggested during review of this paper (7). It is possible that variance in estimates of both V and n is large enough that the coefficient, 100 in the empirical relation contains X as a factor. Let $V = BX/n$ represent this hypotheses. Data in table 1 are averages estimated from (3) for drift particles at 200 cm, by 10 m windspeeds that span the range of measurements. It appears a factor of X could easily be "hidden" in the coefficient, explaining the difference in functional form between (4) and $V = 100/n$.

The same date allow a rough calculation of the visibility predicted by (4). To do this, particle frequency must be estimated. Since $F = NU$, determining the volume concentration of particles will allow calculation of F, if U_{10} is reduced to the 2 m windspeed, using a standard wind profile. To estimate N, the drift density, n may be divided by the average particle mass. For the skewed size distribution, the diameter of a particle with average mass is estimated to be 1.2 times the mass of the particle with average diameter (1) or $\overline{M} = 1.2 (\rho\pi/6)X^3$ where density ρ is assumed to be 0.92 gm/cm^3 (ice). Dividing drift density by $\overline{M}$ determines N, and using a 1/7 power law wind profile gives $U_2 = 0.795\ U_{10}$. Visual range estimated by (4) is 2.2 to 2.8 times greater than values computed by $V = 100/n$.

The quantitative comparison will be left at this point, with the expressions agreeing in the functional relation of F, U, and X^2 and a factor of 2.5 difference in the coefficient. The empirical relation uses the value of drift density at 2 m because it was a drift measurement height; yet, the observer's line of sight probably was not this high, and the visual targets were poles, which represent a very small visual target, so that the value of liminal contrast assumed in the derivation of (4) may not apply. Most important, our experiments with the photoelectric sensor show that constant particle size is not a valid assumption for drifting in regions where the amount of snowfall available for wind transport is limited, or becomes so during a blizzard. In fact, incorporating particle size in visibility measurement leads to certain advantages discussed at the end of this paper.

Table 1. Comparisons of visual range estimates[a]

	Windspeed U_{10} (m/s) 12	16	20
Factors estimated at 2-m			
drift density, n (g/m^2)	0.2	0.8	1.9
mean diameter, X (μm)	75	90	95
particle frequency, F (no./s/cm^2)	782	2,416	6,090
Visibility (meters)			
V = 100/n	500	125	53
V = BX/n (B = 1.1)	412	124	55
$V = 5U/FX^2$	1,080	325	145

[a]Data from Budd et al., (3)

Sensing Blowing Snow

Research on blowing snow in the earth's polar regions generated two photoelectric sensors at about the same time. In Antarctica, Landon-Smith and Woodbury (8) tested a design that was improved by Wishart (9). Sommerfeld and Businger (10) used a different instrument for studies in the Arctic. Shortcomings in both devices were due primarily to calibration drift, quite understandable considering the temperatures. A new approach, based on the experience of the last authors, was undertaken at the University of Washington in Seattle. This development, directed by Dr. Walter Rogers, Department of Electrical Engineering, produced a blowing snow sensor with which individual particles could be counted in the air stream and which offered particle size and speed information as well (11). Further work by Sommerfeld streamlined the sensor (12), and both the electronics and mechanical design were revised in the version reported by Schmidt and Sommerfeld (13). A complete description of the device presently in use (Figure 1), including all circuit diagrams and shop drawings, is presented by Schmidt (14).

Figure 1. The snow particle counter (SPC) is usually positioned 50 cm above the surface, with the mounting arm and light beam (opening) normal to the wind direction most common during drifting.

The Snow Particle Counter

This sensor produces a bipolar voltage pulse for each particle that intercepts its light beam which is oriented perpendicular to the wind direction. Two phototransistors detect the shadow of the particle as it crosses the light beam (Figure 2). Each photosensor is positioned behind a narrow optical window, one-half mm wide and 3 mm high. An amplifier in the mounting arm connects the phototransistor signals in such a way that the particle's shadow generates a positive pulse on the first window and a negative pulse at the second window, 2 mm downwind. The sampling area is 25 mm long. Since the light from the miniature lamp is not so intense that the phototransistors are saturated, they respond to different particle sizes with different signal amplitudes. The windows are precisely dimensioned by photographic reduction on a stable film base, allowing particle speed to be estimated from the time interval between positive and negative portions of the pulse. Thus, information on size, frequency and speed may be obtained by processing the signal from the snow particle counter (SPC).

A small, battery-operated motor, which spins a 0.5 mm diameter wire through the center of the beam so that each window is completely shadowed, allows the sensor to be adjusted to produce a standard signal. Amplifier gain is compensated to minimize drift over the temperature range, -15 to 0°C. During adjustment, the signal is viewed on an oscilloscope so positive and negative peaks can be balanced to ± 3.0 volts.

Calibration of the SPC was complicated by a variation in sensitivity across the sampling area. Signal amplitude depends not only on size, but also on the location within the sampling area at which the particle intercepts the beam. Shadows that fall near the upper and lower ends of each window produce voltage pulses that may be less than 10% of the maximum amplitude which occurs when a particle crosses the center of the beam, near the sensor windows. This situation results from the overly simple optics, coupled with a variation in axial response of the phototransistors.

Particle size calibration was accomplished by rotating the sensor 90° from its usual position so that sieved particles could be dropped through the sensing area. A procedure developed to transform the distribution of pulse amplitudes into a particle size distribution, compensated for the nonuniform sensitivity across the sampling area. Average particle diameters can be estimated within 10 μm of means for known size distributions, by this method, but an electronic multichannel analyzer is required to make the measurement. Therefore, the technique

Figure 2. Light from the miniature lamp is received by each phototransistor through a separate window, 3 mm high and 1/2 mm wide. A differential amplifier combines the photocurrents so each particle shadow produces a pulse of positive amplitude at the first window and neagative at the second.

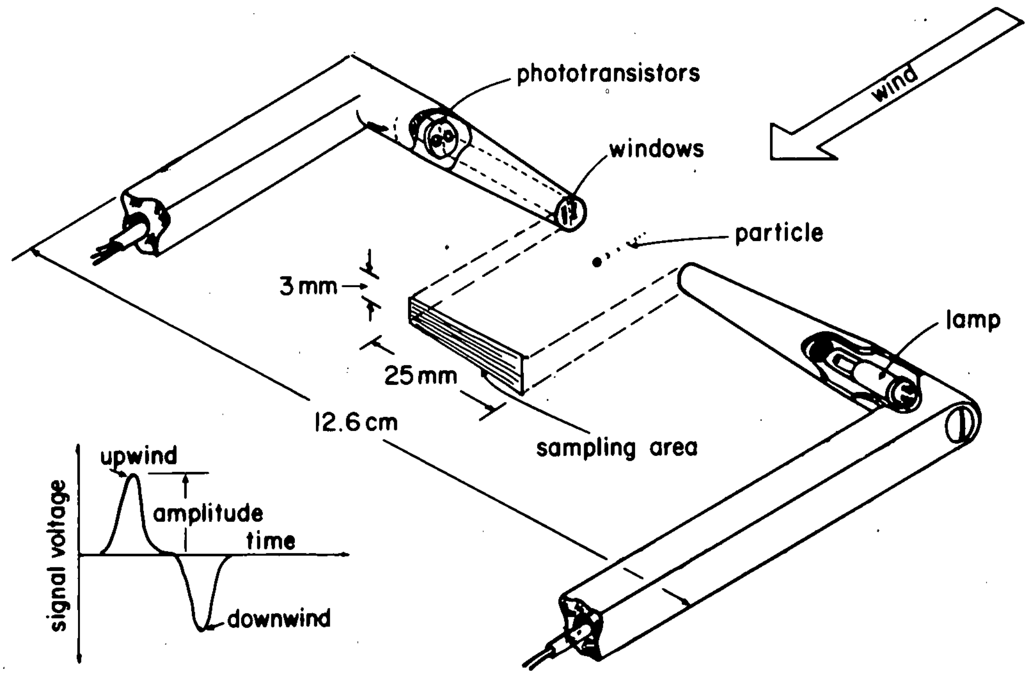
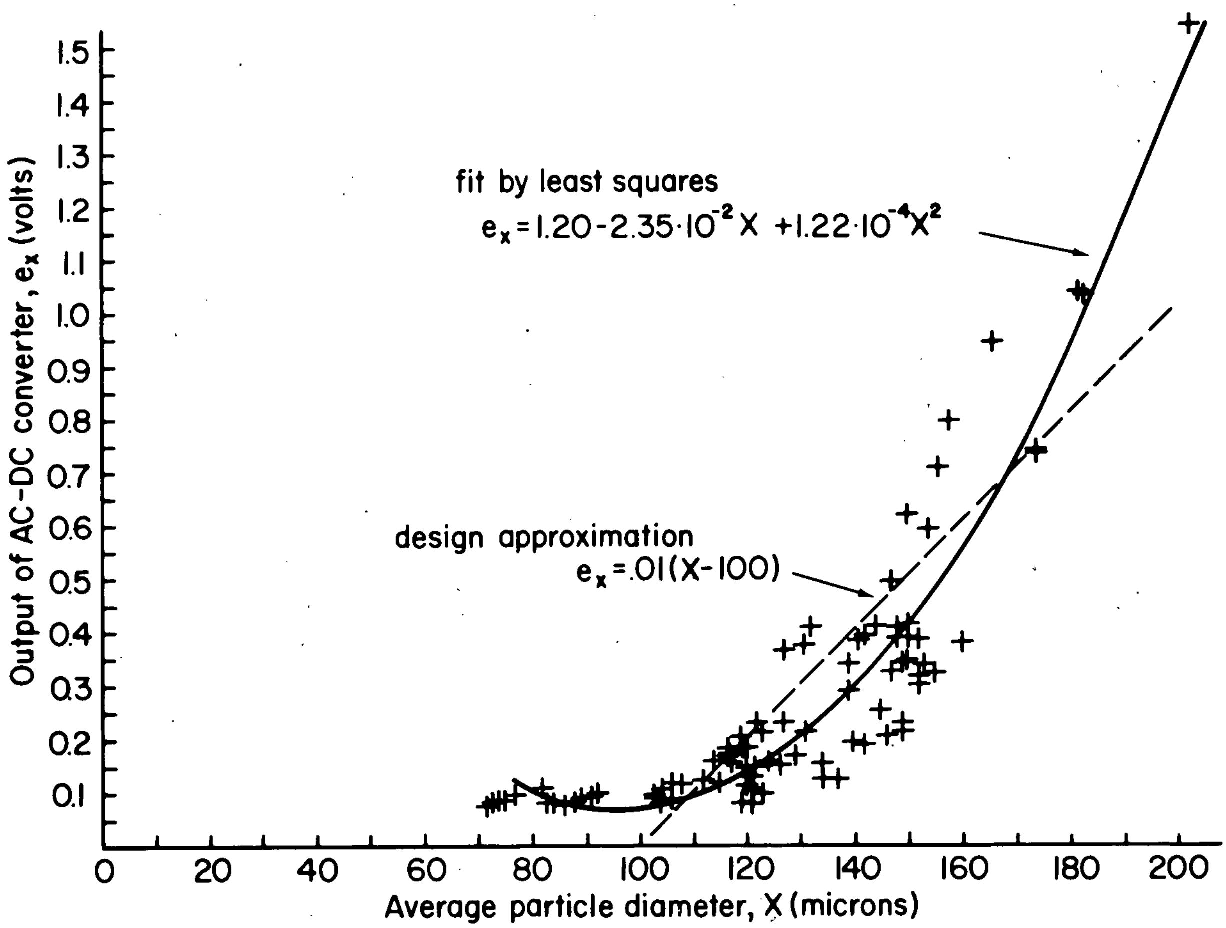


Figure 3. Output voltage of the a.c.-d.c. converter is a function of mean diameter, for 1-minute samples at several heights in drifting snow. Particle size distributions were determined from the distribution of signal amplitudes accumulated by an electronic pulse height analyzer, using a transformation developed with sieved particles in the laboratory.

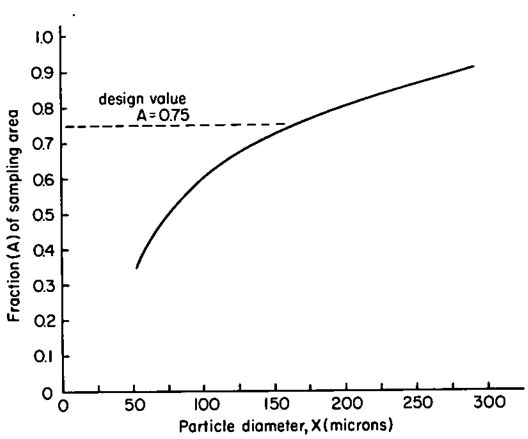


was used to find a relationship between average snow particle diameter and the root-mean-square value of the sensor pulse train (Figure 3), using 1-minute averages from signals recorded on magnetic tape during drifting events. If only mean particle diameter is required, an a.c.-d.c. converter contained on a small printed circuit card is then sufficient. A low pass filter on the card is designed to produce an output voltage e_x that represents the 5-second running average particle size. The linear relation e_x (volts) = (X-100)/100, where X is diameter in microns (X > 100), was used as a design approximation.

Particle frequency estimates are also affected by the variation in sensitivity across the sampling area, since some threshold of sensitivity must be specified to separate particle signals from electronic noise. If the light beam was perfectly collimated, the sampling area of the sensor would be equal to the distance between lamp and sensor windows (25 mm) times the sensor window height (3 mm) or 0.75 cm^2. However, the actual sensitive area is wedge shaped and closer to 1.0 cm^2. By mapping the variation in sensitivity across the sampling area, corrections for frequency estimates were determined as a function of particle size (Figure 4). If f is number of signals per second measured by the SPC, then the estimated particle frequency in number per square centimeter each second is F = f/A where A denotes the fraction of the total sensitive area (1 cm^2) which provides signals greater than the trigger level. Estimates of particle frequency are close for diameters between 150 and 200 μm, using the design value A = 0.75 and are low for smaller particles. No effort was made to correct this apparent error mainly because no independent measure of in situ particle frequency was available during the development. Another printed circuit produces a voltage e_f which is a linear function of the signal pulse frequency f and reaches 10 volts when f = 5000 per second, again with a filter which provides about 5-second averages. Thus, the transfer function is $e_f = f/500$, so F = 500 e_f/A, or F = 667 e_f, for A = 0.75.

In summary, the snow particle counter produces signal pulses corresponding to individual snow particles, and electronic circuits have been designed and calibrated to convert the sensor output signal into voltages proportional to particle size and frequency, with averaging times of about 5 seconds. Overall accuracy appears to be such that mean diameters are estimated within 10 μm, and frequency within 500/sec/cm^2, under natural drifting conditions, but no independent calibration standard was available.

Figure 4. Reduced sensitivity near the edges of the sampling area causes the frequency of smaller particles to be underestimated. The value, A = 0.75 was used for design.



Computing Visual Range

The electronic computer that provides a real-time solution of (4) uses analog techniques, primarily because the author had more experience with these methods than with digital computer design, at the time the design was begun (1972). Analog computation uses operational amplifiers and function modules to manipulate voltages that represent the parameters of the equation, and the solution is also a voltage. Part of the design problem is to scale amplifier gains in such a way that voltages remain within the limits of the amplifiers and modules.

The Computer Design

Visual range can have very large maximum values and sometimes it is so small, "you can't see your hand in front of your face", but the values of most concern for surface travel are between 50 and 500 m. To emphasize this range, the computer produces a voltage e_v, that is proportional to the reciprocal of visibility. The full scale output, e_v = 10 volts was chosen to correspond to a 200 foot (61 m) visual range, because this is the standard distance between highway delineator posts, and might be used as a practical lower limit. Therefore, e_v = K/V, where K = 610 (in volt-meters).

Another important part of the design was to select a measurement height for the SPC that would provide representative data for solution of the visual range equation. The critical sight path of a motorist in blowing snow was judged to be the line from his eye to the road surface some distance in front of the vehicle, rather than a horizontal path. Because the drift density increases so rapidly near the surface, measurements at eye level were expected to overestimate visual range defined with respect to motorists. Experiments with the SPC at a height of 1 m demonstrated that the sensor output at this level was inadequate to detect either low intensity drifting, or the very beginning of snow transport. However, if the sensor is positioned below 10 cm, it tends to "saturate" at relatively low intensities, and the lower the height, the greater the effect of new snow depth on the measurement. These considerations led us to select 50 cm as the height at which to measure the particle parameters for the most useful monitoring of motorist visibility. It is possible to adjust the system for other measurement heights.

To stimulate the equation, $V = 5U/FX^2$, a voltage proportional windspeed is required, in addition to the particle frequency and size voltages already discussed. A windspeed signal is a desirable secondary output from the visual range computer since the hazard of high winds is, in itself, a real concern in traffic safety. For this reason, and to reduce the influence of local small scale obstacles in the visual range computation, a standard (NWS, FAA) anemometer was chosen, for use at the standard exposure height of 10 m. Output from this sensor is a d.c. voltage, e_u that increases as a linear function of windspeed, giving 4.0 volts at 44.7 m sec^{-1} (100 miles per hour). The 1/7 power law wind profile can be applied to estimate U at the 50-cm level chosen for SPC measurement. The relation $(U_{10}/U_{0.5}) = (10/0.5)^{1/7}$ gives $U_{0.5} = 0.652\ U_{10}$. From the anemometer calibration, U_{10} (m sec^{-1}) = 11.18 e_u (volts) so that the desired windspeed is U = 7.29 e_u. To summarize the design, the equation to be solved is

$$V = 5U/FX^2$$

and the desired computer output voltage is

$$e_v = K/V = KFX^2/5U \qquad (5)$$

where K = 610 (in volt-meters). Input factors are related to their corresponding voltages by

$$F = 667\ e_f\ (\sec^{-1}\ cm^{-2}) \tag{6}$$

$$X = 0.01\ (e_x+1)\ (cm) \tag{7}$$

$$U = 7.29\ e_u\ (m\ \sec^{-1}) \tag{8}$$

Substituting in (5)

$$e_v = \frac{K}{5}\ \frac{(667\ e_f)(e_x+1)^2\ 10^{-4}}{7.29\ e_u}$$

or

$$e_v = \frac{C\ e_f(e_x+1)^2}{e_u} \tag{9}$$

For K = 610 (in volt-meters), the calculated value of C is 1.12. We consider the coefficient, C, as a scaling factor, the predicted value of which was subject to experimental verification.

Data flow through the VRM system is shown by the block diagram (Figure 5). The computer is contained in a 3.5-inch, standard rack-mounted case. An internal calibrator generates signals that simulate full scale values from the sensors, allowing a rapid field check of computer operation with the front-panel voltmeter.

Calibrating the Visual Range Monitor (VRM)

Two questions were of primary concern, once a prototype system was built. First, "Did the computer combine the input voltages in proper functional form to measure visibility?", and if so, "What value of the scaling factor, C gave the proper full scale value?"

Tabler conducted field experiments to answer these questions during the 1972-73 winter, at a location along Interstate 80, about 60 km west of Laramie, Wyoming. His initial method was to read the values of e_x, e_f, and e_u from strip chart recorders to the audio track of a video tape recorder which simultaneously recorded the image of a set of visual targets, from a television camera. The camera was mounted 1.8 m above the ground surface, in a small building with windows allowing a view perpendicular to the usual wind direction during blowing snow events. Flat black targets were positioned along the sight path, at distances that increased logarithmically, and the width of each target increased in proportion to its distance from the camera. By careful design, each target subtended a one-half degree horizontal arc and the image of each target was separated by the same amount.

After verifying that an observer's visual loss of a target was simultaneous with the loss of the target image on the camera, values of the input voltages were tabulated by target distance, for those blowing snow periods when the video replay showed the threshold of target extinction. Averages of these voltages were used to compute $e_f(e_x+1)^2/e_u$, which was plotted (Figure 6) against the distance to the corresponding target, for the three targets that were most frequently obscured. The value $e_f(e_x+1)^2/e_u$ = 7.0 at a visual range of 61 m (200 feet) was chosen as a design point. Since the desired output at this range was e_v = 10.0 volts, the required value of C was computed as 10/7 = 1.43, by equation (9).

Figure 6. These initial calibration results determined the scaling factor, C. The design point was chosen to give a better fit of equation (9) to the lower visual ranges. Subsequent experiments showed the function was also accurate at greater visual range.

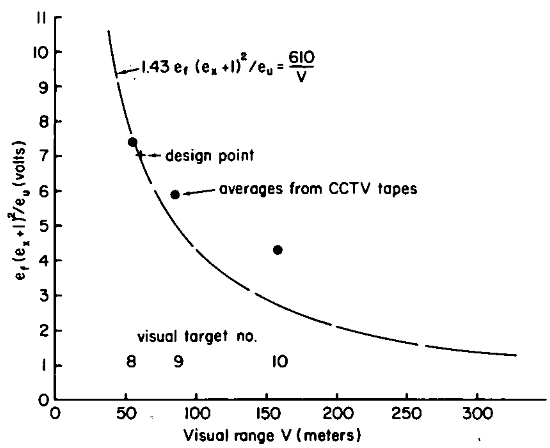
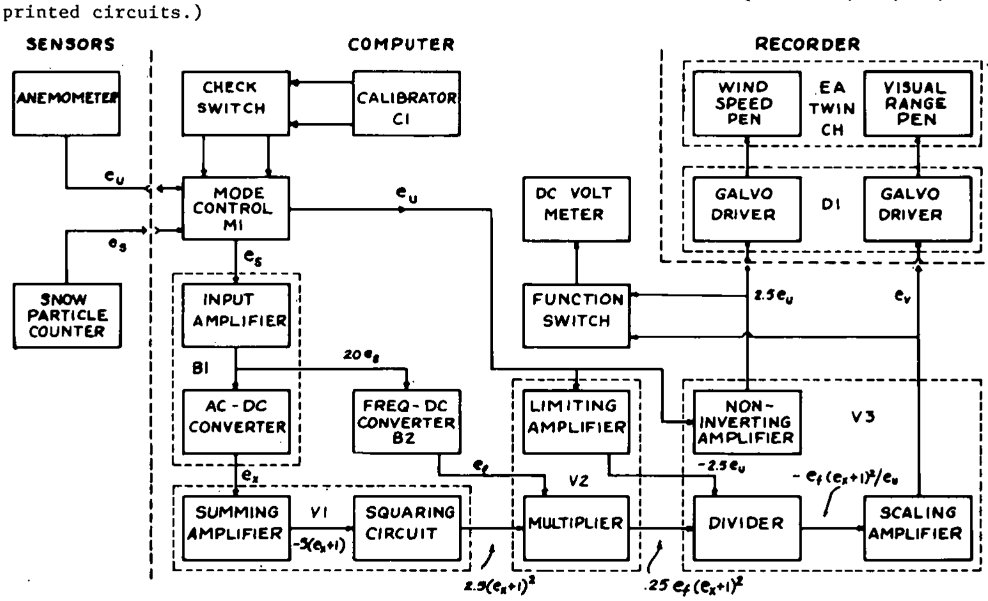


Figure 5. Functions and voltages in the VRM system. (Dashed enclosures designated B1, V1, D1, etc., are individual printed circuits.)



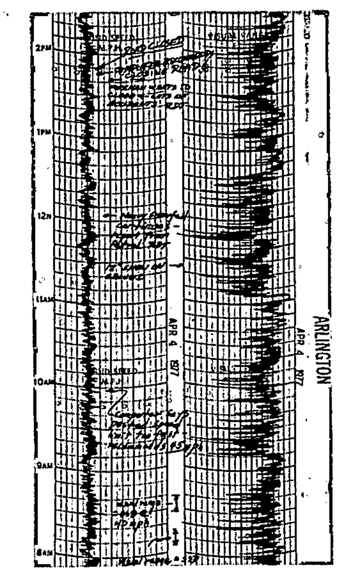
Once the VRM computer was adjusted for the empirical value, C = 1.43, Tabler used a split-screen technique to include a view of the VRM strip chart recorder above the visual range targets on the video image. These recordings convinced us that the computer estimated visual range in very close agreement with actual values. The under-estimation at greater distances, expected from the first experiments (Figure 6) does not occur, and we concluded that the error was due to the difficulty of determining the three separate voltages at the instant the target became obscured.

Perhaps the averaging time of the computer in processing the three input voltages also makes the predicted visual range more accurate. One interesting result of these experiments was that, apparently by the proper (and certainly in this case, fortuitous) choice of averaging times, a very short-path sensor was made to estimate visibilities up to 1 km. As a hypothesis, we suggest that the system compensates for the spatial variation in blowing snow intensity along the sight path by the way in which it averages the time variation due to natural gustiness. Demonstrating this mathematically requires assumptions about the nature of atmospheric turbulence and would prove an adequate subject for an entire paper. Foregoing this, it seems that the number of eddies transporting snow through the sight path vary with time in about the same way as the number passing the sensor during the averaging time interval.

Discussion

Data is recorded on a two-channel strip chart with windspeed on the left channel and visual range on the right (Figure 7). As visibility decreases, the pen moves to the left, and a special chart scale is used so that the left-hand margin of the visual range channel represents a 61 m (200 feet) value, and clear conditions are recorded at the right-hand margin. Very early in our experiments with the VRM, we recognized that the relationship between the two channels could be used to deduce whether travel conditions were improving or becoming worse. For example, if we noted that at some time during a blizzard, a gust of 20 m/s reduced visibility to 80m, but that

Figure 7. This example from an actual VRM record shows the large variation in visibility (right) associated with wind gusts (left). Handwritten notes relate to verification of an automatic analysis system (Tabler 1977).



an hour later a gust of the same magnitude only produced a minimum visibility of 200 m, we would conclude that the amount of snow available for transport was becoming limited. A marked reduction in visibility minimums without a corresponding increase in gust magnitude almost always indicated new snowfall. We began to pursue these new research leads as soon as the first system was placed on-line for operational testing.

In January 1974, the Wyoming Highway Department began testing the VRM as an aid for traffic control and maintenance decisions. The first monitor station was located near Arlington, on Interstate 80 between Laramie and Rawlins. Data from the system was telemetered by radio and telephone to a recorder in the dispatcher's room at the district office in Laramie. Field observations by patrolmen, plow operators, and other personnel were noted on the chart, to demonstrate the correspondence between the record and conditions on the highway. Enough confidence in the system developed during that first season of operation that this new source of information began to be used in traffic control decisions, especially those that involved closing or opening the road. A second monitor station near Elk Mountain began transmitting data to Laramie in 1975. Three years of experience has proven that these systems give reliable data from the remote locations, and that the data can be very useful for traffic and maintenance operations.

All personnel using the VRM were trained to recognize condition trends from correlations between the wind and visibility records, but our new research showed that more useful information is contained in the record than can be determined from routine visual inspection. By analyzing the data with automatic processing equipment, trends became obvious in a much shorter interval, and even estimates of the rate of condition change were possible. A processing system which carries out this data interpretation function was placed on-line at the district office in Laramie during late winter, 1977. The methods and decision logic used in this automatic analysis are reported by Tabler (15).

The snow particle counter has several advantages for application as a sensor in visibility monitoring. It is economical (costing less than $1,000) compared to transmissometers and other devices. Small size makes the SPC readily moveable and its position adjustable, compared to long path sensors which require more permanent mounting. Sensors are easily interchanged if maintenance becomes necessary. However, the instrument exhibits low drift, and requires little maintenance. Lamp replacement each month almost completely eliminates down time from burnout. Weekly checks of sensor gain and balance are recommended, but useable data is obtained with less frequent attention. The use of visible, rather than infrared or monochromatic light makes it easier to check the light beam, and makes the measurement more directly related to visibility. Finally, a signal which measures particle size and frequency rather than light attenuation, allows a visual range estimate based on the functional interaction with windspeed predicted from the theory of light scattering by particles.

Prominent among the factors which aided the rapid development of this system is the support of the Wyoming Highway Department, both financially and in testing the usefulness of the data, allowing us to see immediately what improvements were most needed. The author appreciates this cooperation.

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Visibility in Blowing Snow and Applications in Traffic Operations

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Wind and visibility data continuously transmitted from two monitoring stations on I-80 between Laramie and Rawlins, Wyoming, are analyzed real-time by a computer. Summaries of conditions are printed out hourly, with recommended regulations and warnings when minimum standards are exceeded. Required speed limits are determined by equating "stopping sight distance" to the hourly average minimum visibility, and solving for vehicle speed. Studies reported here show that for wind speeds > 7 m/s in blowing snow, visual range (V) is related to wind speed (U) according to $V = AU^{-5}$, where the A coefficient changes in response to snow availability. The A coefficient calculated from the incoming data is used to index snow conditions, predict visibilities based on wind forecasts, and detect snowfall. This information is used for road closure or opening decisions, and to estimate time required for visibility to reach the prescribed standard for opening a road. Computerized analysis of weather data is essential for timely and objective traffic operations decisions, and the relationship between wind and visibility in blowing snow can provide the basis for standards that are technically sound and unambiguous.

The Visual Range Monitor

Perhaps no other experience can be quite so terrifying to the uninitiated motorist as driving blindly on the highway in a blizzard, unable to proceed and afraid to stop. And yet, paradoxically, no other driving hazard has received so little attention from scientists and engineers. The failure to standardize decision criteria for traffic operations in blowing snow has undoubtedly been due to the lack of a satisfactory device for measuring visibility under these conditions.

In cooperation with the Wyoming Highway Department, Dr. R. A. Schmidt of the Rocky Mountain Forest and Range Experiment Station developed a visual range monitor (1), also described in a separate paper at this symposium. Operational application of this device on Interstate Highway 80 (I-80) since January 1974, has demonstrated the accuracy and reliability of the data; but it has also raised the question of how visibility information should be interpreted and used. This paper presents results of experiments exploring the relationship between wind and visibility, with emphasis on changes accompanying snow cover depletion, and shows how this information is used for traffic operations.

As described by Schmidt (1), the visual range monitor (VRM) uses a photoelectric particle counter to measure size and frequency of blowing snow particles. Given certain assumptions, visual range (V) can be calculated from these data using the equation

$$V = \frac{KU}{FX^2} \qquad (1)$$

where U is windspeed, F is particle frequency, X is particle diameter and K is a constant. A generating anemometer is used to measure wind speed. Although the particle-counter measures a light path only 25 mm long, averages from even a period of minutes appear representative of conditions over the longer but varying sight distance of a motorist.

Another feature of the VRM relevant to later discussions is the standard placement of the particle-counter at 0.5-m height to assure response to light drifting events while minimizing the effect of minor variations in snow depth. This height is also reasonably representative of a driver's sight path, as verified by the visual tests used for calibration. All visual range data presented in this paper should therefore be interpreted as "motorist visibility."

The Wyoming Highway Department has installed VRM units at two locations (Arlington and Elk Mountain) on I-80 between Laramie and Walcott Junction. Data are telemetered via a combination of radio, microwave, and landline to highway department offices in Laramie, where wind and visibility are continuously recorded on strip charts.

After the first year of operational testing, the need for visibility standards in highway operations became apparent. A corollary observation was that relatively subtle changes in the wind/visibility relationship that existed over the course of a drifting event would have to be taken into account in the development and application of standardized decision criteria.

For a given windspeed, visibility was poorer when there was ample fresh snow on the ground, but improved near the end of an event when the ground had "bared up". Evident in retrospect, this relationship between visibility and snow availability is difficult to recognize on the charts during an event, and impossible to quantify because wind is seldom steady long enough to allow conclusive comparisons. The relationship between wind and visibility can change rapidly, as during a period of snowfall, but more subtle gradual changes equally relevant to highway safety can extend over many hours or even days.

For these reasons, a computer was utilized to analyze the data real-time and provide the complex interpretations that boggled the mind of radio operator, scientist, and engineer alike. Two years of intensive research were needed to quantify the relationships between visibility and wind that now provide a more complete assessment of conditions affecting traffic operations.

Relationship between Wind and Visibility

Snowfall with Light Winds

The relationship between wind and visibility during snowfall with light (< 7 m/s) winds is relatively easy to deduce from equation 1. If size of snow particles remains constant, visibility will vary inversely with precipitation intensity. If particle frequency also were independent of wind, then visibility would improve in direct proportion to wind. Our data from study sites on the lee side of mountains in Wyoming, however, suggest that intensity of orographically induced precipitation increases as the square of wind speed, because visibility varies in simple inverse proportion to wind.

Interesting as the low-wind case may be, the associated visibility attenuation is usually not severe. The remainder of this paper will, therefore, be directed to the more critical case where snow previously deposited on the ground is relocated by winds >7 m/s (as measured at 10-m height), with or without concurrent precipitation.

Antarctic Studies

It is not as clear how visibility might vary with wind for the case of relocated snow, because both frequency and mean diameter of particles increase with windspeed.

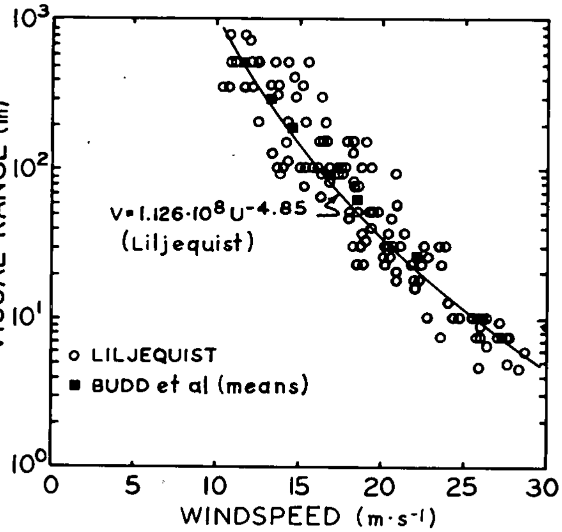
Data presented by Budd (2) suggest particle diameter increases (approximately) as the square root of windspeed (U). Mellor (3) has shown from other Antarctic data that the mass flux of snow particles tends to increase according to U^7 at heights above 0.5 m, and $U^{5.4}$ at lower levels. Equation 1 suggests that visual range should vary as a negative power of windspeed, so that

$$V = AU^{-B} \tag{2}$$

where V is visibility at observer height, U is windspeed at 10-m height, and A and B are constants for a given snow condition. Moreover the above relationships indicate an expected value for B of about 5 at 0.5 m height. As shown in Figure 1, this deduction is substantiated by the visual measurements of target extinction in the Antarctic reported by Liljequist (4) and Budd et al. (5). Liljequist specifically concluded that visibility at observer height (2 m) was related to the -5th power of windspeed over his range of data.

Since both of these experiments were conducted where snow supply on the ground was essentially unlimited, we are left with the problem of how A and B might change as snow cover is depleted. This important question led to the following experiments using the visual range monitor.

Figure 1. Visual range (V) at 2-m height as a function of 10-m wind speed, from visual target data in the Antarctic by Liljequist (4) and Budd et al. (5).



Experimental Procedure

Our studies were conducted at two separate locations. The Cooper Cove site (elevation 2,360 m) is a nearly level area covered by short grass vegetation. The Elk Mountain monitor station (elevation 2,220 m), with low-growing brush vegetation averaging about 20 cm in height, served as a second study site.

The electronic data acquisition system, designed and built by Dr. R. A. Schmidt, used electronic peak detectors to sample the maximum values of wind and visual range signals output from a VRM over a 5-second (s) interval. This method of sampling helped assure matching of visibility and wind values, since the anemometer was installed 10 m above the ground, while the particle counter was at a height of 0.5 m and located about 15 m upwind from the anemometer. An electronic calculator served as system controller for selecting channels, controlling peak detectors and digital voltmeter, and storing data on magnetic tape. The least-squares value for A and B in equation 2 were calculated at 10-min. intervals and output on a printer and X-Y plotter. Visibility and wind were continuously recorded throughout six separate drifting events totalling 234 hours, over a wide range of weather conditions.

Air temperature and humidity at 2-m height were recorded with a hygrothermograph; precipitation was measured with recording gages located in tree-sheltered spots near the study sites. Characteristics of the snow cover were observed and photographed throughout each run.

Results from Wyoming Studies

The power function (equation 2) is an empirical approximation for the complex relationship between wind and visibility. Over the narrow range of windspeeds encountered in a 10-min. sampling period, the power B was quite variable and ranged from 2 to 8, with the lower values generally associated with lower visibilities. To provide the widest possible range in the variables, data were grouped into periods having essentially uniform snow conditions and up to several hours in length. Results of this analysis over all snow conditions gave an estimate for B of 4.90 ± 0.20 (.95 confidence interval), determining an integer value of 5 for the mean.

Statistical analysis of individual storms by hourly intervals showed B to remain essentially constant as snow conditions changed. This is demonstrated by the results shown in Table 1 which describes typical drifting events of February 20-22, 1976. Prior to the drifting, approximately 30 cm of snow (3.0 cm of water-equivalent) fell during a 24-hour period beginning at 1700, February 19. Winds accompanying most of the snowfall averaged between 1 and 5 m/s, with air temperatures between -12 and -4°C. For the last 5 hours of the precipitation period, winds slightly exceeded the threshold (7 m/s) for relocating snowfall, causing low-level drift with visibilities ranging from more than 10,000 m to a minimum of about 600 m. Data for period 2 (Table 1) are plotted in Figure 2, although points with visibilities >10,000 m are not shown.

Air temperature ranged from -15 to -3°C from the end of snowfall until stronger winds abruptly began at about 1800 on February 21. At this time, the snow surface was covered with small dunes and weakly developed erosional features from intervening light winds, but essentially no vegetation showed above the snow surface (Figure 3A). Drifting continued for the next 20 hours with winds seldom exceeding 20 m/s, and air temperatures as shown in Table 1. By 1300, February 22, air temperatures had increased to +2°C, and drift essentially ceased although winds continued to gust as high was 17 m/s. The original snow depth had been reduced by about 75%, exposing vegetation above the snow surface (Figure 3B).

The variation in B throughout this event is typical when hourly periods are used for analysis, reflecting variations in the range of data and the approximate fit of the power function. Nevertheless, there seems to be no consistent change in the general relationship as temperature increased or as snow cover was depleted (Table 1).

Data representative of the beginning of the main drifting event (period 6) are plotted in Figure 2. At this time, the A coefficient of equation 2 (assuming B = 5) was about $7 \cdot 10^8$ m^6/s^5, which is significantly greater than the $1.13 \cdot 10^8$ value the author calculated from Liljequist's (4) plotted data. The only time this latter value was approached was during periods of snowfall (e.g., periods 2 and 3 in Table 1). Liljequist stated that his results are representative of air "saturated" in relation to its snow transport capacity--a condition that might be assumed for periods 2 to 3 in view of the light snowfall intensity (0.5 mm/hr). Certainly, the steady ablation of the snow surface in the absence of precipitation, as occurred over periods 5 to 22, is indicative of "unsaturated" conditions so that A values greater than 10^8 m^6/s^5 would be expected.

Figure 2. Minimum "motorist" visual range as a function of maximum 10-m wind speed over 5-s intervals. Data for three periods, shown in Table 1, are representative of the beginning, middle, and end of drifting events at the Cooper Cove site in Wyoming. Corresponding snow conditions are shown in Figure 3.

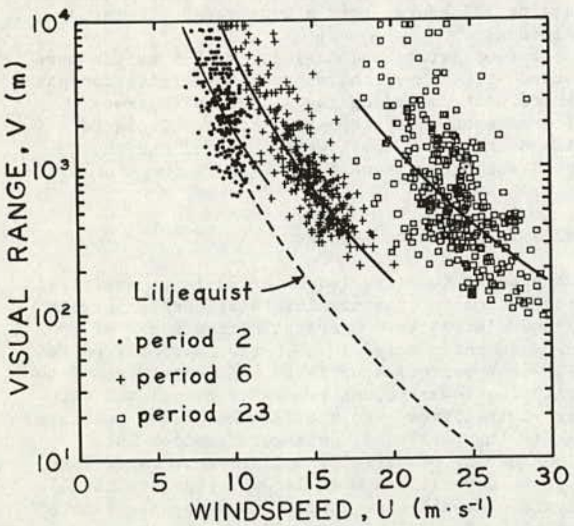


Figure 3. Snow conditions at Cooper Cove, for comparison with data in Table 1 and Figure 2. Snow particle counter extends horizontally from pipe in foreground. A values (in m^6/s^5) refer to the coefficient of equation 2 assuming B = 5.

(A) 1550 February 21, 1976: $A = 7.6 \cdot 10^8$
(B) 1352 February 22, 1976: $A = 1.2 \cdot 10^9$
(C) 1150 February 7, 1976: $A = 1.5 \cdot 10^{10}$

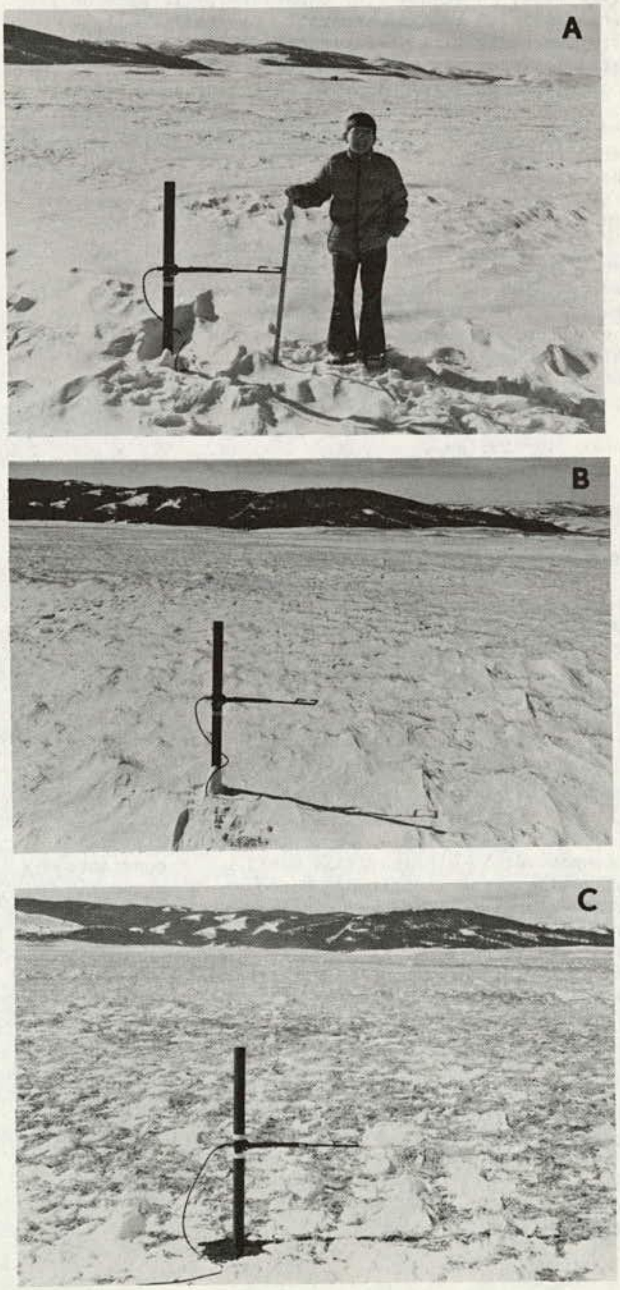


Table 1. Analysis of visibility/wind relationship for typical drifting events at Cooper Cove. $\bar{U}$ is mean windspeed at 10-m height (m/s), $\bar{V}$ is mean visual range averaged over motorist sight path (m), $\hat{B}$ is the least-squares estimate for the power in equation 2 shown with 0.95 confidence interval, $\hat{A}$ is the least-squares estimate for the coefficient (m^6/s^5), r is the correlation coefficient, n is the number of samples, $\hat{A}_{(-5)}$ is the least-squares estimate for the coefficient A ($10^8 m^6/s^5$) assuming B = 5, and T is mean air temperature at 2-m height (°C).

Period	Time	$\bar{U}$	$\bar{V}$	$\hat{B}$	$\hat{A}$	r^2	n	$\hat{A}_{(-5)}$	T
February 20, 1976									
1	1140-1218	8.7	5859	4.6 ± 1.2	$9.57 \cdot 10^7$	.29	136	2.59	-09
2	1218-1321	9.3	3269	4.2 ± 0.8	$2.95 \cdot 10^7$	.29	249	1.90	-09
3	1321-1429	8.9	2659	1.3 ± 0.5	$1.59 \cdot 10^4$	.09	298	1.22	-09
4	1429-1532	9.4	3811	3.3 ± 0.5	$5.22 \cdot 10^6$	.35	300	2.30	-11
February 21, 1976									
5	1802-1904	11.6	4222	3.4 ± 0.7	$1.53 \cdot 10^7$	.29	208	7.58	-07
6	1904-2006	14.4	1531	5.2 ± 0.4	$9.06 \cdot 10^8$	.74	281	6.68	-07
7	2006-2109	15.6	837	4.3 ± 0.5	$9.34 \cdot 10^7$	.46	306	6.42	-07
8	2109-2211	15.5	1074	4.5 ± 0.5	$1.77 \cdot 10^8$	.48	306	8.51	-07
9	2211-2313	15.5	949	4.1 ± 0.5	$6.05 \cdot 10^7$	.46	306	7.26	-06
10	2313-0016	15.6	851	3.8 ± 0.6	$2.10 \cdot 10^7$	.35	306	6.72	-06
February 22, 1976									
11	0016-0118	15.1	1355	5.0 ± 0.6	$7.64 \cdot 10^8$	.50	303	9.71	-06
12	0118-0220	13.6	2319	5.0 ± 0.6	$9.32 \cdot 10^8$	.49	272	9.03	-06
13	0220-0323	15.4	1481	4.9 ± 0.5	$6.82 \cdot 10^8$	.56	303	10.38	-06
14	0323-0425	15.6	1574	4.7 ± 0.5	$4.66 \cdot 10^8$	.52	302	12.47	-06
15	0425-0527	16.8	1070	4.4 ± 0.5	$1.86 \cdot 10^8$	.52	306	12.05	-05
16	0527-0629	17.3	919	3.8 ± 0.4	$3.96 \cdot 10^7$	.49	306	11.25	-05
17	0629-0732	16.0	1245	4.4 ± 0.5	$2.15 \cdot 10^8$	.53	306	11.23	-04
18	0732-0834	14.5	2610	4.8 ± 0.6	$8.20 \cdot 10^8$	.46	283	13.82	-03
19	0834-0936	15.1	1505	4.5 ± 0.4	$2.12 \cdot 10^8$	.58	303	9.76	-02
20	0936-1039	14.6	1864	5.1 ± 0.4	$1.10 \cdot 10^9$	.61	300	10.20	-01
21	1039-1141	14.0	2828	5.0 ± 0.4	$9.50 \cdot 10^8$	.67	275	11.12	+01
22	1141-1244	14.0	2865	5.0 ± 0.5	$1.04 \cdot 10^9$	.56	263	12.42	+01
February 7, 1976 (end of event only)									
23	0808-0910	23.8	1011	5.7 ± 0.9	$3.57 \cdot 10^{10}$	.35	301	66.53	-01
24	0910-1013	22.3	3243	5.9 ± 1.2	$1.63 \cdot 10^{11}$	.31	198	147.80	+01

The visual calibration of the VRM, even though aided by closed-circuit television, leaves room for the same error as might be inherent in Liljequist's target observation data, and so neither experiment provides a standard. Owing to the steep exponential relationship, only a 10% discrepancy in wind measurement could account for the entire difference in A values for conditions of (essentially) unlimited snow. It is not clear if the Antarctic data are truly comparable to our instantaneous measurements. Liljequist used contact anemometers which would tend to underestimate wind speed maxima, as compared to our use of a standard d-c generating anemometer. Further, visibility measurements from the Antarctic studies may represent averages over a presumably short interval of time.

Considering these uncertainties and the expected differences in snow conditions, the quantitative results from the Antarctic and Wyoming studies appear to be in reasonable agreement.

An additional test of the estimation of B is available from a drifting event February 6-7, 1976, that began with about 20 cm of snow on the ground. Strong winds (>30 m/s) and rising temperatures (+1°C at the end of the event) succeeded in removing essentially all relocatable snow after only 12 hours. Results of analyses for the final 2 hours of this event are listed in Table 1 as periods 23 and 24. Data for period 23 are plotted in Figure 2, and snow conditions are shown in Figure 3C.

The hypothesis that B = 5 cannot be rejected even at this extreme stage of snow cover depletion, although the A coefficient has increased by two orders of magnitude from the value for unlimited snow conditions. It is also shown in Figure 2 that variance in the wind/visibility relationship increases as snow availability diminishes, and this is observed throughout the experiment.

Summary

Conclusions from the above studies can be summarized as follows:

1. For practical purposes, it can be assumed that the function

$$V = AU^{-5}$$

applies to all winds strong enough to relocate snow, over the entire range of snow conditions, and with or without concurrent precipitation.

2. The A coefficient ranges from 10^7 for conditions of maximum snow availability with concurrent intense snowfall, to $>10^{10}$ m^6/s^5 in the final stages of a drifting event. A therefore provides a responsive index of snow availability.

3. Variance increases as snow supply diminishes, affecting the reliability of the estimates for the A coefficient.

4. Visibility values obtained with the VRM are in reasonable agreement with published target observation data.

Operational Use of Wind and Visibility Data

Interpretation of the A Coefficient

The preceeding evidence leads to the practical generalization that the power in the visual range equation 2 is constant and approximately equal to 5.0, while the A coefficient changes in response to snow availability. Even subtle variations in the character of the snow surface can bring about significant and identifiable changes in A. A striking example is the abrupt decrease in the A value with the onset of snowfall. Precipitation intensities as light as 0.1 mm of water-equivalent per hour have been observed to lower A from 10^9 to $2 \cdot 10^8$ m^6/s^5 over a period of 30 minutes. The reason snowfall is detectable from an analysis of the wind/visibility data output from the VRM is because older snow consists of subangular grains sintered to form a surface relatively resistant to particle dislodgment. Fresh snow, however, is quickly fragmented and easily transported, so particle frequency rapidly increases whenever new precipitation is received, even though the older snow may lie meters deep on the ground. Therefore, the A coefficient will continue to decrease as precipitation continues until, to use Liljequist's description, the air becomes "saturated" in relation to its snow transport capability. Once the input of fresh snowfall ceases, however, the metamorphosis of particles into "older" snow is rapid.

In general, an A value $\leq 1.2 \cdot 10^8$ m^6/s^5, or an abrupt decrease in this parameter, appear to be reliable indicators of precipitation. On occasion we have also observed smaller decreases in A without precipitation, presumably associated with the disruption of surface crusts at the onset of strong winds. Other changes occur with the arrival of snow from discrete contributing areas upwind, and each location has its unique characteristics that might provide useful information about the progress of a storm.

As demonstrated by Figure 3, the A value can be interpreted in terms of snow conditions and potential visibility attenuation. But the change in this parameter over time can provide additional information about trends in snow availability relevant to traffic operations decisions.

Sampling Visibility and Wind Data

Numerous problems are encountered in choosing the method by which data are collected for analysis. Because adequate sampling procedures are critical and somewhat complex, a brief description of the methods we have developed for the Wyoming Highway Department system may prove useful.

Analog signals of wind and visibility are telemetered from the field monitoring stations at Arlington and Elk Mountain on I-80. Data processing, analysis, and peripheral hardware control are performed by a Hewlett-Packard 9825 calculator with 23k byte memory (the use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable). The calculator controls the clock, scanner relay, and digital voltmeter used to measure instantaneous values of wind and visibility at the rate of one sample pair from both stations each second. This sampling frequency is sufficient to insure that extremes will be sampled within 5% of their maximum or minimum values.

Every 8 s, the largest and smallest values of each variable are determined, and only these are retained for analysis. This allows wind values to be matched with their corresponding visibilities--a procedure made necessary by the fact that the anemometer is located about 10 m above the ground, while the snow particle counter (SPC) is typically installed at 0.5 m height. Although the SPC is positioned about 15 m upwind of the anemometer to help compensate for the resulting arrival lag caused by the logarithmic wind profile, the delay in a gust's arrival at the anemometer and the SPC is a function of wind speed, and so a matching period becomes necessary. Our experience shows little difference between a 5- and 10-s period for this purpose (although variance begins to increase on either side of this range) and so we have chosen 8 sec. Both maximum and minimum values are used to provide the widest possible range of data for statistical estimation of the A coefficient in equation 2.

These paired visibility and wind values are accumulated over approximately 10 minutes to provide an adequate sample number for estimating A by least-squares regression analysis, assuming B = 5.

The Critical Visibility Statistic

In using visibility data for traffic operations decisions, one is faced with selecting the critical statistic. Should traffic operations be based on an average visibility? And if so, over what period of time? If minimum visibility is considered the limiting factor, over what time period? To the author's knowledge, this problem has not been resolved for the case of blowing snow where visibilities exhibit such a complexity of frequencies and amplitudes.

One theory is that visibility information gained by a motorist during a lull between two gusts can be applied to traverse the seen distance safely even though subsequent gusts may at times obscure the "farthest point seen" (with the necessary constraint that the maximum seen distance not exceed the "minimum design sight distance" for the road). Assuming a simple sinusoidal variation in wind gusts having a period of 60 s (typical for primary fluctuations), it can be shown that "stopping sight distance" (SSD) cannot exceed the minimum visibility if a safe vehicle speed is to be maintained. Since amplitude varies with time, a logical course is to base traffic operations on an average of several minimum visibility values measured over a specified time period. To reduce the weight given to anomalous or extreme gusts while providing a statistic representative of minimum visibilities, we have defined the <u>hourly minimum visibility</u> as the geometric mean (i.e., calculated from the logarithms) of the six 10-minute minimum values. This procedure simplifies programming for hourly reports and recommendations, and has given reasonable results in preliminary tests and operational trials.

In summary, although the statistical analysis to determine the A coefficient uses all the wind and visibility data (150 paired values) over each 10-minute period, only the lowest visibility value (and the strongest wind gust) are retained for traffic operations decisions. Although these 10-minute extremes are used to warn the computer operator of dangerous conditions, traffic operations are based on the hourly minimum visibility as defined above.

Use of Visibility Data for Traffic Operations

Traffic operations routines are included in the same program used for measurement and analysis of the wind and visibility data telemetered from the two field monitor stations on I-80. Warnings and notices are printed after each 10-minute sampling period as required. Summaries of visibility and wind conditions are output hourly, along with recommended regulations and warnings when minimum standards are exceeded. A typical printout is shown in Figure 4.

Recommended speed limits are determined by equating SSD to the hourly minimum visibility, and solving for vehicle speed. The metric version of the commonly used equation for SSD (6) is

$$SSD = 0.278U_vT + \frac{0.118U_v^2}{30(f + g)} \tag{3}$$

where U_v = vehicle speed, km/h

T = preception-reaction time, s

SSD = stopping sight distance, m

f = friction coefficient

g = grade, m/m (+ for uphill, - for downhill)

Solving for U_v and substituting hourly minimum visibility $\bar{V}_{min}$ (in meters) for SSD,

$$U_v = -35.34T(f + g) + 127.12\left[0.077T^2(f+g)^2 + 0.016(f+g)\bar{V}_{min}\right]^{0.5} \tag{4}$$

The effect of grade can be ignored in view of the arbitrary definition of $\bar{V}_{min}$. Taking 2.5 s as the usual approximation for T, then

$$U_v = -88.35\ f + 127.12\left[0.48\ f^2 + 0.016\ f\ \bar{V}_{min}\right]^{0.5} \tag{5}$$

Application of equation 5 requires that information on road surface conditions be kept current in the calculator's information file, and that appropriate friction factors are known for various road conditions.

Perhaps the most important function of the on-line computer is to automatically provide recommendations for road closure (or opening) using standardized criteria and decision logic. Minimum visibility standards are specified in terms of the vehicle speed required for the "stopping sight distance" to equal the hourly minimum visibility, thus taking road surface conditions into account. The author has observed an increased tendency for inexperienced drivers to stop their vehicles when speeds <50 km/h are required to negotiate reduced visibility in blowing snow, and this value has therefore been selected as the minimum requirement for keeping the road open to traffic. Although future experience may suggest the desirability of a different value, this standard has provided the basis for traffic operations decisions consistent with the opinions of highway maintenance personnel over three years of operational testing.

Road closure decisions involve many factors in addition to current weather conditions, and the computer allows consistent interpretation of numerical data analyses incorporating past experience of maintenance foremen. Factors included in the decision program include

1. Average hourly minimum visibilities over the last 3 hours,
2. Road surface conditions,
3. Traffic problems,
4. Time of day,
5. Condition of alternate route,
6. Trends in snow availability as indexed by the A coefficient of equation 2,
7. Trends in wind speed,
8. Weather forecast (wind and visibility).

The forecast visibilities referred to in item 8 are calculated from the current A value (as calculated by the computer) and the latest wind forecast issued by the National Weather Service. This is a most important application of the wind-visibility relationship because it allows potential visibility hazard to be expressed in meaningful quantitative terms. As a hypothetical example, current winds

Figure 4. Printout from Weather Condition Monitoring and Traffic Operations Program during storm of April 4, 1977. Original thermal printer output has been retyped for legibility, but text is exact reproduction. Dashed lines indicate deletions, and English units are used throughout (A values are in ft^6/s^5).

```
1131 APR 4, 77
 **DECISION REQUEST BY          cupal
 Conditions do not warrant decision at this time

1141 Apr 4, 77
 WARNING...POSTED SPEED LIMIT TOO FAST FOR CONDITIONS AT Arlington
 visual range equals SSD at 40 mph
 next hourly report will give recommendations

-------------------------------------------------------------------

1204 APR 4, 77            INFORMATION ON FILE
 Regulations in Effect:
      road open
      55 speed limit
 Road Surface:
      snowpacked, sanded
 Precip. Reported:
  Arlington: heavy snowfall
  Elk Mtn.: heavy snowfall
  (note that computer has detected snowfall)
 Traffic problems:
  none
 Weather Forecast:  1044 APR 4, 77
       35 maximum wind
      snow showers in & near mtns.
      precip. probability, % unknown
 Decision Criteria:
      imperative code = 2
      highway 30 condition code = 2
 Operator on duty:
      cupal

1204 APR 4, 77   ************  CONDITIONS LAST HOUR ***************
                                      ARLINGTON          ELK MTN.
 Ave. max. wind (mi/hr)                  37                 31
 Ave. min. visual range (ft)             267                387
 Minimum safe visual range                         185
 Precip. reported?                    heavy snow         heavy snow
 Precip. detected?                       yes                yes
 "A" value                             1.0E 11            7.2E 10
 Computed driving time to/from Rawlins          2:16

1204 APR 4, 77   ************ REGULATIONS INDICATED ***************
 Speed limits required                   35                 45
 WARNING...POSTED SPEED LIMIT TOO FAST FOR CONDITIONS AT Arlington
 WARNING...POSTED SPEED LIMIT TOO FAST FOR CONDITIONS AT Elk Mtn.
 Speed limits should be lowered as indicated above
-------------------------------------------------------------------

1344 APR 4, 77
 **DECISION REQUEST BY          Tabler
 USING STANDARDIZED DECISION CRITERIA, ROAD SHOULD BE CLOSED.
 >>DECISION MADE TO CLOSE ROAD
```

speeds gusting to only 13 m/s with an A value of $3 \cdot 10^8 m^6/s^5$, would imply present visibilities to be more than 800 m. But a wind forecast for gusts reaching 25 m/s would mean visibilities as low as 30 m.

As described previously, visibility data are used to detect snowfall, and this information is also used in the decision logic. This feature is important when reports are not available from the field; in addition, it is often difficult for an observer to tell whether or not it is snowing during a heavy drifting event.

A final application of the wind/visibility analysis is for estimating the time required for visibilities to reach the prescribed standard for opening a road previously closed due to poor visibility. This is accomplished by extrapolating the current rate of change in the A value to determine the time required for the standard to be attained.

These examples show how on-line computer analysis of wind and visibility data can provide the engineer or foreman with essential information not otherwise available to him for making timely and sound decisions. Analysis of the relationship between these variables can provide the basis for objective traffic operations standards that are technically sound, unambiguous, and legally tenable.

Acknowledgments

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Present Status of the Bridge Ice Detection Program at FHWA

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This paper discusses the need for an effective ice detection system for bridges, and outlines an early evaluation program that has led to the selection of a spot ice detector for further testing. This small detector is installed flush with the surface of a pavement and, with its associated electronics package, is capable of transmitting surface conditions to a remote location over a telephone or radio link. The advantages of an area ice detector are discussed and results to date in the development of a microwave radiometer for detection of surface condition are presented.

Introduction

The highway community has long been aware of the hazards presented to motorists by preferential icing of bridges versus roads. The driver proceeds along a road where he observes no frozen precipitation and drives accordingly. Suddenly the road changes to an overpass or a bridge, with possibly a curving transition, and the motorist finds his vehicle out of control in a situation where leaving the road and penetrating the guard rail may result in serious injury or death. In addition to the personal tragedy associated with an accident of this kind, there has been calculated an equivalent cost to society for traffic-related injuries and deaths that is shockingly high, being evaluated at over $300,000 per fatality.

There is reason to believe that the perpetually present signs warning of this hazard lose effectiveness due to their familiarity and to the fact that most of the time their message is not pertinent to the immediate driving situation. It is reasonable, then, to take a position that a justifiable approach to reducing accidents from preferential icing would be either the provision of a hazard warning system that is highly visible and is activated by the occurrence of icing conditions, or a system that can enable maintenance personnel to learn of the existence of hazardous conditions so that they can dispatch salting or de-icing trucks to specific sites. Modifications or combinations of the above may also be taken to achieve the desired result.

From the above discussion it can be concluded that efficient and effective action can be taken only if there is available a dependable ice detector capable of discerning the presence of bridge ice with a high detection probability and a low false alarm rate. As a result of this need, the Federal Highway Administration initiated a program in 1969 to select and/or develop a suitable bridge ice detector.

History of the Program

This first program attempted the initiation of contractor-conducted evaluations of the potential usefulness of nine different commercially available highway ice detectors which operated on a variety of physical principles. As a result of a preliminary screening, four of the nine candidate systems were dropped from further consideration, primarily because they were judged incapable of coping with the effects of deicing chemicals. Of the five remaining candidate systems, it was found that one was not available for purchase, and another (a radiometer) was still in the development stage, and at the time this pursuit was considered to be an excessively costly development program, rather than a purchase.

Two sets of each of the three remaining candidate systems were deployed on a carefully selected bridge near Truckee, California, and an instrumentation/observation trailer with computer, meteorological instruments, traffic recorders, and ice detector data recording equipment on board was parked nearby. The results of the evaluation program were that one manufacturer's product had frequent failures of its sensing head, a second type of sensor was determined to be incapable of operating in the presence of heavy snowfalls, and the third sensor functioned fairly reliably, but with some false and some missed alarms. A new model of this most successful commercially available snow and ice sensor is manufactured by Surface Systems, Inc. (SSI), St. Louis, Missouri, and was purchased for installation in a road at the Fairbank Highway Research Station, McLean, Virginia, so that its long-term performance characteristics under very light traffic conditions could be evaluated.

Current Evaluation of the SSI Equipment

Figure 1 shows a general view of the equipment as installed at Fairbank Highway Research Station, and Figure 2 shows the SSI equipment boxes being serviced adjacent to an experimental solar panel. Figure 3 shows the relative location of the SSI sensor and the local road where it is installed.

Figure 4 is a closeup view of the sensor. The metal conductivity sensing elements are clearly visible, as is the epoxy overlay surface of the sensor. This rough textured surface was added to the previously smooth textured sensor by SSI in an effort to obtain a surface that more closely resembled the thermal response characteristics of typical roads, and also, the new coating spaced any moisture farther from the built-in capacitance bridge moisture sensing system (to reduce sensitivity).

Figure 5 shows the SSI equipment mounted in the left-hand box, and the VHF FM transmitter used to convey the coded signals from the SSI electronics boards to the receiver and decoder located in a laboratory approximately 300 ft away.

Figure 1. General view of equipment.

Figure 2. Servicing of SSI equipment boxes.

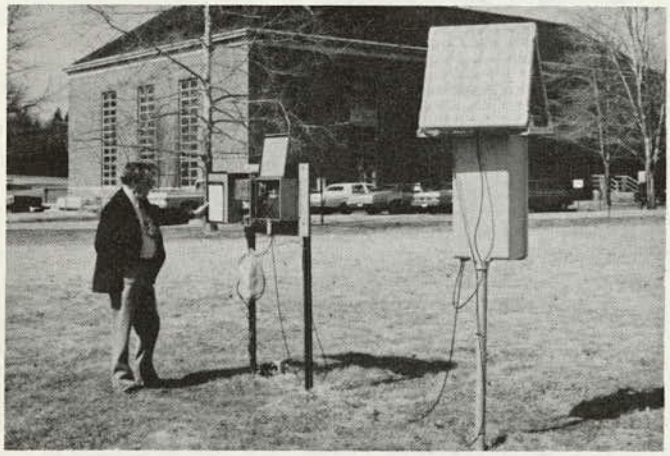


Figure 3. Location of sensor in local road.

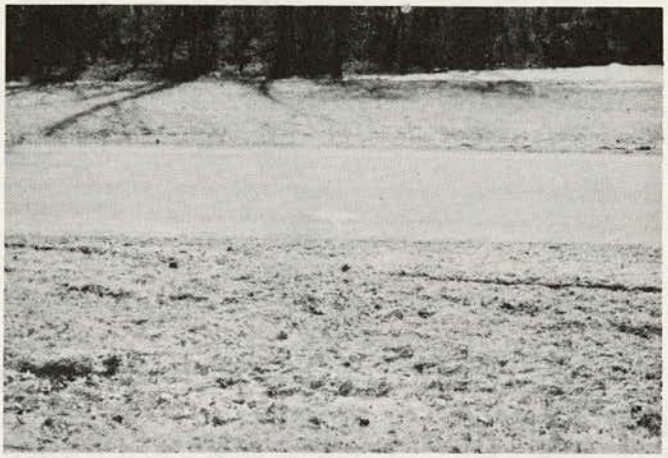


Figure 4. Closeup of sensor.

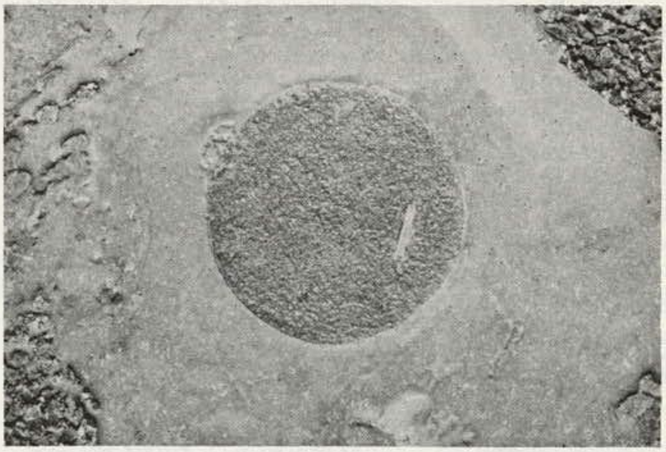


Figure 5. SSI equipment (left) and VHF FM transmittor (right).

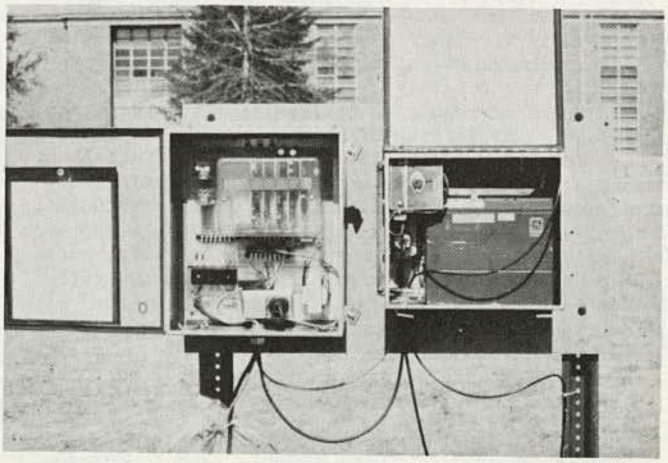
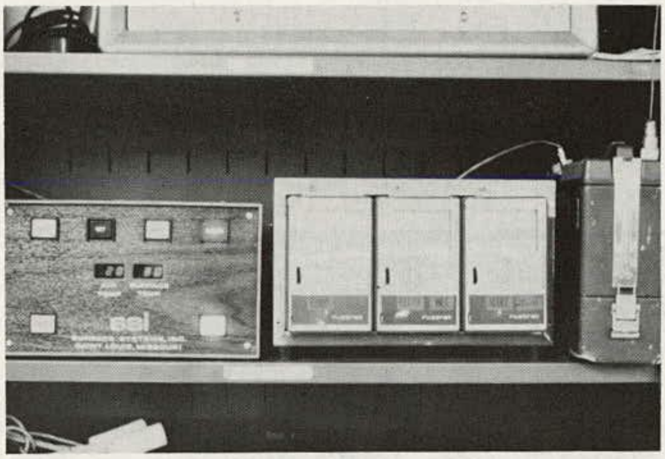


Figure 6 was taken in our laboratory and shows the VHF receiver on the right, the SSI decoder on the left, and three, two-channel strip chart recorders that are used to record the performance of the ice detector unit.

Figure 6. VHF receiver (right) and SSI decoder (left).



Operating Principle of the SSI Detector

The SSI ice detector is a proprietary device that determines the condition of a road to be either "dry," "wet," "alert," or "hazard" as follows.

A capacitance bridge mounted in the 3-in. diameter sensor disk determines the presence of water-containing precipitation. Two closely spaced conductors on the surface of the sensor measure the resistance of any material appearing between them, and a thermistor mounted below the surface of the sensor determines whether or not the temperature near the surface is above or below 32°F (0°C). The logic of the unit is such that if the temperature is above 32°F, warning of Alert and Hazard cannot be activated. If the surface is sensed as wet, and the resistance is very low, the road condition is interpreted as being wet. As water (pure or mixed with de-icing agents) freezes, its resistivity increases greatly over that of its liquid state. Therefore, as measured resistance increases beyond some low threshold value, the Alert condition is announced. As freezing continues, resistance increases further and the Hazard condition is signaled. If resistance becomes still higher than that required for indication of Hazard, it is assumed that only a light frost can be present on the sensor, and the interpretation reverts to ALERT.

Test Results at Fairbank

The SSI equipment was installed and operating by late November 1977, and since that time has suffered no electronic malfunctions. It has operated through a wide variety of weather conditions and has generally been able to indicate the conditions of the surface of the road reasonably well. However, there have been several specific occasions when the unit has false-alarmed and occasions when it has missed alarms. The false alarm condition usually followed a period of rain or snow when the surface of the road had been wet and had not completely dried out when the precipitation ended. If the skies were overcast and the weather cold, the sensor would detect the slight moisture around and in it as water, despite the fact that it was dry to sight and touch. Under these conditions, with the indicated temperature of the sensor being below freezing, and essentially no conductive material shunting the resistance sensor, the unit would indicate "Hazard." Missed alarms were usually the result of circumstances where there was a light dusting of snow, perhaps 1/4 in. or so deep, and the temperature was near freezing. Here the snow was able to rest on top of a thin coat of water, which would shunt the resistance sensor. The instrument would indicate "wet," for on the microscopic scale its surface was wet. However, a driver would observe snow on the surface, and with this set of circumstances the unit might lose credibility with motorists.

Following 6 month's operation the SSI system is not only fully operational, but in addition, the epoxy road sensor appears not to have suffered at all from its winter of very light duty exposure. We plan to continue life testing the unit for at least another year, and will continue to collect data and observe the accuracy of its condition reports.

Area Ice Detection

From the previous discussion it is clear that there are at least three distinct disadvantages of the embedded-in-road sensor.

1. By being in the road in order to sense the condition of the road, it is subject to damage from snowplows, heavy trucks, chains, and studded tires.
2. By being beneath precipitation, and due to the likely use of de-icing chemicals and subsequent imperfect mixing, it is possible that the surface of the road in the vicinity of the sensor is different from what the driver perceives. That is, the driver may observe snow, and the sensor may observe water; both may be correct, but due to their different viewpoints, the sensor is judged to have called the situation incorrectly.
3. Possibly the most serious shortcoming of any "spot" ice detector is its limited sensing area. An attempt is made to place the device at a location that best typifies the condition of the bridge with respect to precipitation. It is not difficult to speculate that the daily and seasonal movements of the sun will cause the location of the preferred sampling spot to vary. It would appear desirable to be able to hedge on the location of a sensor by enlarging its sensitive area, or by being able to move the area being sensed.

Area Sensor Requirements

The operational limitations of a spot ice detector for highway use made it desirable to investigate the possible development of an area-type ice detector. It should then be possible to compare the cost-benefit ratios of both bypes of systems for various climatic and traffic situations.

The development of an area sensor is complicated by the necessity for it to operate over a wide range of temperatures, surface textures and colors, and be unaffected by the passage of traffic, chemicals, dirt, and weather. Furthermore, the system must be relatively immune from various types of interference and, very significantly, it must present no hazard to the motorist or his vehicle. Eventually, the sensor must evolve into a very reliable and low cost device.

After it was determined that the development of an area ice detector would be pursued, a formal procurement resulted in the selection of Lockheed Missiles and Space Company (LMSC) to build and evaluate a microwave radiometer as an ice detector. In this process we were pleased to note that LMSC had previously developed a 10 GHz radiometer and had even collected some data on its ability to detect snow and ice.

Operating Principle

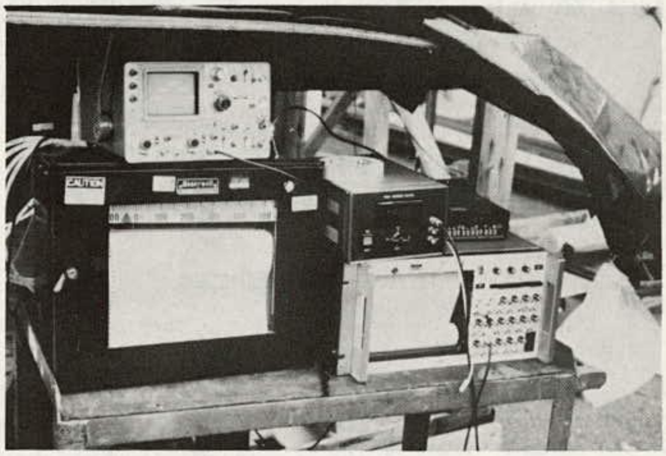
It appears desirable to review briefly the physical principles by which this type of instrument can be expected to detect the presence of snow or ice on a roadway. A radiometer is a gain-stable radiation receiver having such low internal noise that it is capable of detecting the electromagnetic radiation of objects occurring as a result of their being at a temperature higher than absolute zero. If snow and ice have a different radiometric temperature than a wet or a dry pavement at the same thermometric temperature, then we have the beginnings of an ice detector.

The selection of the wavelength (or frequency) of the radiation to be detected in a given radiometer system is a compromise involving object temperature, requisite temperature resolution, size of object and antenna, attenuation in the atmosphere, cost and other parameters. The receiver being built and evaluated under this program is configured to operate at a nominal center frequency of 10 GHz, and will have a noise figure of 6 and an intermediate frequency bandwidth of about 400 MHz. Post-detection bandwidths will be limited to 10 Hz or less in order to increase the minimum discernable temperature difference. This figure is also affected by considerations of the effects of traffic and the possibility that the ice detector will be used to detect traffic as well as ice. A small horn antenna will provide a beamwidth of about 13°, and this will give adequate coverage to detect a 2 x 4 ft icy area from the vantage point of an existing luminaire on the bridge. A larger or smaller area can be obtained from any reasonable height by selecting an antenna having suitable directional characteristics. However, there are limits to antenna directivity. Too much directivity will reduce the detected area to the equivalent of a spot detector, and an attempt to enlarge the viewed area by increasing antenna beamwidth will produce both sensitivity and angle of incidence problems. Because the radiometer will produce a reading which is the average temperature of its field of view, a large viewed area would mean that patches of ice in areas where ice is most likely to be would not be detected when averaged with adjacent non-icy pavement. The other problem is that the viewing angle should not exceed about 20°-30° from vertical. The detector will be protected from the environment by a weatherproof insulated box and a radome covering the antenna.

Calibration

Once of the design features of the selected ratiometer is its continuous, self-calibrating feature (see Fig. 7). Radiometric temperatures are determined following a sequence of measurements of road temperature, the increment of output produced by switching in a calibrated internal source, and the internal noise of the radiometer receiver itself (when the antenna is effectively disconnected). With a well-designed instrument that uses a stable calibrating noise source, it is possible to servo-adjust the gain of the receiver so that indicated radiometric temperatures will remain accurate and stable.

Figure 7. Setup for determining radiometer performance during outdoor engineering development tests. Shown are thermocouple recorder, radiometer internal calibration waveform, and radiometer temperature indicator and recorder.



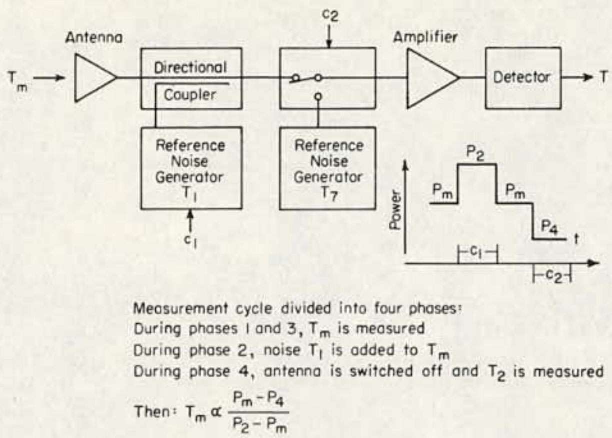
Manual checkout and adjustment of the calibration of the instrument can be simply made at two known values. Pointing the antenna to the sky provides a radiometric temperature of about 10 K. The other calibration value is obtained by placing a block of microwave absorbing material in front of the antenna. This material acts as a black body source, and therefore provides a temperature reading equal to ambient air temperature.

What the Radiometer Sees

The temperature indicated by the radiometer is simply a DC voltage proportional to the intensity of the 10 GHz radiation of the roadway multiplied by the spatial sensitivity of the antenna pattern. Fortunately for us, radiation measured from different surfaces at the same thermometric temperature will vary, being a function of the emissivity of the material (see Fig. 8). The reason for this is that when radiation from any source impinges on some object, some of the energy is transmitted through the object, some is reflected from the object, and some is absorbed by the object, raising its temperature, and causing it to become a radiator in its own right. It is also true that the better absorber an object is, the better radiator it is.

For our purposes, no radiant energy is transmitted through the roadway; it is either absorbed and reradiated at the temperature of the pavement surface, or the pavement acts as a reflector of incident radiation. If we were to have a radiometer view a nearly perfectly reflecting surface (such as a metal sheet) at the proper angle, we would measure

Figure 8. Block diagram of microwave radiometer showing provision for continuous calibration and resulting form of measured power levels.



the radiation temperature of the sky, which is about 10 K. If we were to look at a perfect emitter (or absorber), the radiometric temperature would be identical to its temperature as measured by a thermocouple or a thermistor.

Experiments have revealed that the emissivity of test samples of dry road surface ranges between about 0.85 to 0.90. For these high values, we can conveniently ignore the radiation added by the 0.1 to 0.15 reflectivity and the very cold sky, and we will find the uncorrected radiometric temperature of a road at 25°C to be about 261 K or -12°C. Laboratory and field measurements with our breadboard radiometer have revealed that large (80°C) radiometric temperature differences are observed as a highway surface goes from dry to wet. The radiometer is, therefore, a superb detector of wet pavements.

Field tests reveal that the presence of ice or snow always produces a higher temperature than the dry roadway at the same temperature (see Fig. 9). The presence of sand on the road seems to have no effect on radiometric road temperature, while the presence of salt on a dry pavement increases temperature readings by about 5°C. However, the addition of salt on snow or ice almost immediately converts the frozen precipitation into slush, which has a radiometric temperature somewhere in the wide range between the value of a wet pavement and an icy pavement. Although the radiometric temperature of a snow-or-ice-covered pavement fluctuates in a sinusoidal manner as the thickness of the snow increases, the initial effect on perceived temperature is always to raise it, and the variations never cause the perceived temperature to return to as low a value as a dry pavement (see Fig. 10).

From analysis of the data and reasoning applied as above, it has been possible to build a status and alarm system that can indicate pavement conditions using only the radiometer and a single thermometric temperature sensor imbedded in the roadway.

Summary of Status of the Radiometric Ice Detector

At the present time a breadboard 10 GHz radiometer has been fabricated and subjected to laboratory

Figure 9. Typical outdoor radiometric temperatures showing effect of polarization, viewing angle, and type of substance viewed.

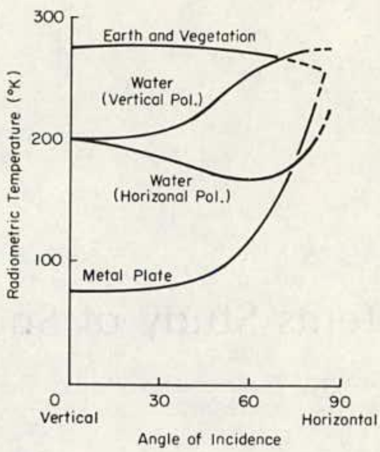
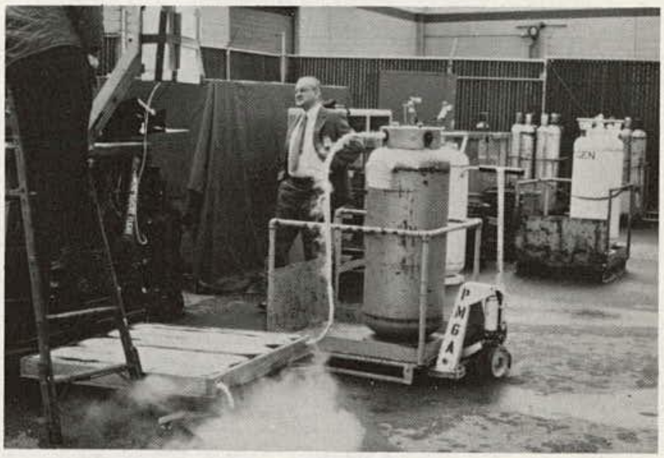


Figure 10. Preliminary engineering test of radiometric measurement of the temperature of frost and ice on an artificially cooled asphalt test slab.



and limited field tests. Overall, these tests are very encouraging. The radiometer operated in good conformance with theoretical predictions, and appears capable of detecting the presence of ice of 1 mm or greater thickness. It can easily and very sensitively detect wet conditions. However, frost and very thin layers of ice are not detectable without auxiliary equipment. The presence of salt or sand appears not to disturb detection criteria. However, the unit as presently configured does require the use of a single temperature sensor in or just below the roadway surface.

Future Plans for the Radiometric Sensor

The contractor is scheduled to deliver a prototype sensor that will be tested and evaluated over the next winter. It is hoped that following these tests, improved, next generation evaluation sensors will be built and will be evaluated by several interested States.

A Systems Study of Snow Removal

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The framework for a systems analysis of snow removal and ice control on roads is presented. Definition of the operating conditions, the principal ones of which are climate and traffic, as well as the system itself, the road net, is required. Equipment factors involved in performing the basic functions of clearing, spreading, loading, and hauling are analyzed.

Snow removal and ice control in the United States is a costly service. A survey of state transportation and highway departments made in 1976 resulted in an estimate of $334,000,000 for this activity on state-maintained roads only. Adding municipal and county expenditures the total is well over half a billion dollars per year. Snow removal on roads has not been analyzed as a system as is the case with airport snow removal and ice control (1). The potential savings in considering snow removal as a system requiring matching of all components for optimum performance is great. It is the purpose of this paper to analyze the system, as part of a larger effort funded by the National Science Foundation which treats decision-related research on technology utilized by local government.

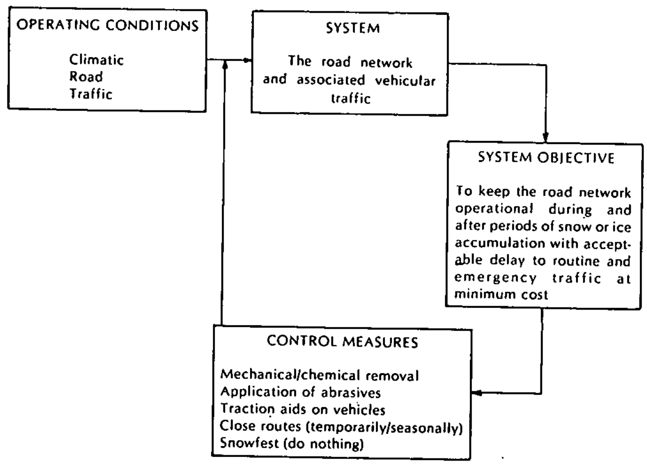
Scope

This paper is limited to the definitions and description of a snow-removal system, the factors affecting it, and the equipment elements that are appropriate to modify the system. It is the intent here to establish the framework for a systems analysis of snow removal.

System Definition

A system is defined by Shannon (2) "as a group or set of objects united by some form of regular interaction or interdependence to perform a specified function." Our system here is the road network and associated vehicular traffic. The system is perturbed by a number of input variables, the operating conditions, the most important of which are climate and traffic, as well as by the design of the system itself. The objective of the system is to keep the road network operational during and after periods of snow or ice accumulation with acceptable delay to routine and emergency traffic at minimum cost. The objective is achieved by applying control measures such as snow clearance or chemical ice removal to modify the influence of the input variables on the system. The functional relationship of these system components is depicted in Figure 1.

Figure 1. Snow removal system.



Objective

A survey of communities indicated that those with less than 2 in. mean annual snowfall need perform essentially no snow and ice control. Those with 2-10 in. mean annual snowfall expend so little for control measures that the cost is frequently not separately budgeted. However, cost increases as some function of mean annual snowfall, but it is also strongly influenced by what the community is willing to consider "acceptable delay." In broader terms, there is a range of adjustments to the snow hazard as shown in Figure 2, after Baumann and Russell (3), which ranges from technological towards the left, behavioral to the right. This study is limited to methods of modifying the hazard.

Figure 2. Range of adjustments to the snow hazard.

MODIFY THE CAUSE	MODIFY THE HAZARD	MODIFY THE DAMAGE POTENTIAL	ADJUST TO LOSSES
Cloud seeding Domed cities	Snow removal Chemical deicing Abrasive treatment Thermal pavements Snow fences	Snow routes Storm forecasting Parking restrictions Chain laws	Bear the loss Insurance Public relief

← TECHNOLOGICAL BEHAVIORAL →

Operating Conditions

Analysis of system performance requires specification of the input variables, that is, the operating conditions, and a measure of the degree, intensity, or duration of the condition. They are listed here:

Climatic	Measure
Temperature	°F or °C
Air	°F or °C
Pavement	°F or °C
Snow	°F or °C
Snowfall	
Total annual	in. or meters
Frequency	events/year
Duration	hours/event
Maximum single storm	in. or meters
Snow	
Density	lb/ft^3, g/cm^3, Mg/m^3
Depth (ave./storm)	in. or meters
Freezing rain	
Frequency	events/year
Duration	hours/event
Solar radiation	ly/min % cloud cover hours sunshine/winter month
Wind	
Speed	Ave. mph or km/winter month
Direction	frequency
Humidity	relative humidity (RH)
Altitude	ft or meters
Road net	
Urban	lane miles or lane km
Rural area	lane miles or lane km
Multi-lane area	lane miles or lane km
One-way streets	lane miles or lane km
Curbed roads	lane miles or lane km
Parking	lane miles or lane km
Emergency routes	lane miles or lane km
Road surface	lane miles or lane km
Cul-de-sacs	number
Intersections	number
Interchanges	number/type
Access ramps	number; ft, miles, or meters, kilometers
Sidewalks	ft, miles or meters, km
Driveways	ft, miles or meters, km
Topography	lane miles or lane km/ gradient range
Traffic	
Volume	Ave. daily traffic (ADT)
Mix	% truck-car-bus
Daily variation	% by hour

Environmental Parameters

Snow is a thermodynamically unstable material whose properties will change with temperature. Surface air temperature often bears no relationship to the form of snow falling on a pavement since formation takes place in the atmosphere where a different thermal regime may exist. However, surface air temperature will influence the subsequent changes in a snow cover, and in addition is the most easily measured. The temperature of the pavement will affect the formation of a glaze (or glare) ice when cold rain is falling. Water when it freezes gives up 144 Btu/lb (335 kJ/kg) of thermal energy which must be absorbed in the environment. Either a pavement below freezing, or a pavement nearly at the freezing point coupled with low air temperatures, is required.

Snow near the melting point may have a high water content and therefore a high density. Liquid film covering each snow grain acts as a lubricant and permits ready flow of one particle past another. A liquid water content of up to 15% permits the grains to achieve maximum packing under tire loads (4), and subsequent cooling will freeze the compacted snow to the pavement with an exceedingly tight bond (greater than the tensile strength of concrete, 275 psi (1895 kPa) is possible). Liquid water content between 15 and 30% permits the wet snow to remain in a loose, unconsolidated state under tire action. A content greater than about 30% results in a slush which is readily splashed off a pavement (4).

The snowfall rate has two principal effects: it will influence the accumulation on a pavement, and it will affect plow capabilities and the resulting route cycle times. Wind will have a two-fold effect also: the most prominent is the snow drifting potential, but also of some importance is the cooling of a wet surface with its influence on freezing of wet snow or melt to the pavement. Humidity will also influence evaporation rates, and therefore the cooling rate. Solar radiation is an extremely important factor in its action on either a bare pavement or on the approximately 1/2 in. of snow in contact with a pavement. Absorption of solar energy and its conversion into thermal energy may be sufficient to melt completely the residue from plowing operations. The time of day when snow removal is performed will therefore greatly affect the actions that need be taken, e.g. clearance in the late afternoon cannot depend upon solar energy to dissipate plow residue, and chemical treatment may be necessary as a follow-up if it was not done earlier.

Traffic/Road Parameters

Average daily traffic (ADT) is the most important traffic factor for reasons to be discussed below under maintenance level analysis. The type of road surface will influence plowing speed and the plowing residue that may be required or may be an undesired consequence; a blade cutting edge can be run in contact with a portland cement concrete or asphaltic concrete pavement, but a blade must be run above a macadam road to avoid gouging. The smoothness of a pavement will affect the plowing residue even when a blade edge contacts the pavement.

Topography, that is, the variation in elevation of a road surface about some arbitrary datum caused by hills, valleys, and rivers, will influence snowplow truck horsepower/weight ratio, speed, and removal strategy. As an example of the latter, in one hilly city a snowplow is sent to the top of a hill prior to the onset of snow in order to plow downhill because it has been found difficult if not impossible with their equipment to negotiate the route uphill with snow on the pavement. Snow depth will influence plowing speed, number of passes required to plow a road completely, and therefore route cycle time.

Maintenance Level Analysis

A road network generally consists of a hierarchy of routes from the heavily traveled arterial to the low volume road in sparsely populated rural or uninhabited regions. The demands for snow and ice control may therefore be distributed according to a priority scheme generally based on ADT, which reflects the importance of the route. However, significant bottlenecks which affect access to or egress from a high priority route must themselves be given high priority. A typical maintenance level hierarchy is given in Table 1.

Community Service Demand

The degree to which a community is willing to be taxes to provide public services will affect the level of response to snow and ice on the road network. A community generally budgets expenses well before the winter on the basis of historical experience (understandably on the low side), but a more severe winter than usual may result in a high level of maintenance in the beginning of winter giving way to reduced levels as winter continues and equipment breaks down, funds are exhausted, and personnel are not replaced.

Cost Analysis

The selection of the appropriate technology for achieving a specified service objective must consider social, environmental, and equipment aspects as acted upon by the constraints developed above. These relationships are shown in Figure 3.

Equipment Characteristics

Four basic activities are involved in snow removal and ice control: clearing snow accumulation from the pavement surface, spreading chemicals to melt snow residue or ice or spreading abrasives to improve the coefficient of friction between rubber and the ice-covered pavement, loading snow into trucks where there is insufficient storage space for displaced snow, and hauling this snow to a disposal area. Mobile equipment to perform these basic functions must also meet necessary mobility criteria. These requirements are related as shown in Figure 4 where the activity involved is shown above the horizontal lines in the box, and the measure of performance of this activity is below the line.

The four basic activities are achieved by the action of well-defined functions performed by the equipment; each function has a measure for establishing performance in the system, and a set of influencing factors. These are tabulated in Tables 2-6.

Figure 3. Important factors in designing a snow and ice control system.

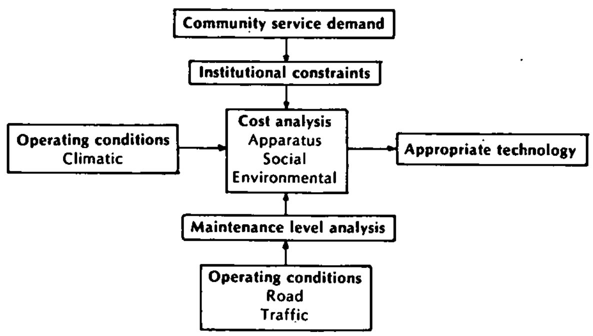


Table 1. Maintenance levels (typical).

Road Class	Priority	Starting Time	Max. Depth Permitted	Clearing Requirements
Arterial	1	When depth reaches 1/2 in.	1 in.	Clear to bare pavement within 2 hr after snowfall ends
Feeder	2	When depth reaches 1 in.	2 in.	Clear to bare pavement within 6 hr after snowfall ends
Local	3	When depth reaches 2 in.	6 in.	Residue permitted, but passable 8 hr after snowfall ends
Rural	4	When depth reaches 4 in.	No restrictions	Open roads within 24 hr after snowfall ends; residue permitted

Figure 4. Functional classification of snow and ice control equipment.

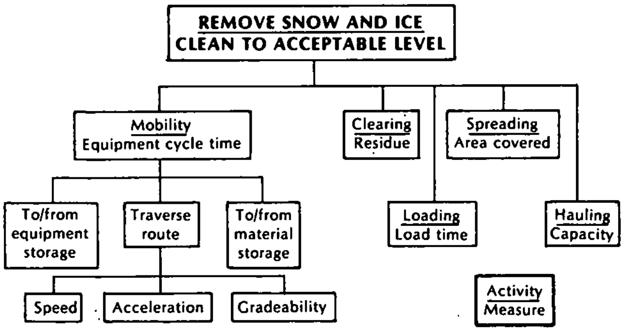


Table 2. Clearing (displacement).

Function	Measure	Equipment Factors	Other Factors
Shear snow	Force/unit blade length	Plow weight Blade (vertical) angle Blade material Blade condition Cutting/total length ratio Truck speed Truck power	Snow shear strength Snow hardness Snow/pavement adhesion Water content Pavement type Pavement condition
Lift snow	Energy or power/unit mass	Blade geometry Blade dimensions Blade surface characteristics Truck speed Truck power	Snow density Snow depth
Transfer snow	Energy or power/unit mass Cast distance (to center of mass) Dispersion	Blade geometry Blade dimensions Blade (horizontal) angle Truck speed Truck power	Snow density Snow volume Wind speed Wind direction
Protection	Obstacle clearance without damage	Blade trip mechanism Blade/pavement clearance Blade vertical loading Shoe or blade contact resistance Truck speed	Pavement condition

Table 3. Clearing (rotary).

Function	Measure	Equipment Factors	Other Factors
Shear snow	Force/unit cutter length	Cutter angle Cutter velocity Truck speed Truck power Cutter power	Snow shear strength
Gather snow	Power/unit mass	Volumetric capacity Cutter dimensions Truck speed Truck power Cutter power	Snow density
Cast snow	Power/unit mass	Rotating element velocity Rotating element dimensions Chute dimensions Truck speed Truck power Cutter power	Snow density
Protection	Overload prior to power disengage	Shear pin location Shear pin capacity Truck speed Truck power Cutter power	Debris in snow

Table 4. Spreading.

Function	Measure	Equipment Factors	Other Factors
Load	Time to load capacity	Feed opening dimensions Chassis/hopper dimensions Height of opening above ground GVWR	Density of material Legal load limits
Transport	Road speed	Truck dimensions Truck power/weight	Legal speed limits
Distribute	Feed rate to distributor	Conveyor dimensions Conveyor speed Body elevation	Material form (liquid or solid) Material water content Material grain size Material uniformity
	Mass/unit area/ unit time	Distributor location Distributor dimensions Distributor rotation speed Control mechanisms Number of jets and placement Jet pressure Truck speed	

Table 5. Loading.

Function	Measure	Equipment Factors	Other Factors
Shear snow	Force/unit cutter length	Cutter angle Cutter velocity	Snow shear strength
Lift snow	Energy or power/unit mass	Conveyor speed Conveyor dimensions	Snow density
Load snow	Mass/unit time	Discharge capacity Directional control	Snow density

Table 6. Hauling

Function	Measure	Equipment Factors	Other Factors
Load snow	Time	Volumetric capacity Truck creep speed Axle loads Turning radius	Snow density Snow volume
Transport	Road speed	Truck power/weight	Road grade Legal speed limits
Unload	Time	Tailgate opening dimensions Cargo box elevation	Snow cohesion

Summary

Snow removal is primarily a materials handling problem with the problem compounded by the highly variable properties of the material being handled. Ice control by chemical methods is in a sense materials handling also, but in this case it is the delivery of a chemical onto the ice-covered pavement in the most efficacious manner. The types of equipment used and the method of operating them in the system to achieve the service objective are interacting, i.e. capabilities and numbers will influence the choice of control strategy such as routing, and the inverse is equally true. A computer simulation of snow removal, reported by Tucker at this symposium, has been used to perform the analysis of many combinations of routes, equipment types and numbers, and strategies. Further research remains to be done to translate these analyses into a form that will be directly usable by a jurisdiction in making the proper choice of equipment, and in the development of performance specifications and methods of evaluating performance.

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Research on an Air Lubricated Snow Plow

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The development of high speed guided ground transport systems has been carried out in North America and elsewhere for over a decade. For these systems to be applied in temperate zones that experience snowfalls, some improvements in dealing with snow will have to be made if the high speed systems are to be used advantageously in winter as well as in summer. Investigations have been conducted on unconventional methods of removing snow from a substrate. One of the methods investigated was a means of reducing the dynamic friction of snow on a snow plow blade. Air is supplied to the surface of a blade to provide a lubricating film.

In another presentation the subject of snow accumulations on possible high speed transportation system tracks is discussed (1). This work on snow accumulations resulted in the Low Temperature Laboratory at NRC reviewing the then current situation on snow clearing as it applied to airport runways, highways and railways. At a time when research and development organizations in the transport field were looking at guided ground transportation based on either air cushion or magnetic levitation technologies it appeared that high speed snow removal was 100 km/h (60 mph) providing the snow accumulation did not exceed 2.5 to 5 cm (1 or possibly 2 in.). On airports the clearing of runways was in fact more likely to be carried out at 25 km/h (15 mph) by the multiple vehicle system where the limitation was dictated by the speed and capacity of snow blowers fed by snow plows operated ahead and in parallel (2). On railways the equipment currently in service has in some cases been in use for 50 to 60 years and no major advances have been made in railway snow removal equipment in that period of time with the only change being the provision of diesel locomotives in place of the older steam locomotives. In a storm during February 1978 a snow plow powered by two diesel locomotives was caught in snow drifts near Gull Lake, Saskatchewan and eventually had to be dug out by construction equipment. In the meantime one of the transcontinental lines was out of service.

It should be noted that the various railways have tried a number of different schemes for snow removal including the use of jet engine exhausts to clear snow from the right-of-way. This latter method was observed to remove ballast as well as snow under some conditions. Some improvements have been made in North America in equipment for snow removal from tracks in limited areas such as yards and terminals. However, nothing is known to exist in North America comparable to the so-called "snow trains" designed to clear out snow from yards and terminals in Moscow and other Russian metropolitan centers (3).

Considering the average speed of vehicles on the various transportation systems there is doubt regarding the necessity for higher speed snow removal equipment. On roads and highways the presence of other vehicles will always be a limiting factor. On railways the speed limits in various sections are limited by curves, superelevation and the quality of the roadbed. The removal of snow from airport runways could be accomplished more rapidly by either higher speed equipment or the provision of more equipment. However, in any case there is an economic limit that also must be taken into consideration. Thus, at the present time with existing transportation systems there does not appear to be any necessity for considering snow removal equipment with higher vehicle speeds. If high speed guided ground transport becomes a reality from the current developments then systems will be available with vehicle speeds in the 250 to 300 kilometre per hour range. In order for these high speed systems to operate in the temperature zones that experience winter snows, either prevention of accumulation or removal of snow must be considered.

The prevention of snowfall accumulation by the classical method of snow melting is a possible solution for high speed guideways. In an area such as Buffalo, N. Y. an input in the order of 1070 kilocalories/h m^2 (400 BTU/hr. ft^2) is required for snow melting (4). For the upper surface of the box beam design track originally proposed by British Tracked Hovercraft a thermal input of approximately 1.6×10^6 kilocalories/h/km (1×10^7 BTU/hr/mile) of track would be required. The high speed systems have been designed primarily for intercity traffic and one of the routes considered in Canada has been between Toronto and Montreal. For the thermal protection of a single track between these two centers a power input of approximately 1×10^9 watts is required. In view of the rising cost of energy there is little doubt that other more energy-conserving means must be considered.

The removal of snow from the guideways of high speed transportation systems by conventional or modified snow plows should not involve any great problems if current snow removal speeds are acceptable. The application of snow removal vehicles limited to say 100 km/h (60 mph) on tracks designed for vehicles with speeds 3 times faster would cause severe interference with normal traffic except in instances of low density applications. It would be desirable if the operating vehicles were capable of snow removal simultaneously during normal operation. As an example considering the box beam track a 2.5 cm (1 in.) snowfall accumulation at a density of 0.16 (10 lb/ft^3) would result in approximately 5,700 kg of snow/km of track (20,000 lb of snow per track mile). At a vehicle velocity of 90 m (300 ft) per second a snow removal rate of 1,800,000 kg/h (2000 tons/hr would be required. Snow blowers for use on airport runways exist with capacities up to this range; however, these vehicles are designed for low speed operation. They are indicative that snow removal rates of this order can be realized with sufficient energy input.

Unconventional Snow Removal

In order to study various possible methods of snow removal a simple test facility was installed at the Helicopter Icing Research location adjacent to the Ottawa Uplands Airport. In the design of this research set-up it was decided to use a standard gage steel rail track to guide the propulsion vehicle and the experimental equipment. This method would allow for longitudinal guidance while simultaneously maintaining good vertical alignment. For the initial phase of the work, i.e. the low speed preliminary evaluation of various concepts, a 90 meter (300 ft) long track was installed of which 54 meters (180 ft) were of conventional construction with wooden ties and a ballast roadbed. The central section of the track included a concrete pad 36 meters (120 ft) long mounted between the steel rails and elevated above the rail head. The steel rails and the concrete pad are mounted on continuous steel beams supported on concrete columns. In the central section the test track is elevated approximately 1.2 meters (4 ft) above the surrounding terrain. Figure 1 shows the track under construction.

Standard railway maintenance-of-way vehicles were purchased as a propulsion vehicle and a vehicle for mounting research equipment. The propulsion vehicle is powered by a gasoline engine and drives the rear wheels through a multi-speed transmission and a differential rear axle. The research equipment vehicle is a standard four-wheel flat top car used to carry maintenance-of-way tools and equipment in normal use. It was modified and strengthened to a limited extent prior to use for mounting research equipment.

One of the developers of tracked air cushion vehicles had assumed that the frequent operation of these vehicles would remove snow as it accumulated on the track surfaces, and therefore a major build-up of snow would not occur except during periods without normal traffic. It was decided to investigate this supposition as one aspect of the research on unconventional methods of removing snow.

The first equipment placed on the research vehicle was a centrifugal fan powered by a 50 HP 3-phase electrical motor. A trailing cable supplied power to the motor from a track-side power terminal. The centrifugal fan had a maximum flow capacity of 340 m^3/min (12,000 cfm) of air and a maximum discharge head of 45 cm (18 in.) water column. Inlet shutter control is available to control the output of the fan. The discharge from the fan was directed through an elbow and a three-channel diffuser into a rectangular plenum. From the plenum air could be directed through nozzles to impinge on the concrete track surfaces. The first nozzle tested was a forward facing full width slit representing the discharge from the clearance between a hovercraft skirt and a substrate. Within the speed limits of this vehicle, allowing for acceleration and braking on this length of track, the nozzle cleared dry snow accumulations well but failed to clear heavy cohesive and adhesive snow formations. A number of different nozzle designs were investigated on this vehicle and track with varying degrees of success. None removed the snow cleanly from the concrete substrate if the snow deposit was highly adhesive or if some freezing and sintering had taken place between accumulation and attempted removal.

During the tests on the snow removal air nozzles it was noted that the snow once removed from the surface was moved horizontally considerable distances. This observation ultimately led to the development of the horizontal air curtain for railway switch protection, thus this research work had an unexpected spin-off.

In the operation of hovercraft the supporting air provides almost frictionless motion for the vehicle. After it was displayed that the escaping air from an air cushion would not remove snow in all instances from a substrate, consideration was given to the inversion of the air cushion principle as a means of aiding in snow removal. Since air provides a low friction for movement of the ACV, might it not also provide low friction for snow removal? In the mechanical removal of snow from a substrate by a plow the forces involved include detachment of the snow from the substrate and the friction force of the snow moving across the blade. It was thought possible to reduce the friction force on the plow blade if a film of air could be supplied and maintained on the surface of the blade. The air would act as a supporting and lubricating film for the snow moving across this surface in a manner similar to its application on hovercraft. It was considered desirable that the air flow should be directed to assist the preferred directional flow of the snow in preference to using an air flow perpendicular to the plow surface, i.e. one that would be supporting only.

Air Lubricated Snow Plows

In order to investigate this concept it was decided to purchase a small standard cylindrical design snow plow and modify the blade surface to provide the air-lubricated feature. A commercial snow plow, intended for use on smaller vehicles such as a pick-up truck, was procured. To provide air to a blade surface it proved to be simpler to mount a false blade surface in front of the existing blade. The false blade surface was made of aluminum especially perforated and oriented to give directional flow to the supply air. The aluminum sheet was attached to the standard blade by multiple zig-zag truss members. Together with end and bottom pieces, this assembly formed a plenum for the air which was supplied from the fan outlet by a number of flexible hoses. Figure 2 shows material being perforated for construction of an air lubricated snow plow, while Figure 3 shows the

Figure 1. Experimental track under construction.

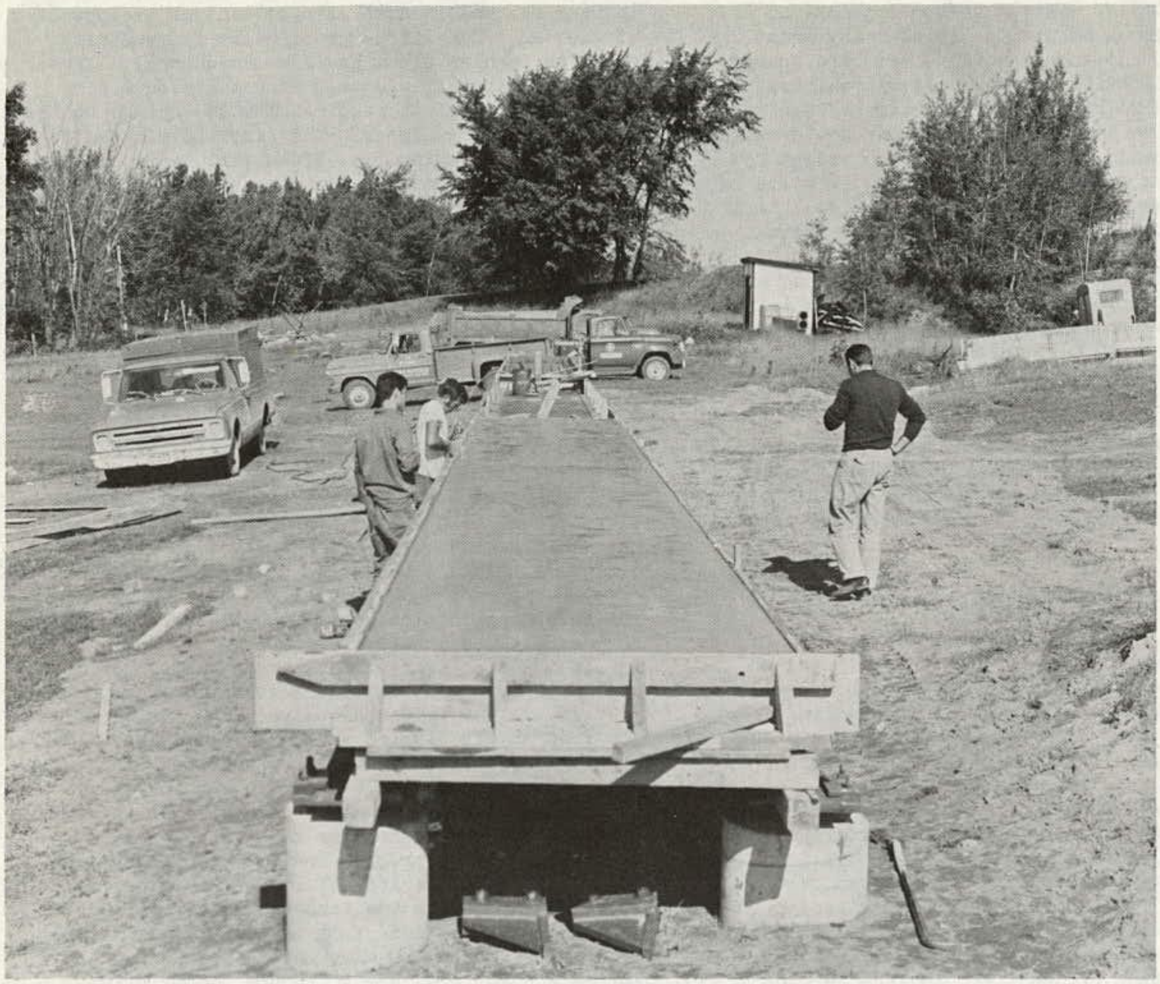

Figure 2. Preparing perforated material for an air lubricated snow plow blade.

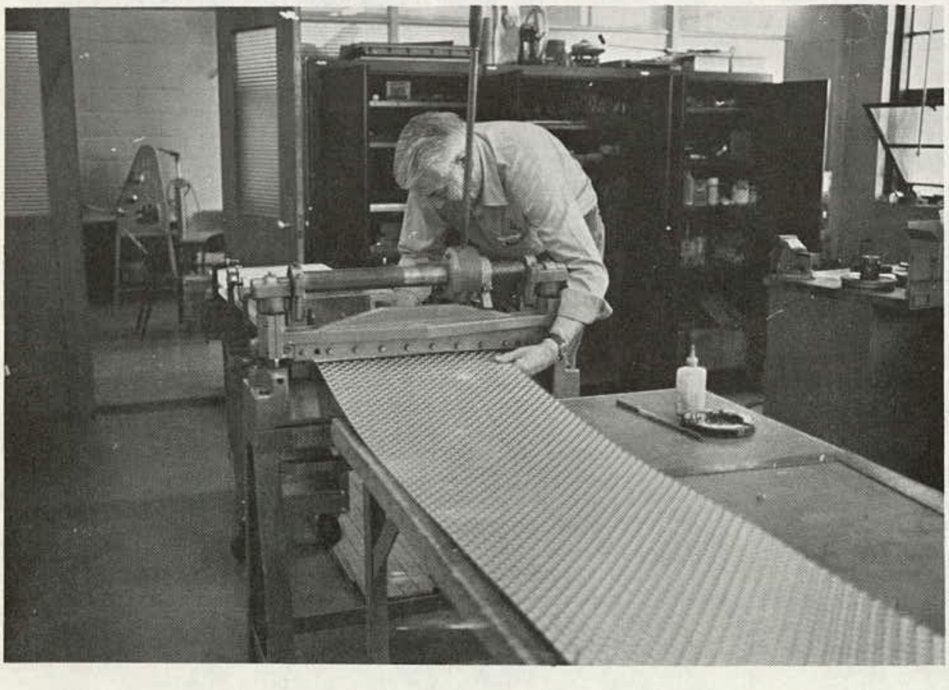

Figure 3. MK 1 air lubricated snow plow ready for tests.

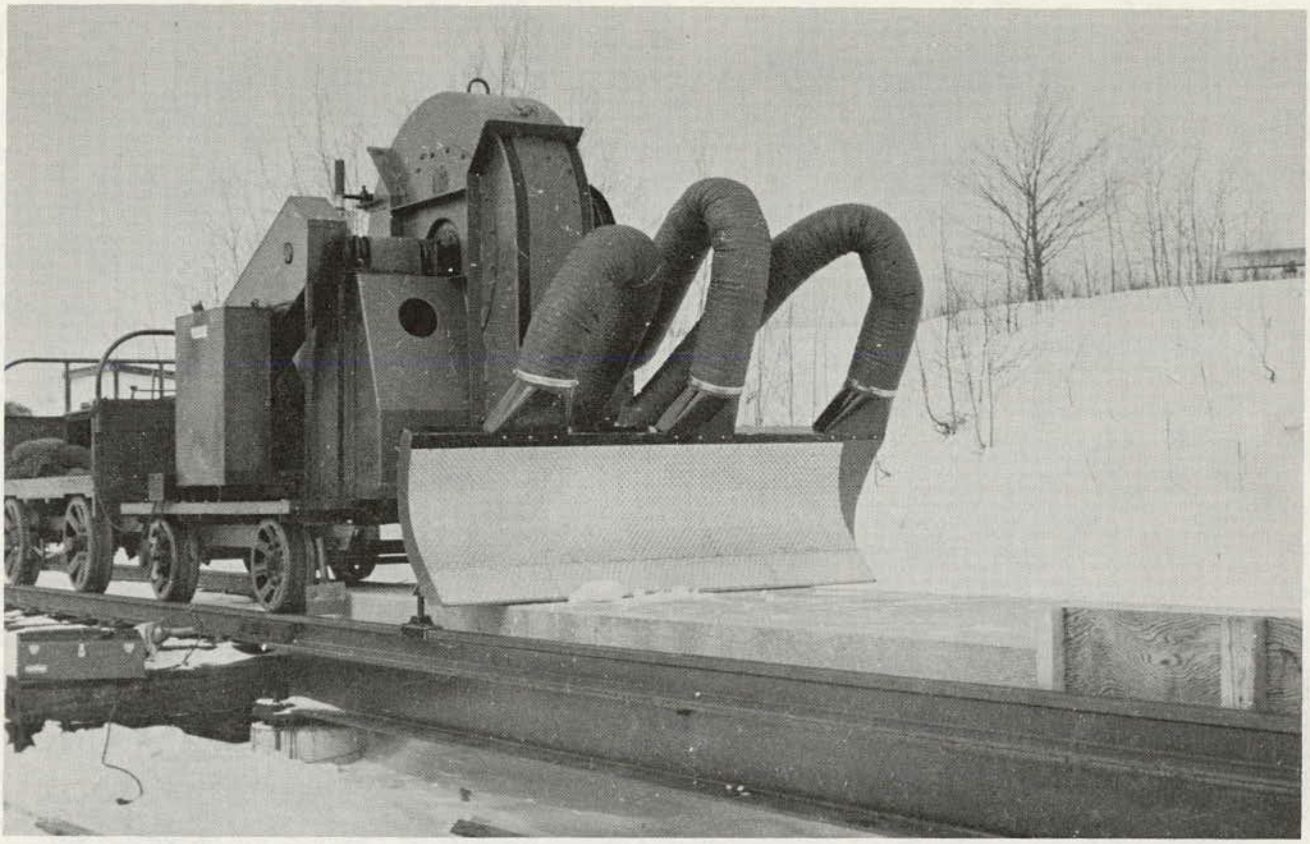

Figure 4. MK 1 air lubricated snow plow at approximately 15 km/h.

Figure 5. MK 2 air lubricated snow plow on the experimental track.

Figure 6. MK 2 air lubricated snow plow in road service.

completed MK 1 plow mounted on the experimental vehicle ready for tests.

The first few tests with this plow showed two things rather dramatically, i.e. air provides a virtually frictionless surface and without friction the snow flow is uncontrollable. The next figure displays what happens when this snow plow blade lubricated with air hits a snow accumulation of approximately 5 cm (a few inches) at a speed less than 16 km/h (10 mph), see Figure 4. Various tests were conducted for one winter season with the MK 1 design using either freshly fallen snow, recast snow or manufactured and recast snow.

After the observation of the snow explosions resulting from the air lubricated simple blade hitting a snow accumulation, consideration was then given to how a blade might be designed to take advantage of the air lubrication and still provide directional control of the flowing snow. A number of design concepts were considered, and of these one was selected for the next construction. The MK 2 was designed to give some directional control by partial containment coupled with air lubrication. This air lubricated snow plow contained a much larger perforated blade surface of a somewhat modified hole design. The outlet area of the perforated surface was designed to take the maximum available output from the centrifugal fan. It should be noted that this fan had been changed from electrical motor to diesel-engine powered to eliminate the trailing cable and allow for ultimate use elsewhere.

The MK 2 was mounted on the experimental vehicle and a series of tests have been conducted during two winter seasons. This air lubricated snow plow has provided the directional control desired while taking advantage of the low friction feature. At low vehicle speed it provides high cast distances due to the high velocity of the exit air.

The initial tests of this snow plow blade on a standard vehicle and a roadway have been conducted during the past winter. Figure 5 shows the vehicle installation while Figure 6 shows the air lubricated plow in experimental service.

We have proven that the concept of air lubrication can be applied to a snow plow blade. It will take further development and evaluation of this principle to deterfine its possible merits for either high speed snow removal or improved snow plow efficiency at existing speeds.

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A Study on the Resistance of Snowplowing and the Running Stability of a Snow Removal Truck

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Recently, a demand for higher speed snowplowing has arison to cope with the increase in traffic. However only a few research papers on the resistance of snowplowing and the running stability of snow removal trucks are available. This paper deals with the resistance of snowplowing and the running stability of the snow removal truck at high speed. The resistance of snowplowing was obtained from the results of field experiments and the running stability of the snow removal truck was derived by the calculation of the maximum speed of the snow removal truck without unstable motion on a tangent and curved road section.

This paper deals with the resistance of the snowplowing, namely the snow load acting on the snowplow as obtained from field experiments in actual snow removal truck and its running stability by theoretical equations on a tangent and curved road section. The field experiment was made by Hokkaido Development Bureau using specially designed snow removal truck for this research. Table 1 and Figure 1 show the specifications, the performance and the dimensions of the truck. The meaning of snow removal in this paper is limited to snowplowing alone. The running stability of the truck was derived from a calculation of the maximum speed of the truck without an unstable motion on a tangent and on various curves of a road by application of the running stability theory of an automobile.

Snowplowing Resistance of the Snow Removal Truck

Snowplowing resistance in addition to the ordinary running resistance acts on the snow removal truck.

The total resistance of the snow removal truck must be considered as (1) running resistance of the snow removal truck itself (2) sliding resistance of the snowplow on the snow surface (3) resistance when snow is flies off by the snowplow, namely the snow removal resistance.

Running Resistance of the Snow Removal Truck

When the snow removal truck runs during snowplowing on a tangent and level road section, the running resistance of the snow removal truck itself R_1 can be expressed as follows;

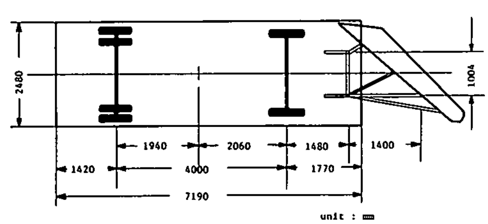
$$R_1 = R_r + R_\ell = \mu_r W + k_a A v^2 \quad (1)$$

where R_r = rolling resistance of the snow removal truck.
R_ℓ = air resistance of the snow removal truck.
μ_r = coefficient of rolling resistance; 0.03 for the truck equipped with the round tire chain.
W = wheel load; 11,569 kg for the truck.

Table 1. Specification of the snow removal truck.

Type	NISSAN DIESEL Snowremoval Truck MF61D	
Total Length	7,190 mm	(without snowplow)
Total Width	2,480 mm	(")
Height	3,450 mm	
Wheel Base	4,000 mm	
Total Weight	11,460 kg	
Front Axle	5,560 kg	
Rear Axle	5,900 kg	
Max. Power	240PS/2,200rpm	
Max. Torque	92kg-m/1,400rpm	
Tire	11.00-20-14PR	(Stud Tire)

Figure 1. General plan of the snow removal truck.



k_a = coefficient of air resistance; 0.045 for the truck.
A = frontage projected area m^2; 5.0 m^2 for the truck.
v = relative air speed between truck and air; m/sec.

The running resistance of the test truck is calculated as 410 kg at 60 km/h.

Sliding Resistance of the Snowplow on Snow Surface

The sliding resistance of the snowplow on the snow surface R_2 is calculated by

$$R_2 = \mu_s W_s \quad (2)$$

where μ_s = coefficient of sliding resistance; 0.1 between iron and snow.
W_s = weight load on the runner of the snowplow, this weight consists of the weight of the snowplow and the weight of the suspention system of the snowplow; 600 kg for the truck.

For the test truck, this resistance is calculated as 60 kg. In addition to these resistance, cutting resistance by the cutting edge of the snowplow acts on the snow removal truck. As a result of the experiment conducted by the Ministry of Construction the resistance was 0.7 kg/cm at the cutting edge length; this value was adopted in this study. Cutting resistance of the test truck is estimated as 175 kg.

Snowplowing Resistance

The snowplow of the snow removal truck has an angle of 45° in the forward direction. Therefore it is necessary to consider that the snowplowing resistance is divided into two resistances; one is the resistance in which the snowplow flies off snow, namely the backward resistance as opposed to the forward direction and the other is the lateral resistance at a right angle to the forward direction.
Here the backward is defined as the forward resistance. As snow moves in a similar to that of liquid when the behavior of snow movement on the snowplow is observed, the law of conservation of momentum was introduced to estimate the forward and lateral load. It must be considered that the speed of snow after the snow comes in contact with the snowplow decreases because snow is a compressive material as compared aginst water which is imcompressive one. Although snow actually moves in a three dimensional pattern on the snowplow, in this study, it is assumed that snow moves in a two dimensional pattern as shown in Figure 2 and 3, because the resistance in the upward and downward direction can be neglected due to its lesser influence.

Figure 2. Top view of snow flow on the snowplow.

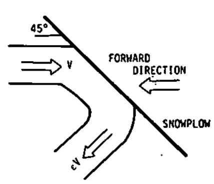


Figure 3. Side view of snow flow on the snowplow.

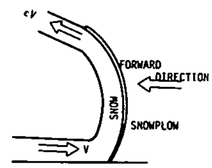


Figure 2 and 3 show the snow moving pattern from the top and the side of the snowplow. The speed of snow causing in contact with the snowplow equals the snow removal truck speed. When snow is flung off the snowplow, the speed of snow decreases due to the compressibility of the snow and also because of the friction between snow and the snowplow. The speed of flung off snow is given by εV, where V is the speed of the truck and ε is the decreasing coefficient of the snow speed. The snow enters the snowplow at an angle of 45° and the snow flows along the curvature of the snowplow and finally it is flung off at an angle of α from the upper edge of the snowplow. The magnitude of the snow removal resistance which is separated into the forward load F_x and the the lateral load F_y can be calculated using the law of conservation of momentum as follows:

$$F_x = \gamma/g \cdot Q[V - \{-\varepsilon V\cos(\alpha - 45°)\}]$$
$$= \gamma S V^2/g \cdot \{1 + \varepsilon\cos(\alpha - 45°) \quad (Q = SV) \quad (3)$$
$$F_y = \gamma/g \cdot Q[0 - \{-\varepsilon V\sin(\alpha - 45°)\}]$$
$$= \gamma S V^2/g \cdot \varepsilon\sin(\alpha - 45°) \quad (4)$$

where γ = density of snow.
Q = volume of snow.
S = cross sectional area of snowplowing.

If we substitute α = 90° and ε = 0.6 into equations 3 and 4, F_x and F_y can be rewritten as

$$F_x = 1.42 \cdot \gamma \cdot S \cdot V^2/g \quad (5)$$
$$F_y = 0.42 \cdot \gamma \cdot S \cdot V^2/g \quad (5)'$$

The value of ε and α were derived from the cine-film taken during the field experiment.

The Ratio Resistance of the Snowplowing

The ratio resistance of snowplowing is introduced to allow for a convinient comparison of the snowplowing resistance under various conditions because the snow removal resistance is affected by the cross sectional area of snow removal and snow density.
The ratio resistance of snowplowing N_r can be expressed by

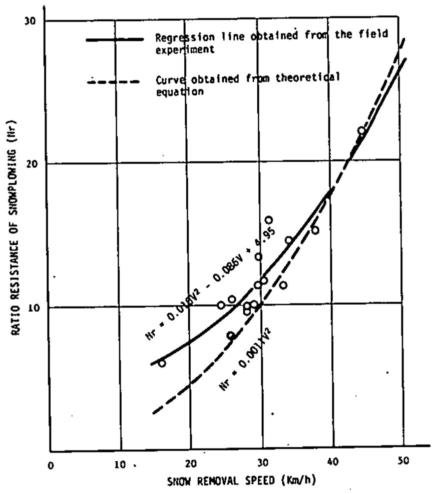
$$N_r = F_x/\gamma S \quad (6)$$

From equation 5, we get

$$N_r = 1.42V^2/g \quad (7)$$

Figure 4 shows the comparison between the ratio resistance of the snowploing calculated by equation 7 and those obtained from the field experiments.
The solid line is the regression line calculated from the field experiments and the broken line gives thr calculated value by equation 7. These two lines are the slmost the same at speeds from 30 to 50 km/h, but at lower speeds the value of the broken line are

Figure 4. Relation between the ratio resistance of snowplowing and the snow removal speed.

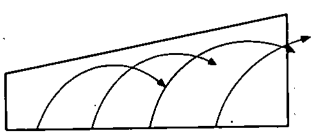


less than those of the solid line. This may have arison from the change of the snow flow pattern at speed lower than 15 km/h, in other words, when the snowplow enters the snow, the snow collapses in front of the snowplow and is pushed aside in a rolling motion by the snowplow. As the conditions of this research is at higher speed, the snowplowing resistance may be calculated by equation 7.

Figure Distribution of the Snowplowing Resistance

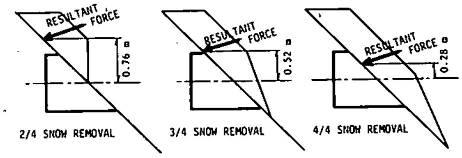
In order to obtain an acting point of the resultant force of the snowplowing resistance, it is necessary to have a distribution pattern. The flow of snow which runs off the snowplow, when the flow of snow on the snowplow is observed on the cinefilm, is shown in Figure 5. At first the snow runs against the lower edge of the snowplow at the same speed as the snow removal truck, and second, it moves to the left side in a forward direction of the snowplow while moving upward and at finally, it runs off from the upper end of the snowplow.

Figure 5. Snow flow pattern observed on the snowplow.



As to the shape of the snowplow of the truck, since the height ratio of right to left of the snowplow is 1:3, it is assumed that the left side has a larger load than the right even when snow is removed by the whole snowplow. Moreover as the flow of snow on the snowplow may be expressed as in Figure 5, the right side snow resistance is much smaller than that of the left side. The snow removal resistance increases as the snow moves to the left side of the snowplow but a further increase is not seen because at some point the snow begins to run off from that point. As a result, the snow removal resistance was simulated by a trapozoid as shown in Figure 6.

Figure 6. Figure distribution of snow removal resistance.



In Figure 6, 4/4 snowplowing means the state of the snowplowing using the entire blade of the snowplow, 3/4 means 3/4 of the snowplow from the left edge of the snowplow is in use and 2/4 means only a half of the snowplow from the left edge of the snowplow is being used. The position of resultant force which was calculated using Figure 6 is 28 cm to the left from the snowplow center for 4/4 snowplowing, 52 cm for 3/4 and 76 cm for 2/4 respectively.

Discussion of Lateral Load

The lateral load was not measured directly but instead the bending moment for the suspension arms was measured by the load cells installed on the two arms which were connected with the snow removal truck body and snowplow, because the direct measurement of the lateral load was very difficult due to the complicated connection mechanism of the snowplow.

Figure 7 shows the relation betwen the forward load and the bending moment of arms. The lateral load can be calculated to divide the bending moment by the distance from the acting point of the lateral load to the position of load cell by

$$F_y = M/h \tag{8}$$

In this equation, M is the bending moment of arm and h is the distance from the acting point of the lateral load to the load cell. Table 2 shows the calculated values of the lateral load for the position of acting point of resultant force for 3/4 snowplowing which was obtained in the preceding section.

Figure 7. Relation between forward Load and bending moment of arm.

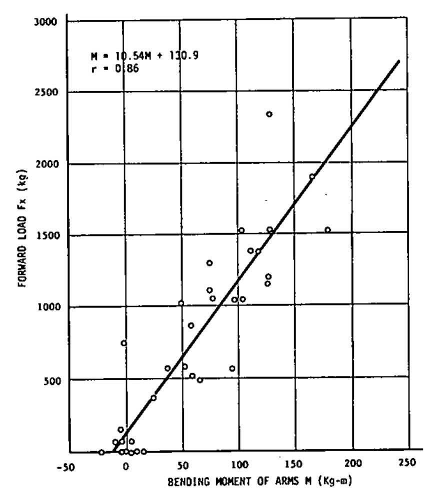


Table 2. Calculated lateral load.

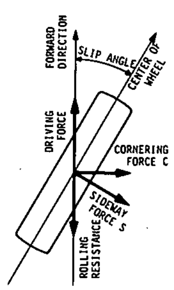
Forward Load A, kg	Bending Moment kg-m	Lateral Load B, kg	B/A
500	35.0	125	0.25
1,000	82.5	295	0.29
1,500	129.9	464	0.31
2,000	177.3	633	0.32
2,500	225.0	804	0.32

As the load cell is located 23 cm apart from the arm end and the distance from the arm end to the acting point of resultant force for 3/4 snowplowing is 5 cm, the value of h in equation 8 was taken as 28 cm. From the result, the lateral load is about 30% of the forward load and this value is of the same percentage as obtained from equation 4 and 5 theoretically.

Cornering Force and Slip Angle

When the lateral force acts on the snow removal truck during snowplowing, the driver tends to achieve balance with the lateral displacement of the vehicle using cornering force which is generated by the side slip of the front wheels with a slip angle. In this case, the side slip of the front wheels or tires mean the motion which is not kept in line with the central line of the tires and the proceeding direction of the tires. Figure 8 shows the forces

Figure 8. Forces acting on the side slipping tires.



acting on the side slipping tire. In Figure 8, the force which acts at right angle to the central line of the tire is sideway force S, the force which acts at right angle to the forward direction of tire is cornering force C and the angle between the forward direction and the central line of the tire is the slip angle β. These values have the following relation:

$$C = S\cos\beta \quad (9)$$

$$S = \mu W \quad (10)$$

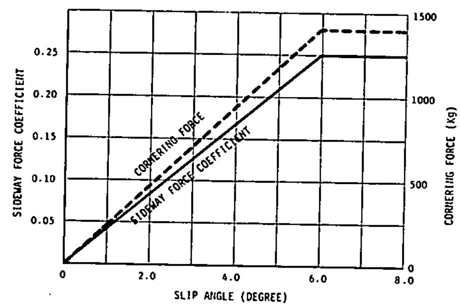
where μ = sideway force coefficient.
W = tire load.

From above equations, the cornering force can be given as

$$C = \mu W\cos\beta \quad (11)$$

Although the value of μ varies in accordance with the slip angle, and especially on the snow surface, we found after many skidding tests on the snow surface that the sideway force coefficient increases in proportion with the slip angle up to 7° or 8° and then it becomes a constant value when the slip angle is in excess of these angles. The critical slip angle which is considered from the safety side is assumed to be 6° and the maximum sideway force coefficient which correspondes to the critical slip angle is assumed to be 0.25. Figure 9 shows this relation. The solid line in Figure 9 shows the relation between the slip angle and the sideway force coefficient which is assumed for this study.

Figure 9. Relation between slip angle and cornering force.



Here, if we assume $\cos\beta = 1$, equation 11 can be rewriten as

$$C = \mu W \quad (12)$$

From Figure 9

$$\mu = 0.25/6\cdot\beta \quad (13)$$

$$C = 0.25/6\cdot W\cdot\beta \quad (14)$$

For the test truck, W = 5,560 kg then

$$C = 0.25\cdot 5{,}560/6\cdot\beta \quad (15)$$

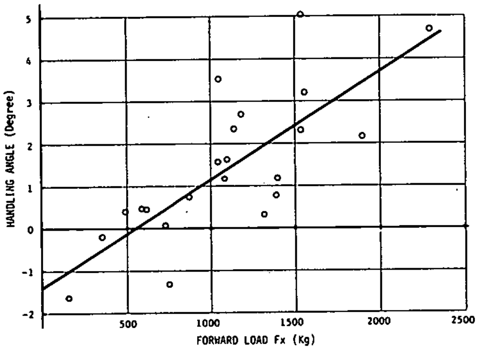
The broken line in Figure 9 shows the relation between the slip angle and the cornering force which is obtained from equation 15.

Relation Between the Snow Removal Resistance and the Steering Angle

As mentioned in the preceding section, the front wheel of vehicle with the slip angle by steering generates the cornering force. The steering is expressed by the handling angle that is not an actual angle of the steering handle which is rotated by the driver but it is the steering angle of the front wheel. As the steering angle equals to the slip angle when the vehicle body is running in the same direction as the forward direction, the handling angle means the slip angle which arises after this and handling in a counterclockwise direction takes a positive direction. The forward load and the handling angle were measured simultaniously, but the lateral load was not measured.

But, as the lateral load equals 30 % of the forward load as discussed in the preceding section, it can be calculated from the relation between the forward load and the handling angle. This relation is shown in Figure 10. In this Figure, the reaction

Figure 10. Relation Between forward load and handling angle.



time of 0.5 second is considered. This time was obtained by the field experiment. From Figure 10, the regression line can be obtained as follows:

$$\theta_1 = 0.0028F_x - 1.40 \quad (16)$$

where θ_1 = handling angle.

From the above equation, we can see that the handling angle increases proportionally with the forward load, namely the lateral load. The handling angle shows -1.4° when the forward load is zero, indicating that the handling angle is in a clockwise direction. Table 3 shows the handling angle obtained from the field experiments when the snow removal truck runs without load while the snowplow contacts to the ground so that the snow removal resistance does not act on the snow removal truck.

Table 3. Handling angle with no load.

Test No.	Snowremoval Speed km/H	Handling Angle degree
1	25	-1.6
2	24	-1.3
3	40	-1.3
4	33	-1.9
5	42	0
6	42	-1.3
7	47	-1.0
8	47	-1.3

The Force acting on the Two Arms

During the snowplowing, the force rate, acting on the two arms of the left and right arms (Figure 11) varies in accordance with whwther the snowplow is used wholly or partially. The forces which act on both arms, are shown in Figure 12. The relation between the acting point of the resultant force and the rate of the force acting on the two arms referred to in Figure 12 can be given by

$$P = 0.5x + 0.2 \quad (17)$$

In this equation, P is the ratio of the force acting on the left side arm and x is the distance from the position of the resultant force to the center of the snowplow, which is measured in a right angle direction. For 4/4 snowplowing, x = 0.28 m, P = 0.34 : for 3/4 snowplowing, x = 0.52 m, P = 0.46; for 2/4 snowplowing, x = 0.76 m, P = 0.58 are obtained respectively for the truck.

Figure 11. Plan of the snowplow.

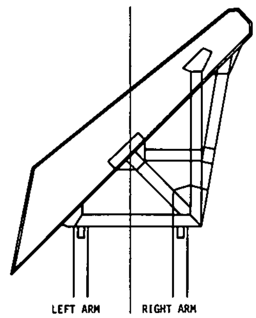
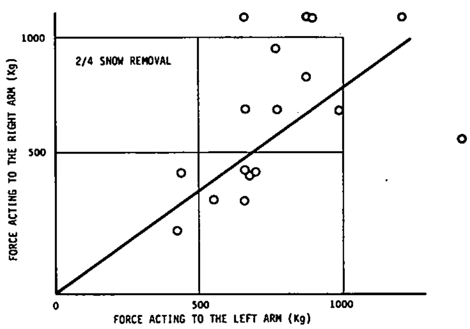


Figure 12. Relation between forces acting on the two arms.



Running Stability of the Snow Removal Truck

Running Stability of the Snow Removal Truck on a Tangent Section of the Road

When we treat the running stability of the vehicle, it is sufficient to consider the force and the moment equlibrium acting on the vehicle on the assumption that the vehicle is a rigid body. For the force equilibrium, the force in the forward direction to the center of gravity of the vehicle (direction to v, level), the force to the right angle and level direction to the road surface are considered. However, when we consider the running stability of the snow removal truck, it is most important that the snow removal truck rotates around the perpendicular axis passing through the center of gravity of the truck due to the snow removal resistance acting on the snowplow. Therefore, it is needs to consider the moment equilibrium around the vertical axis passing through the center of gravity of the truck. Although the snow removal force acting from the out side to the snow removal truck was discussed in the preceding section, it is sufficient to consider the snow removal resistance, running resistance of the snowplow and the moment equilibrium to the moment due to the cornering force of the front wheel around the center of gravity of the snow removal truck. The moment due to the snow removal resistance is divided into two moments, that is the moment due to the forward direction and the transverse direction. The moment due to the transverse load can be obtained as the product of the distance from the acting point of the resultant force of the transverse load on the snowplow to the center of gravity of the snow removal truck and the transverse load. On the other hand, the moment due to the forward load can be obtained as the product of the distance from the snowplow to the center of truck body and the load acting on the two arms of the snowplow.

Next, numerical calculations are discussed. Assume that the F_{xL} is the force acting on the left hand arm and F_{xR} is the force acting on the right hand arm, then

$$F_{xL} = PF_x$$

$$F_{xR} = (1 - P)F_x$$

The moment (clockwise direction is plus) due to the sliding resistance of the snowplow is -668 kg-m. Therefore, the moment around the center of gravity of the snow removal truck can be given as follows:

$$M = F_{xR}\cdot 0.5 - F_{xL}\cdot 0.5 + F_y(4.11 - x) - C\cdot 2.06 - 668 \qquad (18)$$

where x is the distance from the center of gravity of the snowplow to the acting point of the resultant force of the snow removal resistance. The handling angle θ_2 is adjusted so that the moment which is calculated from the equation 18 may zero may be given by

$$\theta_2 = M/2.06 \times 6/0.25\cdot 5{,}560 \qquad (19)$$

When the handling angle θ which is the moment around the center of gravity comes to zero, it may be calculated by

$$\theta = \theta_1 + \theta_2 \qquad (20)$$

If θ is under 6 degrees, the snow removal truck can run in stable state.

Assuming that the snow density is 0.1 g/cm^3, snow depth h is 0.2m, snow removal speed v is 16.7 m/sec. and S is 0.2 x 2.5 = 0.5 m^2 for 4/4 snow removal, we can obtain 4.11° of θ. As 4.11° of the handling angle less than 6° is obtained from the assumed conditions, the snow removal truck can be driven in stable state. Table 4 shows the handling angles obtained under the following conditions; 3/4 snow removal, snow density is 0.1 and 0.2 g/cm^3, snow depth is 10 and 20 cm. From the results of calculation, we can assume that the snow removal truck may enter unstable motion state such as yawing or spinning over a speed of 50 km/h for the conditions of 4/4 snow removal and over 65 km/h for 3/4 snow removal, 0.2 of snow density and 0.2 m of snow depth.

Running Stability of the Truck on Curved Road Section

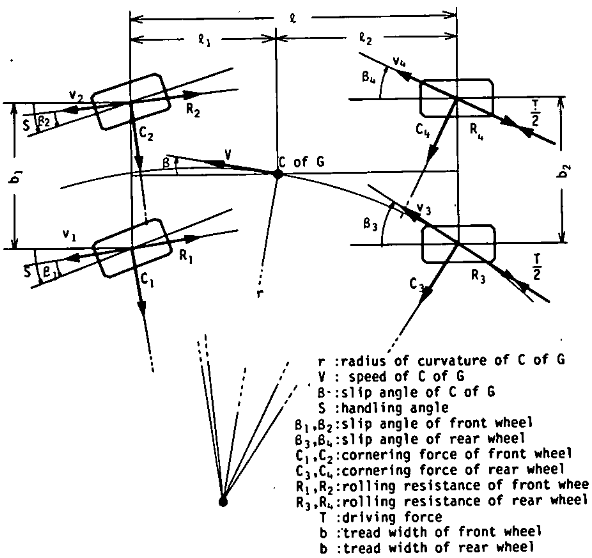
When the vehicle runs along a curved road section, the front wheel of the vehicle rotates with a certain slip angle. In the case of the snow removal vehicle, when it runs on a curved road section in a counterclockwise direction, the front wheels have a counterclockwise slip angle, and in addition to this slip angle the excess slip angle which responds to the snow removal resistance. Then the snow removal truck has a larger slip angle than that of an ordinally vehicle. If this slip angle of the snow removal truck is over a certain angle, namely the critical slip angle, the cornering force which increases linearlly with the slip angle does not increase further with a slip angle over the critical slip angle and when a larger force acts on the front wheels, the cornering force does not resist the force. As a result, the snow removal vehicle skids outerwards from the curve or it may fall into a spin motion. Therefore the running stability of the vehicle is achieved by obtainning a maximum slip angle without an unstable motion of the vehicle. To obtain the radius of curvature, the slip angle and the handling angle, it may be sufficient to consider the force equilibrium in the right angle direction to the forward speed V and the moment equilibrium around the center of gravity of the vehicle. If we consider the force acting on the vehicle during the turning motion on a curved road section as shown in Figure 13, the equilibrium of the right angle direction to the forward direction can be given by

Table 4. Relation between snow removal resistance and the handling angle for the stable running of a snow removal vehicle at various speeds.

Speed	γ = 0.1 g/cm^3 h = 20 cm			γ = 0.2 g/cm^3 h = 20 cm			γ = 0.1 g/cm^3 h = 10 cm			γ = 0.2 g/cm^3 h = 10 cm		
(km/h)	Fx (kg)	Fy (kg)	θ (Deg.)	Fx (kg)	Fy (kg)	θ (Deg.)	Fx (kg)	Fy (kg)	θ (Deg.)	Fx (kg)	Fy (kg)	θ (Deg.)
20	168	50	-1.00	336	101	-0.61	84	25	-1.20	168	50	-1.00
25	262	79	-0.78	523	157	-0.17	131	39	-1.09	262	79	-0.78
30	377	113	-0.52	754	226	0.36	189	57	-0.95	377	113	-0.52
35	513	154	-0.20	1,027	308	1.00	257	77	-0.79	513	154	-0.20
40	671	201	0.17	1,341	402	1.73	336	101	-0.61	671	201	0.17
45	849	225	0.59	1,698	509	2.56	426	128	-0.40	849	255	0.59
50	1,048	314	1.05	2,097	629	3.49	526	158	-0.17	1.048	314	1.05
55	1,269	381	1.56	2,537	761	4.52	636	191	0.09	1,269	381	1.56
60	1,510	453	2.13	3,020	906	5.65	757	227	0.37	1,510	453	2.13
65	1,772	532	2.74	3,545	1,064	6.87	889	267	0.68	1,772	532	2.74
70	2,053	616	3.39	4,107	1,232	8.18	1,029	309	1.01	2,053	616	3.39

$$W/g \times V^2/r = C_1 + C_2 + C_3 + C_4 \tag{21}$$

Figure 13. Forces acting on the vehicle.



The moment equilibrium around the center of gravity of the vehicle can be expressed as follows:

$$(C_1 + C_2)\ell_1 = (C_3 + C_4)\ell_2 \tag{22}$$

Here, the force and the moment due to the air resistance are neglected because the values are small. The relation between the cornering force and the slip angle within a linear relation are

$$C_1 = k_f\beta_1,\ C_2 = k_f\beta_2,\ C_3 = k_r\beta_3,\ C_4 = k_r\beta_4 \tag{23}$$

where k_f = cornering force of front wheel.
k_r = cornering force of rear wheel.

From Figure 13, the slip angle β_1 and β_3 are

$$\left.\begin{aligned} \beta_1 &= \{S - \tan^{-1}(\ell_1 - r\sin\beta)\}/(r\cos\beta - b_1/2) \\ &= S + \beta - \ell_1/r = \beta_2 \\ \beta_3 &= \{\tan^{-1}(\ell_2 + r\sin\beta)\}/(r\cos\beta - b_2/2) \\ &= \beta + \ell_2/r = \beta_4 \end{aligned}\right\} \tag{24}$$

From equations 23 and 24

$$C_1 = C_2,\ C_3 = C_4 \tag{25}$$

Substituting equations 23 and 24 into equations 21 and 22, we get

$$W/g \times V^2/r = 2k_f \cdot \beta_1 + 2k_r \cdot \beta_3 \tag{26}$$

$$2k_r \cdot \beta_3 \cdot \ell_2 = 2k_f \cdot \beta_1 \cdot \ell_1 = 0 \tag{27}$$

Converting equation 24 into degrees, we have

$$\beta_1 = \beta_2 = S + \beta - 57.3\ell_1/r \quad \text{(degree)} \tag{28}$$

$$\beta_3 = \beta_4 = \beta + 57.3\ell_2/r \quad \text{(degree)} \tag{29}$$

From equations 28 and 29, S is obtained as

$$S = \beta_1 - \beta_3 + 57.3\ell/r \quad \text{(degree)} \tag{30}$$

In the above four equations, there are six variables $V, r, \beta, \beta_1, \beta_3$ and S, then it is necessary to give the two variables in advance of the six variables to the equations. Here we give equations V and r.

Solving equations 28 and 29 for β by sustituting into equations 26 and 27 gives

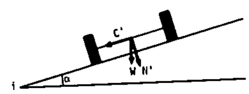
$$\beta = \frac{(W/g \times V^2 \times \ell_1/\ell - 114.6 \times k_r \times \ell_2)}{2k_r \times r} \tag{31}$$

β_1, β_3 and S can be obtained from equations 28 to 30.

$$\left.\begin{aligned} \beta_3 &= \beta + 57.3 \times \ell_1/r \\ \beta_1 &= (k_r \times \ell_2/k_f \times \ell_1)\beta_3 \\ S &= \beta_1 - \beta_3 + 57.3 \times \ell/r \end{aligned}\right\} \tag{32}$$

Next, when the vehicle runs on the road surface with superelevation, the component force C' due to the superelevation i acts on the center of gravity of the vehicle (Figure 14).

Figure 14. Force component by superelevation.



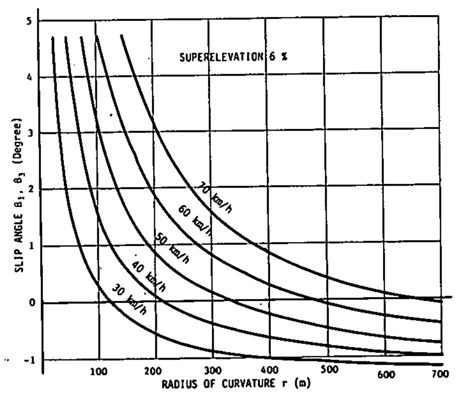
As α is very small, $C' = \sin\alpha = W \cdot \tan\alpha = W \cdot i$.

Then the left member of equation 21 becomes to $W/g \cdot V^2/r - W \cdot i$.
Similarly,

$$\beta = \frac{(V^2/g - r \cdot i) \times W \times \ell_1/\ell - 114.6 \times k_r \times \ell_2}{2k_r \times r} \tag{33}$$

β_1, β_2 and S are the same as equation 32. The calculated result which are expressed the relation between β and r related to the speed of the snow

Figure 15. Relation between radius of curvature and slip angle.



removal truck V without snow removal resistance is shown in Figure 15. In this case, the calculation was made under conditions where k_f is 116 kg/deg., ℓ_1 is 2.06 m, ℓ_2 is 1.84 m, k_r is 123 kg/deg., ℓ is 4.0 m and W is 11,560 kg. As β_1 equals $0.99\beta_3$ from equation 31, we assumed that $\beta_3 = \beta_1$. From Figure 15, for example, we can find that the radius of curvature for the stable running of the snow removal truck is more than 100 m at a 6 % superelevation for a speed of 60 km/h.

Next, the slip angle of the snow removal truck which runs on a curve to the left hand with snow removal resistance can be obtained by adding the handling angles due to the slip angles on the curved road section which were obtained in the preceding section. Figure 16 and 17 show the calculated results which express the relation between the slip angle and the radius of curvature in the case of 4/4 and 3/4 snow removal under the conditions where snow density is 0.1 and 0.2 g/cm^3, snow depth is 10 and 20 cm and the superelevation is 6 %.

Figure 16. Relation between radius of curvature and slip angle.

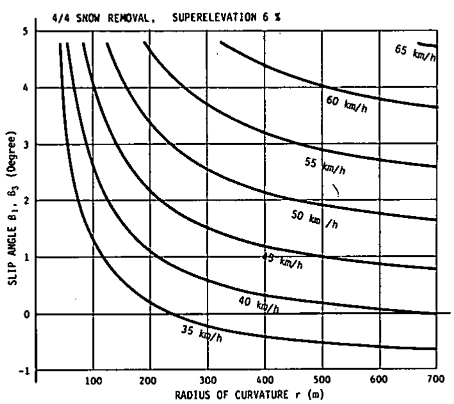
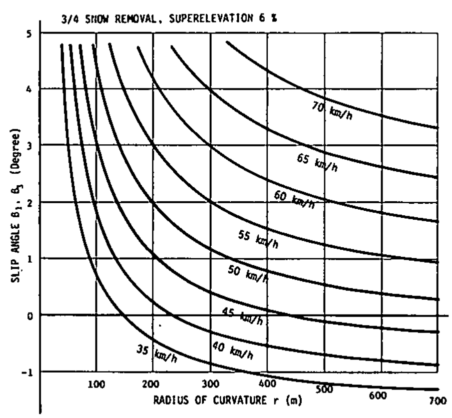


Figure 17. Relation between radius of curvature and slip angle.



In these Figures, the critical slip angle was decided to be 4.8 degrees when the sideway force coefficient is less than 0.2 considering safety on the curved road section. The radius of curvature at the 4.8 degrees of the slip angle was decided to the minimum radius of curvature for each running speed of the snow removal truck speed. From these Figures, we can find that the snow removal truck can run at a higher relative speed than we expected at first.

Concluding Remarks

In this paper, the snow removal resistance and the running stability of the snow removal truck during snowplowing were discussed and some results by numerical calculations were obtained. Although these do not give sufficient results because this study is the first of its kind to approach the various problems involved and in addition because of the lack of data which can be used directly from field experiment, numerous assumption were used.

But it is considered that from the calculations of the running stability of a snow removal truck which depends largely on experience and sixth sense alone, we have obtained a rough outline of the operation. Numerous problems such as the visual field of the following vehicles remains unsolved.

We are now continuing this reasearch including the above problems for ordinary snow removal vehicle which were not specially designed for research purpose.

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Snow Removal and Ice Control on the Italian Turnpike Network

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This report, as a complement to the preceding ones carried out in Italy,aims to bring in the light,statistically as well as under a quality analysis,the meaning and results of a highly efficient winter maintenance of a highway network.If we compare north european countries to mediterranean ones,we find there is a vast variety of problems and solutions.In Italy, due to the particular orographical structure of the peninsula, the need of an efficient road and highway winter maintenance is always increasing and has become of vital importance.In fact, 80 per cent of the runs, in tons/km, for the transport of goods, takes place by road and as much as 60 per cent of this traffic is served by the turnpike network.A further aim of this study, which reports the winter campaigns results of 1974-1975 and 1975-1976, making comparisons with the former ones,is to furnish useful information concerning technologies and organization procedures being applied today,as well as the tendencies and updating in progress. We think necessary to point out, furthermore that the present report handles only a commentary of a wider survey comprehending several Tables.Theese Tables contain, properly indexed, all the analytic data concerning the operation and the efficiency of the winter maintenance service on the Italian turnpike network during winters of 1974 - 1975 and 1975 - 1976. Therefore whoever might be interested to obtain the complete survey, as well as those previously carried out, may request the same writing to: A.I.S.C.A.T. - via Sardegna 40 - Rome - Italy.

The Network under Study

The turnpike sections that underwent winter maintenance during the winter of 1974-1975 or wich were fitted with the relevant equipment,had a length of 3,873.5 km. equal to about 90 per cent of the total turnpike network, operating on 31.3.1974.

This proportion increased during the winter of 1975-1976 reaching an approximate value of 95 percent; this fact points out once again how the majority of Italian highways are located in geographical and orographical zones characterized by such weather conditions requiring a certain maintenance organization.

Referring to the mentioned environmental conditions and to their natural diversification, so as to provide possibilities of comparison on the most possible homogeneous basis, we outline the following operative sections:

I GROUP: North Italy hill or flat land Highways;
II GROUP: Mountain highways;
III GROUP: Coastline highways and flat land and hill highways of central and southern Italy.

In Table 1 are listed the elements relevant to length and area development of the network under study, the modifications of said elements from 1972 to 1976; some gaps are due to some operative sections' restructuration as well as to the exclusion of others from this report.

Table 1. Length and area development of the network under study.

	Group	72-73	73-74	74-75	75-76
Extension km.	I	1,729.1	1,864.2	1,890.7	1,908.4
	II	417.4	417.4	477.3	485.2
	III	1,363.0	1,605.6	1,505.5	1,774.5
	Total	3,509.5	3,887.2	3,873.5	4,168.1
Area in millions of sq. m.	I	39.8	41.0	43.4	44.8
	II	8.4	8.4	10.0	10.2
	III	28.9	32.8	30.6	37.0
	Total	77.1	82.3	84.0	92.0

In operative terms, the extension on which an intervention or continuous control must be carried out, increased of 18 per cent during the period 1972-1976.

Regarding the orographical characteristics of the layouts, the maximum quota levels reached in each of the three groups are found in the following sections:

I GROUP: Torino-Savona 650 m. above sea level
II GROUP: Brennero-Chiusa 1,381 m. above sea level
III GROUP: Roma-Carsoli 626 m. above sea level

Cut slopes do not exceed 4 per cent, except on some particular steady gradients; this is of major importance not only because of the satisfactory service results under normal or optimum weather conditions, but also for the easier interventions for the control of ice film formation or snow removal.

The Organization

To be able to carry out an efficient winter maintenance service, the turnpike network is subdivided in operative sections, whose extension variates depending on weather conditions and traffic density and characteristics.

During the two winter seasons the following average extensions were taken for each of the groups:

I GROUP: average operative section 85 km.
II GROUP: average operative section 70 km.
III GROUP: average operative section 105 km.

A slight increase of such values was observed, respect to the values arisen during the preceding research,probably due to improved techniques and intervention means which, reducing the duration,lead to wider operation ranges.

Examining the equipment installations, devices,transport means, and manpower available for the average operative section of each group, the following data was taken:

Operative Sections. Each operative section, independently from the group it belongs to, is averagely equipped with two centers with fixed installations such as aprons or parking areas, warehouse, etc. The total number of such centers in the whole network amounts to 95.

Meteorological observation Stations. All data relevant to current weather conditions are supplied by meteorological observation stations installed on highways or near toll boxes and equipped with special measuring devices.

Averagedly, this stations have a density per km.of 0.02 on highways belonging to Group I (1 each 50 km); 0.07 on II Group highways (1 each 14 km.) and 0.05 for III Group highways (1 each 20 km).

The differences appearing in the above mentioned data relevant to I and II Group highways are due to the fact that III Group highways are most recent ones,therefore presenting a larger number of more sophisticated equipment.

It has to be pointed out that besides the data obtained from such devices, there is also a vast network of information operated by different organizations,such as the aerological data bulletins, broadcasted by the Military Aeronautic Service.

Measuring Instruments. In Table 2 is outlined the number of turnpike section using each type of devices during the winter of 1975-1976.

We can see there is sufficient equipment but automatic equipment for meteorological data processing, survey and trasmission is not widely used at present.

We hope that experiments keep improving these modern techniques verifying their efficiency so that their techno-economical possibilities may be utilized on a wider scale.

Table 2. Number of turnpike section using listed type of measuring instruments

Instruments	Number of sections	Intruments	Number of sections
Thermometer	34	Barograph	8
Barometer	26	Hygrograph	8
Hygrometer	22	Pluviograph	2
Pluviometer	1	Motometer	3
Polymeter	4	Icelert	1
Thermograph	8	Anaemograph	2

Open Depots, Shelters, Silos. Regarding spaces and areas for the deposit of materials and parking of the operative means on the network under study, it was found that open depots are predominantly in use and that they amount to 171 on an average area of 1,200 sq.m.

Shelters are few, they total 29 with an average sheltered area of approx.250 sq.m., silos are even less, they are only to be found in few units with a stocking capacity on the order of 200 cu.m.

It is important to point out the interesting operative characteristics of silos such as loading and unloading rapidity,reduced space requirements, good conservation of melting salts,little need of personnel and quick and automatic dosing for the preparation of solutions.

Operative Means. The number of means for each operative section did not show any important variations in the period from the winter of 1974-1975 to 1975-1976 and,indipendently from the type of acquisition (rented or owned)the average number is listed in Table 3.

Table 3. Means issued to the average operative section.

Means	I Group (85 km)	II Group (70 km)	III Group (105 km)
Shove-blade trucks	28	27	11
Rotary snowplows	1	3	-
Saltspreading trucks	5	6	3
Tank trucks	1	1	-
Warning and coordination means	3	3	2
Loading snowplows	3	4	2
Conveyor belts	-	1	-
Total	41	45	18

As only average operations were carried out,the indicated values are purely indicative; in fact it is evident that if on a definite section only the salt solutions are utilized, there will be a greater need of tank trucks than the above, while the salt-spreading trucks shall not be listed.

The observation of the relevant data of park on the network under study and of its evolution in time (see Table 4) points out that the park increase is not proportional to the network increase and that there were even some reductions.

This can be explained by means of very mild winter seasons; it is also due to the constant research by the concessionary firms for a winter maintenance service both efficient and economical.

Moreover, this may be observed because except for some particular operative machinery, there is an increa

Table 4. Evolution of the park on the turnpike network.

Winter	Shove-blade trucks			Rotary snowplows			Salt-spreading trucks			Tank trucks			Warning & coord.			Loading		
	N	P	T	N	P	T	N	P	T	N	P	T	N	P	T	N	P	T
69–70	689	12	701	2	7	9	142	32	174	9	3	12	119	123	242	113	29	142
70–71	714	20	734	5	14	19	151	38	189	10	6	16	39	212	251	123	21	144
71–72[a]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
72–73	789	33	822	3	22	25	159	47	206	7	13	20	47	192	239	122	40	162
73–74	870	36	906	6	21	27	165	59	224	13	15	28	65	217	282	138	49	187
74–75	870	27	897	2	30	32	192	32	224	18	16	34	77	196	273	122	37	159
75–76	886	27	913	2	30	32	192	32	224	16	15	31	71	184	255	129	38	167

Note: N – rented
P – owned
T – total

[a]the winter of 1971-1972 data were not processed.

sed tendency to rent the means, on a call or permanent basis, obtaining in this way a more rational and ecomical utilization of the same.

Personnel. Also during the winter seasons of 1974-1975 and 1975-1976 it could be observed that company's personnel is one of the most costly items of the winter maintenance service. From the absolute values relative to the whole network and keeping in mind the increased length of the same, it is possible to observe that the general tendency to call bids for the winter maintenance and to rent the equipment rather than buying it, has also influenced the reduction on the number of personnel of these companies. Viceversa, there was a slight increase in the number of enterprises' personnel. (See Table 5)

Regarding the average operative section, the staff is pointed out in Table 6.

Table 5. Total personnel employed.

Personnel	72-73	73-74	74-75	75-76
Coordination personnel	206	212	198	188
Workers, drivers, etc. of the companies	473	549	461	479
Workers, drivers, etc. of the enterprises	1.250	1.554	1.580	1.591
Total	1.929	2.315	2.239	2.258

Table 6. Personnel employed on average operative section.

Personnel	I Group	II Group	III Group
Coordination personnel	3	6	6
Workers, drivers, etc. of the companies	9	17	12
Workers, drivers, etc. of the enterprises	45	48	23
Total	57	71	40

Winter Campaigns of 1974-1975 and 1975-1976

The weather conditions of the network under study were different in the winter of 1974-1975 from those during the winter of 1975-1976.

While during the former winter and preceding seasons (see Table 7) weather conditions were quite mild in temperature and with few, even if heavy snowfalls, during the period from November 1975 to March 1976 winter was much more severe.

If such phenomena could lead back to tendency laws, even based on an approximate and incomplete knowledge of the present winter's characteristics, one could probably argue that after the severe winter registered in 1971-1972, there was an exceptional milder stage until 1974-1975. From this year on, winter seems to have returned to normally expected conditions.

The relative implications of highway winter maintenance service which can be analytically deducted from the Tables enclosed in the complete study, are summarized and commented upon in the following paragraphs.

Operation and utilization of means. Referring to the Tables of the complete survey concerning the analytic examination of each operative section and presenting a comparison between the operation of the means in charge of snow removal operations or those of ice control, we make some general considerations on both campaigns under study, paying special attention to the utilization and efficiency levels; this levels, even if indirectly, may provide elements of judgement economically speaking or in terms of service quality, acquired for the turnpike network.

The analyses of the operative sections' equipment pointed out the great importance of renting equipment, a procedure that induces a greater adaptability and flexibility of the services regarding the real maintenance requirements. Let's remember that renting of equipment may be achieved as follows:

Permanent renting. With which the operative means, together with the personnel in charge of it, station permanently in the operative centers at the complete disposal of the Concessionary, during the whole winter season or for one or more months.

Table 7. Summary of meteorological data of the winters from 1969 to 1976.

Elements	Group	69-70	70-71	71-72	72-73	73-74	74-75	75-76
Average temperature	I	N.C.	N.C.	+ 4	+ 4	+ 4	+ 5	+ 5
°C	II	N.C.	N.C.	+ 6	+ 6	+ 5	+ 3	+ 4
	III	N.C.	N.C.	+ 9	+ 8	+ 8	+ 9	+ 9
Minimum temperature	I	N.C.	N.C.	- 17	- 9	- 10	- 8	- 10
°C	II	N.C.	N.C.	- 16	- 17	- 19	- 12	- 16
	III	N.C.	N.C.	- 7	- 10	- 10	- 8	- 14
Hours n. with temperature	I	554	891	420	651	449	318	428
< 0 °C	II	683	1.127	397	592	481	314	497
	III	94	176	82	147	113	99	128
Snowfalls	I	N.C.	N.C.	7	4	2	2	6
average number	II	N.C.	N.C.	21	17	14	9	11
	III	N.C.	N.C.	4	2	2	1	4
Total snowfall hours	I	11	37	66	31	13	18	59
hours	II	153	128	153	102	150	119	101
	III	63	56	11	7	11	8	20
Total snow accumulation	I	N.C.	N.C.	69	30	17	13	45
cm.	II	N.C.	N.C.	247	137	149	145	167
	III	N.C.	N.C.	24	8	23	1	29
Max accumulation per snowfall	I	N.C.	N.C.	66	39	35	30	130
cm.	II	N.C.	N.C.	60	60	150	340	153
	III	N.C.	N.C.	52	20	63	9	16

Note: N.C. not collected data.

Renting on call. Whenever the operative means is required, the Concessionary requests it; therefore, the owner may also utilize the means for other purposes.

The type of renting varies from section to section depending on the equipment availability of each zone and on the operative requirements. The sections with a high traffic density and with no surrounding traffic alternatives clearly need equipment rented on a permanent basis (specially snowplows) because any delay of operation, even regarding minutes, may lead to unsafe traffic conditions and block circulation.

Therefore, checking the percentage proportion between the means actually utilized and those issued to the sections, we may observe that during the last two winters, it reached higher peaks especially due to the renting equipment procedure.

The percentage proportion between parking and working hours is also favourable, due to the same reason.

Anyways, if we want to compare both seasons of 1974-1975 and 1975-1976, the same proportions confirm the fact that, due to a milder starting winter season, there was less need of equipment (always in proportion to the same availability) for snow removal operations: being ice film control a preventive and usual operation, there was not a great difference for the same during both seasons.

Regarding the coefficients of utilization obtained from snow removal operations relating the number of hours/km of equipment utilization to the number of hours of snowfall, and from the ice control operations, to the hours whose temperature fell below 0 °C, we can see in Table 8 that there is a general increase of these coefficients. This means that under the same weather conditions there was an increased utilization of the same means.

It is not easy to furnish an explanation of such phenomena through statistics only, therefore we retain it useful to advise all the operators of this field calling their attention to this phenomena so as to verify and be able to pass judgement on the above, for future suerveys.

De-icing Salts and Abrasives

The utilization of chlorides and abrasives has followed, also during the winters of 1974-1975 and 1975-1976, the same tendencies as those verified during former surveys.

The most widely used de-icing salt is still NaCl. About 350,000 kg. of NaCl were utilized during the winter of 1975-1976 on the whole network; calcium chloride solution comes next; more than 22,000 kg.were utilized; and last solid calcium chloride 13,600 kg.

Looking at the data shown on Table 9,which indicates the consumption of de-icing salts and abrasives during the period between 1969 and 1976, one sees that though the validity of rock salt is confirmed, CaCl2 solutions are now being widely used (with a slow rate of diffusion) together with a higher sophistication of storage, preparation and dosage of the mixture.

Table 8. Coefficient of utilization of means
(Hours of utilization-km/showfall hours or hours with temperature below 0°C)

	Group	72-73	73-74	74-75	75-76
Shove-blade trucks	I	0.148	0.067	0.093	0.166
	II	0.140	0.144	0.112	0.351
	III	0.145	0.057	0.0008	0.017
Rotary anowplows	I	0.0002	-	0.002	0.001
	II	0.007	0.009	0.0004	0.003
	III	-	-	-	-
Saltspreading trucks	I	0.021	0.014	0.072	0.046
	II	0.014	0.013	0.046	0.151
	III	0.024	0.006	0.002	0.043
Tank trucks	I	0.001	0.0001	0.0005	0.0004
	II	0.001	0.0004	0.018	0.0001
	III	0.002	0.0002	0.001	0.001

During the last two seasons there was an increase in the use of abrasives which were scarcely utilized before.

Although the data on the total consumption might appear altered due both to new operative sections and to the fact that the last survey include sections which were not considered before, such increased utilization of sand could be explained not only under a technical aspect but especially from an economic point of view, due to the low maintenance budgets through which some concenssionaries are forced to operate.

Table 9. De-icing salts and abrasives winter consumption.

Winter	$CaCl_2$ solid	$CaCl_2$ solution	NaCl	Sand
69-70	10,117	4,293	278,320	161,497
70-71	16,528	7,764	373,969	169,997
71-72	N.C.	N.C.	N.C.	N.C.
72-73	9,847	17,417	236,911	86,029
73-74	9,506	11,726	152,984	33,385
74-75	8,965	16,085	142,262	84,602
75-76	13,569	22,389	348,138	149,694

Conclusions

Besides the observation carried out in the former chapters and any further elements of judgement deriving from the data contained in the enclosed tables, the degree of efficiency of the whole organization of winter maintenance of the turnpike network may be verified through the level of the services obtained.

The numbers regarding this level may be obtained immediately even if empirically, from the observation and consideration of the hours of blocked circulation due to snowfall or ice formation, as well as to accident data which depend directly on the former.

During winter of 1974-1975, traffic was blocked for 2 hours on one only section of the entire network; the number of hours with a temperature below 0 °C variated depending on each group - between 100 and 300 hours approximately; the number of snowfall hours was between 10 and 110.

During the same seasons, 87 accidents happened due directly to the presence of snow or ice formation on carriageways. Only 4 of these accidents were mortal with a percentage incidence on the total accident number (6,834 total accidents and 172 mortal accidents between October 1974 and March 1975) in the order of 1% and 2% respectively.

During the winter of 1975-1976, circulation blocks appeared only an 7 sections with a minimum duration of half an hour and a maximum one of 4 hours, while the hours with temperature below 0 °C were, depending on the geographic conditions of the sections, between 130 and 500 hours; the snowfall hours totalled 20-100.

The rate of accidents amounted to 7,938 total accidents of which 204 were mortal; of these accidents 162 and 2 (2% and 1%) were caused directly by the presence of ice or snow on highways.

Certainly, the above results would have been quite different if there had not been a winter maintenance service or if the existing service had not been sufficiently organized; not only accidents would have been plenty but circulation blocks would have caused many inconveniences to both the drivers and the entire surrounding community.

As a conclusion, it can be pointed out that the present techniques applied by highways concessionaries have given proof of their validity, on the basis of the achieved results. Moreover, the most recent national or international congresses on winter road conditions have not brought up any substantial changes of means and materials technology; the present studies in progress now in Italy concern mainly, therefore, the search for economy and organization and the consideration of optimum rates that shall link this economy to the effective needs of circulation.

Hence, future research should aim to introduce economic analysis elements which will give a greater significance to highway winter maintenance service.

Snow Removal and Ice Control for Ground Transport Channels and Terminals

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A study was undertaken to determine the current state of the art of snow removal and ice control for ground transport channels and terminals in the Upper Great Lakes Region of the U.S. Selective interviews were made of engineers and individuals in the region who were intimately involved on a daily basis with local snow and ice problems. A seminar-workshop was also held to provide information exchange and experience sharing by those who had considerable interest in or working knowledge of these operations in the area. This paper is a brief summary of the findings of the research effort.

The Upper Great Lakes Region of the United States, embracing northern Minnesota, northern Wisconsin, and the Upper Peninsula and northern portion of the Lower Peninsula of Michigan (Figure 1), covers an area of 300 Gm^2 (116 000 square miles) and harbors a population of approximately 2.9 million. The region is predominantly rural and somewhat underdeveloped, and is located in the snow belt of our northern border where the annual snowfall averages between 1.3 m (50 in.) and in some areas as much as 7.4 m (290 in.) in a single season (Figure 2). The first snow varies with the locality and, from available records, dates from October 1 in Upper Peninsula of Michigan to October 16 in northern Minnesota and Wisconsin. The average annual number of days in which snow falls ranges from 80 days in the extreme upper part of Michigan to about 50 days in the other parts of the region. In addition, the entire area is exposed to winds that traverse the lake from most of the directions of the compass. These winds, coupled with a fairly low mean temperature, pile the heavy snowfall into drifts that may reach heights up to 3.0 m (10 ft) or even 4.6 m (15 ft).

The movement of people and goods within the region and to and from locations outside the region depends largely upon a network of land transportation routes, including both highways and railways, and limited air transport service. Water transport is easily interrupted by bad weather and winter ice, and is confined only to low-grade freight for which speed is less important than quantity movement, even under suitable operating conditions. Because of the public's complete dependence upon the uninterrupted use of the highways, railroads, and airports during the long and severe winter months, snow removal and ice control for these facilities are vitally important. The amount of money expended each year for these activities varies a great deal from place to place, depending in large measure on the length and intensity of storms and the amount of snowfall in a particular area. It is estimated, however, that it amounts to many millions of dollars each year for the entire region.

The current practice for snow removal and ice control has developed, generally speaking, through trial and error methods within a particular area, and by training operators on the job in the procedures which the local experience has determined best suited to the conditions. While very little organized research has been conducted, the present state of the art seems in most instances adequate for meeting the local demand for maintaining the desired service conditions for the ground transport facilities in the region. In an effort to evaluate the performance of these operational systems, an investigation was undertaken to determine the current state of the art, with an objective of identifying problem areas, as well as future research needs. Initially, a literature review was conducted to determine various aspects of the problem, including basic approachs of snow removal and ice control and the present-day procedures and equipment employed. Selective interviews were made of engineers and individuals in the region who were intimately involved on a daily basis with local snow and ice removal problems. In addition, a seminar-workshop was held to provide information exchange and experience sharing by those who had considerable interest in or working knowledge of, these operations in the area. The participants included city and county road commission engineers, engineering administrators and research personnel from state highway agencies, airport maintenance engineers, and other qualified persons. This paper is a brief summary of the general findings of the aforementioned research effort.

Snow Removal Practices

Snow removal from land transportation channels and terminals may be accomplished by mechanical clearing of snow in its solid state, or by melting and draining it off at water. Because the energy

Figure 1. The Upper Great Lake Region.

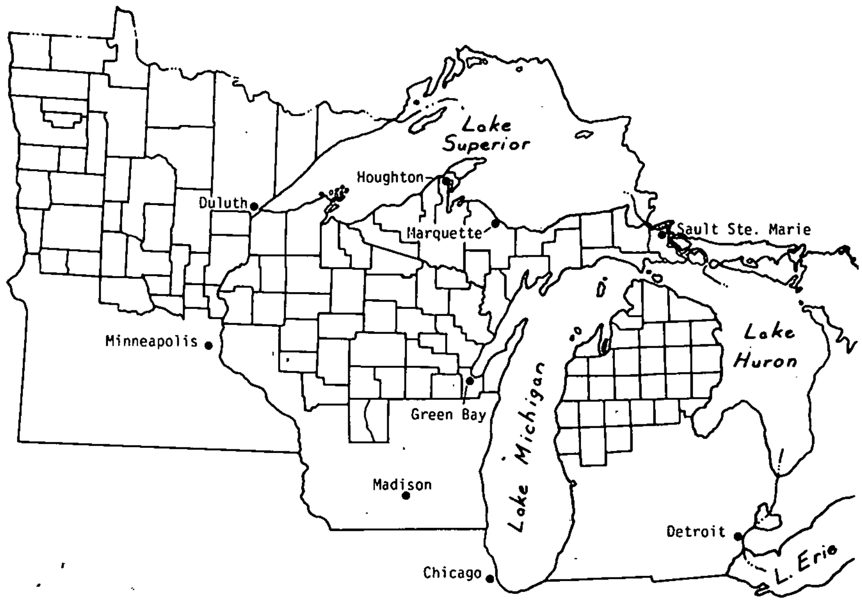
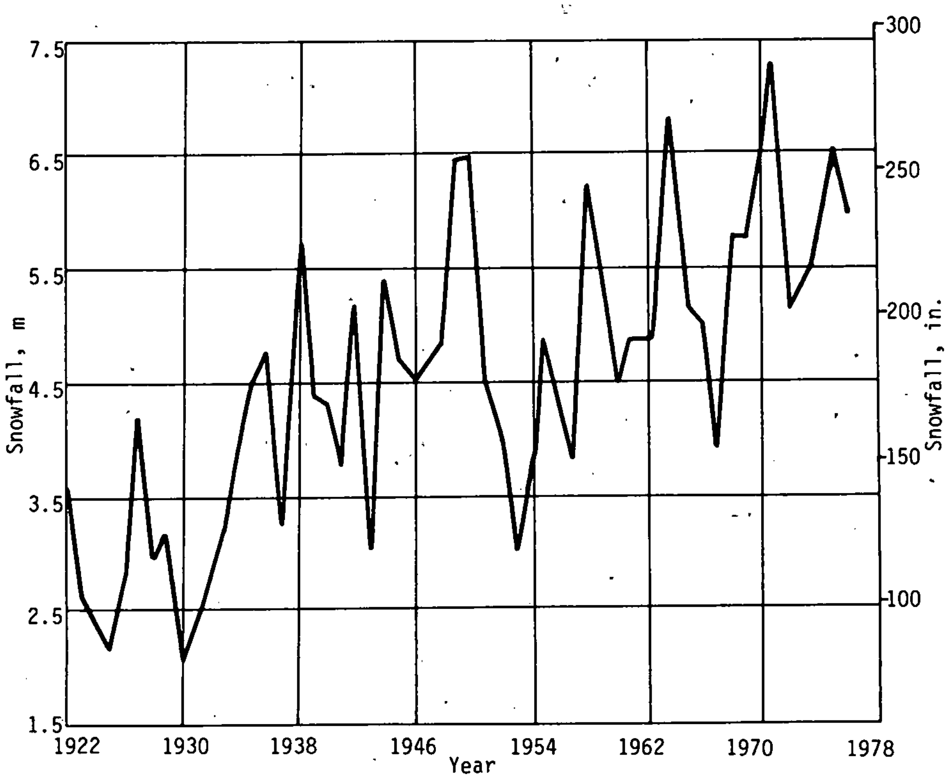


Figure 2. Snowfall in Houghton County, Michigan (1922-1976).



requirement for mechanical removal is much less than that for melting, bulk removal is commonly done by plowing. Melting is needed, however, in situations where no storage space is available in the vicinity of a transport channel or terminal, or long hauls are required for its disposal.

Equipment commonly used for clearing snow mechanically includes various types of self-propelled power units equipped with one or more attachments. Typical equipment embraces trucks equipped with underbody blades and front mounted one-way plows, with or without wing plows; V plows with or without wing plows; motor graders equipped with V- and wing plows, or one-way and wing plows; and rotary plows mounted on chassis. Among the power units, truck equipment is the most commonly employed. Trucks of 2.3 to 4.5 Mg (2 1/2 to 5 tons) are used extensively for light snow removal, but preference under heavy conditions is often given to trucks of 14 to 18 Mg (15- to 20-ton) or more capacity. The proper kind of equipment depends upon the type and location of channel or terminal facilities; the storm conditions, particularly the amount and nature of snow drifting tendencies; the condition of traffic; and upon the specific standard of clearing which may or must be adopted.

Snow removal is essentially an emergency operation, and work is strongly affected by organization and training factors. The nucleus of the work force is formed, as a rule, by the regular maintenance personnel of an agency, supplemented with other workers who may be called into service in times of heavy snow. It is essential that all personnel be instantly available for work, and for each person to be thoroughly familiar with his particular phase of the operation, as well as the peculiarities of the area in which he is assigned. Since snow removal often involves long hours of disagreeable and uncomfortable work, good morale is important, thus the selection of supervisors and operators is an important feature of the organization. In order for the organization to operate efficiently, constant training of personnel is also necessary. Many snow removal agencies hold training sessions prior to the winter season. The purpose is to teach those who are experienced in the many intricacies of the various pieces of equipment, and those who have had previous experience the latest development in equipment and organization methods.

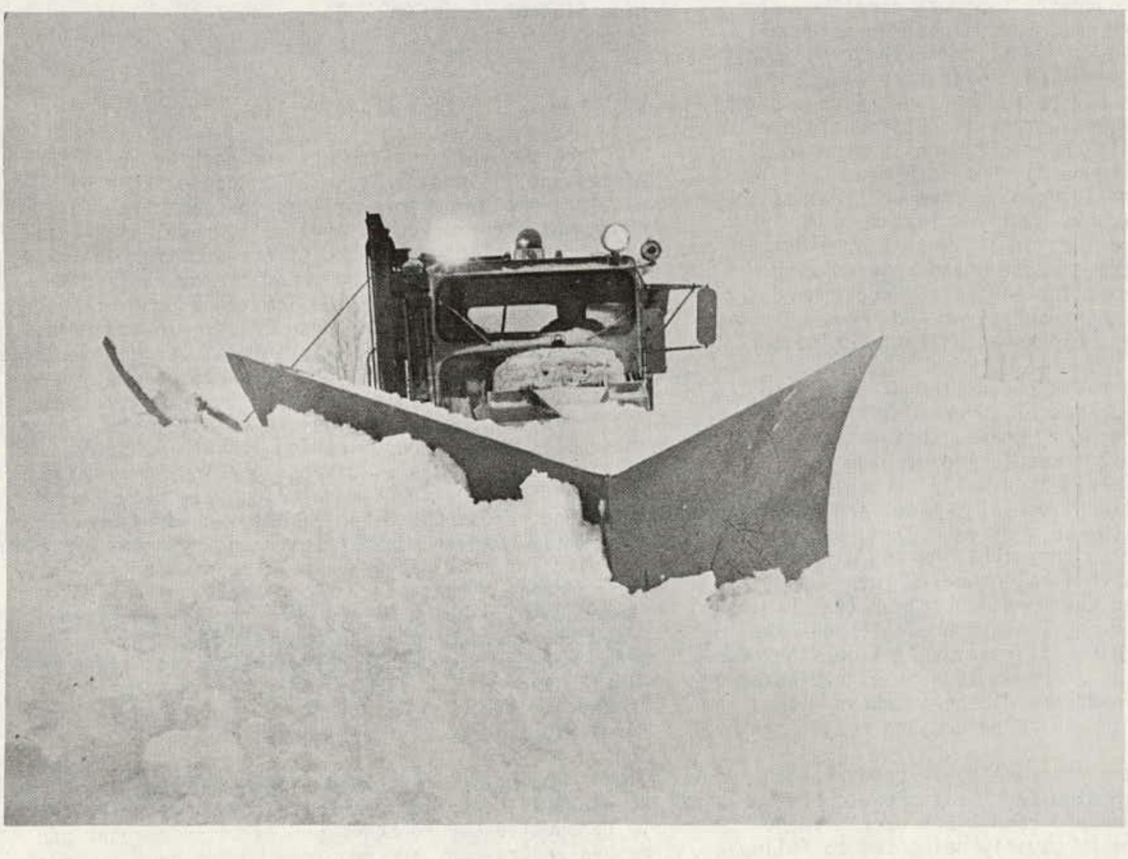
In addition, an advanced warning and information system to make snow removal operations readily responsive to public needs is extremely important. To determine the expected magnitude of the problem, arrangements are usually made with local U.S. Weather Bureau offices and airport weather observation stations for complete daily weather reports, and for special and detailed forecasts in case of an approaching storm. In highway work, many agencies maintain a weather reporting service, with all maintenance units reporting adverse weather or road conditions to a central office. The collected data is then rebroadcast through local radio stations to serve as a source of information for the traveling public.

Snow Removal on Rural Highways

Removal of snow from rural highways in the Upper Great Lakes Region is performed essentially by the long established method of plowing. While the basic approaches are similar to other parts of the country, the types of equipment and techniques for their use sometimes differ because of the unique geographic location and climatic condition of the region. Due to the severity of the quickly successive storms, snow handling equipment must be provided in order to cope with the worst conditions promptly and efficiently. Furthermore, since the winter work extends to about six months, and sometimes from October through early May, many engineers feel that specialized equipment is highly important. It is generally recognized, for example, that winter maintenance equipment such as trucks and graders must be greater, heavier, and more powerful than those for summer work such that converting summer maintenance equipment for winter work is regarded as impractical and wasteful.

For rural roads with high traffic volumes, the current practice generally requires that "bare pavements" be provided as expeditiously as possible. "Bare pavements", however, may be specified only

Figure 3. Truck - Mounted V-Plow with Side Wing.



near the centerline to give traction in both directions for low traffic volume roads if it is impractical to clear the entire traveled way. The priority of snow removal is established on the basis of the types of facilities and their traffic volumes. In Michigan and Wisconsin, county road agencies are usually contracted to perform winter maintenance on the state highway system in addition to work with the local roads under their jurisdiction. During critical storms, priority is always given to the maintenance of state highways. Moreover, in the Michigan state highway system, those channels carrying 1 000 vehicles or more per day have higher priority, and work on these sections is continuous after each storm until the pavement is completely cleared. For state highways carrying less than 1 000 vehicles per day, clearance of snow and ice is required until 1.8 to 2.4 m (6 to 8 ft) of the bare pavement is obtained. In regard to the county and local road system, school bus routes are generally priority roads for snow removal. In addition, many miles of local roads carrying only a small volume of traffic during the winter months are maintained with a compacted snow surface, which under sustained cold weather is capable of carrying vehicles so long as it is properly sanded to provide sufficient traction.

For a snowfall with little wind to drift, plowing is started as soon as travel becomes difficult. Trucks with one-way plows and underbody blades are commonly used because of their rapid movement, up to 56 to 64 kilometre/hour (35 to 40 mph) on fairly smooth road surfaces, thereby casting snow far onto the roadsides. These plowing units can also clean the snow closer to the road surface than V-plows do. The maximum depth of snow which can be moved depends on the power or traction of the vehicle and the height of the plow. In case of heavy snowfall with drifts involving an accumulation of 0.3 m (1 ft) or more, trucks equipped with V-plows, sometimes also with side wings are employed. These units usually operate at speeds up to 48 kilometre/hour (30 mph) without wings in operation. With side wings, the speed of operation may be reduced, but a considerably added width of plowed surface is obtained in one trip. Usually, only the right wing is used to allow traffic to pass (Figure 3), but both right and left wings are occasionally used if snow and traffic conditions permit. Trucks employed in this work are usually all-wheel drive, of at least 7 or 9 Mg (8- to 10-ton) rated capacity, and powered with either diesel or gasoline engines. Trucks used for plowing generally carry abrasives and, for heavy units, with concrete blocks as ballast for better traction.

Because of the rapid succession of storms in the region, and the problems of severe drifting associated with these storms, special efforts are needed to prevent the rapid accumulation of high snow banks along road sides. This is usually accomplished through the intelligent use of V-plows and wings to properly disperse the snow at each pass, so that the snow is not pushed up too high. As the windrows increase in size with time, however, rotary plows are needed to widen the roads and clear the shoulders for future snow storage (Figure 4). Although the speed of these machines is relatively slow, they can nevertheless move an enormous tonnage of age-hardened snow. After the roads are widened, trucks with side wings are then called on to reduce the height of the side banks.

Rotary plows are also useful in opening roads when drifts are too high for the V-plow to break through. In such severe conditions over a large area, a rotary plow is usually delegated to follow a V-plow unit. When the V-plow becomes stuck in a drift, the rotary plows around the truck, opening the rest of the drift, thus permitting the plow to proceed.

To control the drifting problem, portable and permanent snow fences are erected at critical locations parallel to and usually not closer than 23 to 30 m (75 to 100 ft) from the roadway centerline on the side of the roadway from which prevailing winds blow. These fences facilitate drifting of snow but confine it to the space between the fences and the roadway instead of covering the roadway. Since wind velocity, slope of ground, height of fence, and other factors influence the effectiveness of a snow fence, each location is studied as a separate problem and determined by a trial-and-adjustment method.

Motor grades equipped with V-plows and side wings are also widely used in removing snow. For light snowfall, a motor grader with its moldboard and wing can clean the pavement and shoulder in one trip, although the movement may not be as fast as a truck plow unit. Motor graders are usually employed, however, in locations where truck units with one-way plows and underbody blades cannot handle the situation alone. A motor grader can break the path with its V-plow, and use the moldboard to clean the road surface. Where the drifts are deep, the operator may choose to pull up the side wing and moldboard, pouring all the power into the V-plow. He may also use only the V-plow to wedge back snow that is already piled high from previous operations, then make another pass with the moldboard down to shave the snow closely. Motor graders are particularly useful in breaking up impacted snow on the pavement. With their wings, motor graders are also employed to cut down snowbanks, throwing the snow farther away from the roadway, thus giving truck plows enough room for the next layer of snow during the successive storm. One advantage of using motor graders for snow removal is that one man can operate both the moldboard and side wing of a grader. For a truck-plow unit, a second operator is usually needed to handle the wing.

Snow Removal in Cities and Villages

Snow removal from streets and parking areas in cities and villages is generally accomplished by plowing, employing more or less the same types of equipment and procedures applied to rural highways. In most cases, however, the strategy of removal also includes provision for the immediate or early disposal of snow because of the limited amount of space available for storage in these areas. In addition, high-speed plowing is usually infeasible due to close maneuvering requirements, the presence of obstacles, and the danger of violent casting to property.

The usual operation consists of plowing the snow into piles or windrows, loading it into vehicles, and hauling it to places of disposal. Plowing is in general performed by truck-mounted one-way plows, with or without underbody blades. Motor graders are also frequently used in many cities. Rotary plows are not employed for routine work; they are used primarily for widening streets or parking areas. The windrows pushed up by plowing may be temporarily deposited along the edges of streets or, in urban areas with wide roadway, along the centerline to facilitate parking and traffic flow. The gathered snow is then loaded for disposal without delay, a procedure particularly important if additional snowfalls are expected. Since parked cars often interfere with the plowing operation, extended parking during heavy snowfall is generally prohibited by city ordinances. In communities where heavy snowfall is frequent and removal operations are required before dawn, such as in Houghton, Michigan, parking on city streets between 2:00 to 7:00 a.m. is also forbidden.

Figure 4. Rotary Plow Dispersing Windrow Formed by V-Plow.

Plowed snow is commonly disposed of by hauling it in trucks to convenient dumping areas such as lakes, rivers, vacant lots, or outlying districts where it will not be objectionable. The trucks are loaded by rotary plows, fitted with chutes for the operation, and by bucket loaders. Flushing of snow by means of mobile snow melters, a method being experimented with by a number of large north American metropolitan areas where problems of snow disposal are created by increasing transport distances to fewer available dumpsites, is seldom considered in the Upper Great Lakes Region since the area is predominantly rural and does not lack space for snow disposal.

While "bare pavements" are required for the major streets in many cities in the region, there are numerous small communities that have adopted the policy of maintaining a snow cover for their streets during the winter months. In these places, the snowfall is generally so heavy and the cold is so intense that the snow does not melt appreciably until spring. Under these circumstances, it is not so much a question of completely removing the snow as it is making the streets passable. The roadway is thus only smoothed out by plowing after each storm, and the surface is sanded regularly to provide traction.

As in rural work, the snow removal strategy in cities is formulated well in advance of the snow season. It is essential that every responsible member of the organization knows his duties and has the necessary equipment in good condition and available for immediate use. In common practices, a city is divided into a number of districts, each having its equipment and operators assigned for the snow season, under the supervision of a foreman. The same operators are usually assigned to the same equipment and districts to provide familiarity with road and traffic conditions, drifting tendencies, and other particular problems in the area. In addition, auxiliary equipment and personnel are stationed at convenient locations and held in readiness to give assistance in case of need. Before the snow season, markers are placed at drainage structures, hydrants, guardrails, and other required points, to guide equipment operators, and to help avoid damage both to equipment and objects marked. A commonly used marker consists of a 5 cm by 5 cm (2 in. by 2 in.) stake with the top painted different colors to indicate the type of object.

Snow Removal in Airports

Snow removal in airports involves several types of equipment similar to those for removing snow from highways and streets. The operation is somewhat different, however, because of the extensive width of the surfaces to be cleaned, and because of the fact that a time limit is imposed to make the facilities operational. Consequently, proper removal techniques, and efficient organization of equipment/manpower are even more important than those required for clearing snow from other types of ground transport facilities.

Among the various areas to be cleaned in an airport embracing runways, taxiways, parking aprons, and other pavement areas in the terminal, runways are as a rule given priority. Snow removal usually starts when the accumulation reaches a depth of approximately 5 cm (2 in.). The equipment most commonly used consists of truck-mounted one-way plows, with or without underbody blades, which are teamed with rotary equipment, also mounted on trucks. The truck units may have a gross weight as much as 25 Mg (27 ton) to provide weight and power for high-speed operation, and are equipped with chains for better traction. The clearing procedure is largely controlled by the condition of the wind. Without crosswinds, plowing generally begins from the centerline of the runway, where right-cast one-way plows, operated in tandem, move the snow progressively outward to both sides of the runway. Rotary plows are then employed following the one-way plows to clear the windrows from the edge and from around the runway lights. In areas of heavy snowfall, extra widths beyond the runway are also cleared for storage of snow during the rest of the winter season.

With crosswinds, plowing will generally start from the upwind edge, working across the runway toward the downwind edge, so that snow is moved with the wind, and drifting is minimized by limiting the windrows to windward. For these operations, reversible type of plows are particularly desirable because the plow direction can be reversed to cast the snow downwind on the return trip as well as the initial pass. In general, operation of one-way plows is not influenced by adverse winds to the same degree as rotary type of equipment. When it is impractical to move the snow with the wind, dispersal of windrows by rotary plows may have to be postponed until there is a shift of wind direction. Wind conditions are also considered in planning a clearing operation of other areas in an airport. When equipment is unable to cope with the snow during storms of unusual intensity, priority treatment is usually given to the in-the-wind runway and taxiways serving it.

The clearance of large aprons and other areas may sometimes be hampered by parked aircraft or vehicles, as snow cannot be removed by pushing it from one side of the area to the other by one-way plows. In this case, removal is accomplished by loading the snow into trucks by front-end loaders, and hauling it to suitable disposal places. Following the operation of one-way plows, motor graders are sometimes utilized to keep the plowed area as bare as possible. With moldboards, motor graders can usually remove the small amount of snow on the pavement that the one-way plows cannot move. Motor graders are also used to clean the snow when it is falling lightly or the accumulation is not appreciable.

For the snow removal program to function efficiently, the airport manager and his crews must be constantly prepared for immediate action. Complete weather reports, as well as special and detailed forecasts in case of an approaching storm, are obtained from the weather station at the airport in order to be aware of developing conditions. Two-way radios are commonly used as dispatching equipment. These units provide the necessary communication between the central office and individual operations in the field. They are of particular value in dispatching equipment in trouble spots during a storm, and in summoning aid in case of equipment breakdown or empty fuel tank.

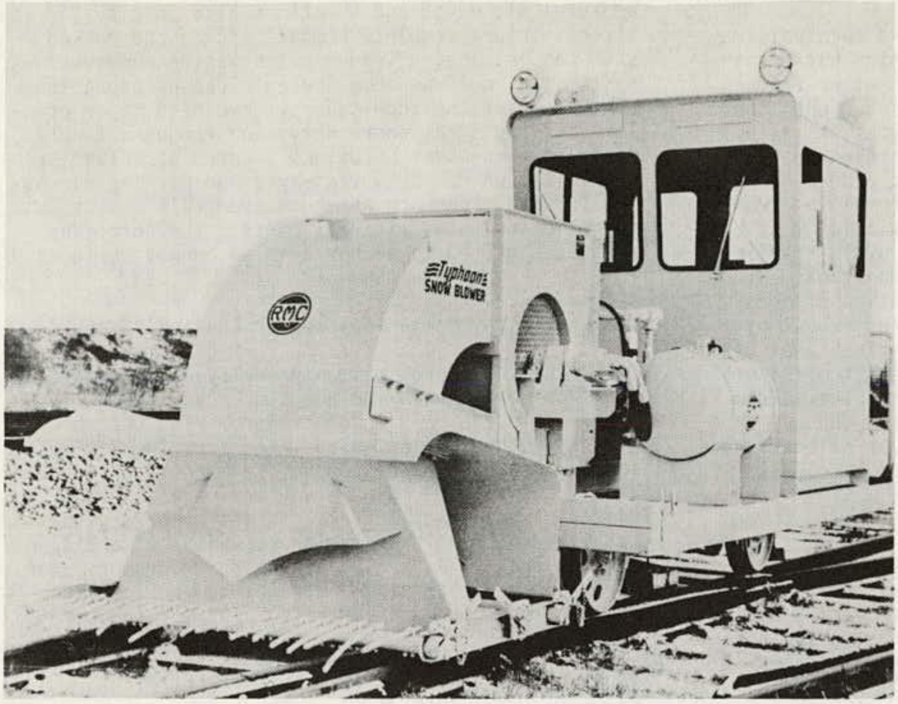
Snow Removal on Railroad Tracks and Terminals

Removing snow from railroad tracks and terminals requires an array of mechanical devices most of which are specifically designed for this purpose. In plowing snow from main line and branch line tracks where accumulation is deep enough to impede or stop progress of trains, various types of V-plows and rotary plows are employed. These plows are usually mounted on a specially built car with heavy steel frame construction and powered by locomotives which are capable of supplying a tremendous amount of propulsive force for the clearing operation. In addition, truck-mounted units similar in design to those used widely on highways and equipped with flange caster wheels, are used both for off-track and on-track operations. These units may be powered by either gasoline or diesel engines, and provide a mobile task force which can be shifted from point to point as trouble develops.

Some locomotive-powered V-plows have a separate hinged nose section which can be lowered or raised between or above the rails, and movable hinged wings which can be adjusted out from the side of the plow. Plows without wings will throw the snow clear of the right-of-way. On main line track, these plows are usually operated between 32 to 56 kilometre/hour (20 to 35 mph), depending on the locality and depth of snow. Rotary snowplows are used principally for clearing snow drifts that are too deep and compacted for ordinary railroad snowplows to handle. The speed of operation depends on the depth and density of snow, but usually reaches about 11 to 16 kilometre/hour (7 to 10 mph). Rotary units may load snow into cars, trucks, or blow it into open fields. For clearing operations on lines, ample space is usually available alongside the tracks for snow storage.

Another piece of railroad equipment for handling snow is the flanger, used mainly to clear snow which is not too deep over the rails and to follow up on heavy plowing. A flanger is a metal scoop type blade mounted under the center of a car. It can be adjusted pneumatically or hydraulically to cut 5 cm (2 in.) below the rail top, thereby providing flangeways for the wheels so as to increase adhesion of locomotives and reduce resistance to car wheels, guarding against the freezing of snow following sleet or cold rain. Flanger cars are usually attached to the rear of passenger or fast freight trains, and operated at a speed of 48 to 64 kilometre/hour (30 to 40 mph). A

Figure 5. Self-Propelled Snow Blower for Removing Snow from Switches.



fairly fast operating speed is required so that the snow is thrown as far as possible as it is scooped up by the blades. At 56 kilometre/hour (35 mph), the snow can be thrown about 12 m (40 ft) outward.

It is generally recognized by railroad men that snow and snow removal present more problems in terminals and yards than on line of road, because combating snow on line usually involves only plowing the tracks clear, whereas in most terminals entire removal of the snow from the yards is necessary. For clearing operations in terminals, track-mounted spreaders are often used, in addition to the V-plows and rotary plows. These spreaders are built primarily as ballast spreading machines, but can be used in place of, and sometimes in conjunction with, snowplows. The spreader has a wide wing spread, making it adaptable for spreading snow across yard tracks. It can be used as a snow plow by equipping it with a detachable high plow, making the machine a combination unit which can both plow and spread snow. When thus equipped, one spreader will often do the work that is otherwise required to be done by a plow and a spreader working as separate units. The principal use for spreaders is in railroad yards where the tracks are cleared by pushing the snow off one track to another successively throughout the width of the yard to a point where it can be piled or loaded.

One of the serious threats to railroad operations is the stoppage of switch movements by packed snow or ice, and various types of snow melting devices are used to keep switch points sufficiently free of snow to insure operation. This is usually accomplished by the application of heat to the rails in the point area to raise the temperature of the steel parts and thus melt the snow. Portable devices, such as snow melting cans, are used to pour a flaming liquid on snow or ice to be removed. These cans are equipped with a pilot wick on the discharge nozzle which ignites the fuel immediately as it leaves the nozzle. Electric tubular heaters, placed under the stock rails and controlled by hand or thermostatic switch from interlocking towers, are permanent melting devices. In addition, gas heaters consisting of burners laid outside the head of the stock rail, lighted automatically or by hand, direct flames against and underneath the stock rail. Sometimes, physical removal of snow from switches is made by mechanical or manual means. In regions where temperatures are low and the snow is dry and powder-like, mobile air compressors are used to blow the snow from tracks and switches. A typical self-propelled machine, as shown in Figure 5, utilizes a centrifugal fan which blows air through a nozzle at a high velocity. The nozzle is adjusted hydraulically from top-of-rail elevation to 0.3 m (12 in.) above the rail. Steel cable fingers loosen the snow immediately ahead of the nozzle. This allows the snow to be blown clear of the track and dispersed into the atmosphere where wind currents carry it away for settlement over a larger area.

As in any other snow-fighting campaign, effective snow removal from railroad tracks and terminals requires advance planning and centralized direction. Preparations for these operations usually begin long before the first snow falls. Printed instructions are issued which make specific assignment of men and equipment for each location. At prewinter meetings of key personnel, the plan is reviewed to make certain that each man understands what has to be done in advance and exactly what his responsibilities will be when snow starts to fall. Snow fences are placed at strategic locations to reduce wind velocities and cause the snow to drift before it reaches the roadway. In actual operation, special emphasis is placed on obtaining weather reports regarding approaching storms, keeping the equipment in operation at the earliest possible moment after the start of a storm, and operating it at frequent intervals to keep the situation under control. In addition to track and yard areas, platforms, walkways, and driveways are kept clear for the convenience and safety of employees and the public, and to prevent damage claims. Equipment for these areas usually include dump trucks equipped with one-way plows, mechanical brooms or sweepers, front-end loaders, and other conventional snow removal machines.

Ice Treatment Procedures

Ice on transportation channels and terminals may be formed by packed snow or slush which hardens in place before it is removed, by frozen water from melted snow or ice which drains across or onto the surface, or by sleet or rain freezing as it falls. While some of the formations can be prevented by effective snow removal techniques and proper drainage provision, ice coatings on roadways resulting from precipitation or unpreventable accumulation must be controlled or treated in some way to avoid traffic hazards caused by skidding. The common treatment procedures consist of (1) the application of abrasives on the icy surfaces, and (2) the removal of ice by mechanical or/and chemical means. The types of treatment depend largely on the ambient temperature and the adhesion characteristics of the ice. From the viewpoint of transportation safety, channel and terminal areas must be treated wherever slippery conditions exist and for as long a period as necessary.

Application of Abrasives

Abrasives commonly applied on icy roadways to improve traction and braking performance of vehicles include sand, cinders, stone screenings, slag, and other appropriate materials. The abrasive material must have grains that are clean, hard, sharp, and free from clay lumps. Experience has also shown that material containing an excess of fines does not provide good traction. Likewise, coarse material is likely to whip off the surface, thus it is ineffective in combating skid hazard. An abrasive generally favored by engineers in the Upper Great Lakes Region is an angular coarse sand, although consideration of local availability and unit cost often determine the choice of many other materials.

Abrasives in bulk are commonly placed in bins, sheds, and covered stockpiles prior to the first storm in the fall. Occasionally, they are also stored in the open. Since these materials almost always contain moisture, calcium chloride at a rate of 29.6 to 59.3 kg/m^3 (50 to 100 lb per cu yd), depending on the type of abrasives, is usually incorporated and mixed thoroughly with the abrasives to prevent the grains from freezing together in the stockpile. The treatment also serves as an aid to anchoring the material in the ice or packed snow, thereby keeping it from being blown off the surface. The loading of abrasives into trucks for application is speedily done by gravity discharge, conveyor, or bucket loader. In addition, abrasives in small quantities are often placed in barrels along the roadway or in locations where hazardous conditions exist. These materials are provided for use by the public, if necessary, before regular application can be made by the maintenance forces.

Abrasives are distributed from trucks with a mechanical spreader operated by a power take-off with the control mechanism in the truck cab. The amount of abrasive to be used varies with the type of ice and the weather conditions. The areas where immediate treatment is needed after icy conditions develop include hills, curves, schools, approaches to railroad crossings, and intersections. As in snow removal operations, priority of the treatment work is established in advance on the basis of such items as volume and type of traffic, geometric design, and topographic conditions. In general, major channels and traffic areas are treated with abrasives for the entire length or surface, whereas spot treatments are often made on less important facilities, depending on the needs in a particular situation.

Abrasives are used extensively for ice treatment on rural highways, and sometimes also on city streets before complete removal of ice and packed snow can be made. Clogged catch basins and sewer systems, as well as complicated clean-up operations at the end of the snow season, have been major problems in some areas where heavy and frequent treatment had been made. Chlorides treated abrasives are prohibited on runways, taxiways, and parking aprons in airports, inasmuch as these chemicals may promote corrosion of metal aircraft parts. The abrasives are often heated to anchor them on runway surfaces.

Ice Removal by Mechanical and/or Chemical Means

Mechanical means commonly employed for removing ice from paved areas include trucks equipped with underbody blades and motor graders. The underbody blade is a hydraulically operated scraping device fitted beneath a heavy truck; the blade can be hydraulically loaded to give vertical pressure at different angles of attack. To get good results it has been reported that the gross weight of the truck must be over 10.9 Mg (12 tons). Motor graders that are capable of exerting a sufficient vertical pressure on the moldboards are also used for the same purpose.

The effectiveness of mechanical ice removal is largely dependent upon the ambient temperature and the condition of the ice. In general, ice on the pavement can be completely removed at a temperature near its melting point. At temperatures below this point, often only the top portion of an ice layer can be successfully removed by scraping. The lower portion may sometimes be so tenaciously adhered to the pavement that it is practically impossible to break it away from the pavement without damaging either the pavement or the blade. Because of the inadequacy of mechanical equipment of exposing bare pavement, chemical means are widely employed either alone or in combination with mechanical means for better results.

For highway and street work, both calcium chloride and sodium chloride are extensively used for ice removal. Raw sodium chloride in the form of rock salt is used for clearing the pavement of ice or compacted snow when the temperature is above -6.67 C (20 F) or at approximately -6.67 C (20 F) and rising. The chemical is applied by mechanical spreaders at a rate ranging from 28.2 to 84.6 kg per lane per km (100 to 300 lb per lane per mile), depending on the degree of control required, traffic volume, climatic conditions, weather predictions and other considerations. For a very thin film of ice on a rural two lane highway, the chemical is spread nearly over the full pavement width. For a heavy accumulation of ice on the same facility, the application is concentrated near the high point of the pavement crown, allowing the brine to loosen the accumulation of ice from the pavement surface as it works to the pavement edge. The accumulations of loosened ice or snow is then removed by mechanical means to prevent refreezing to the pavement.

For temperatures below -6.67 C (20 F) and lowering, but not less than -17.78 C (0 F), calcium chloride is added to the sodium chloride, in amounts usually no more than 25 percent of the weight of sodium chloride. The calcium chloride starts and accelerates brine action at this temperature range where sodium chloride alone is less effective. For temperatures at -17.78 C (0 F) and lowering, raw chlorides are usually ineffective, and treated abrasives are applied at critical areas to provide suitable traction.

In addition to ice removal operations, chlorides are used to prevent ice formation on highway or street pavements. This practice is used when snow compacts under traffic and adheres to the pavements, during freezing rains or immediately following plowing operations if snow still remains on the pavement. Experience has shown that traffic packed snow usually occurs between -7.78 to 1.11 C (18 to 34 F), and blading operations will begin when approximately 1.27 cm (0.5 in.) has accumulated on the pavement. Sanding and salting operations will follow the blading as closely as possible with only minimal chemical treatment to sufficiently remove the small amount of snow left after blading. When the temperatures are -6.67 C (20 F) and rising, the minimum amount of 84.6 kg of sodium chloride per km (300 lb per mile) should be sufficient. If the snowfall continues, this application will aid in preventing the snow from bonding the pavement. The procedure will eliminate the necessity of using excess amounts of chemical and blading off of varying amounts of loose slush and snow after the chemical action has taken place. As the storm continues, underbody blades will be kept in operation to hold the accumulation of packed snow on the highways to a minimum. This may make salting and sanding operations unnecessary except for hills, curves, railroad crossings and intersections. At such locations, a stronger mixture of chemical may be necessary during a heavy snowfall.

In the case of freezing rains and sleet storms, sodium chloride or a mixture of sodium chloride and abrasives are spread as soon as ice appears on the pavement. Generally, one application of 56.4 to 112.7 kg of chloride per km (200 to 400 lb per mile) on the middle of a two-lane pavement will suffice to dissolve existing ice and provide a bare pavement when the storms have passed. Blading operations are usually needed to remove the accumulated slush and snow from the pavement to prevent refreezing. In the event of rapidly dropping temperatures, little chemical reaction can be obtained by sodium chloride alone. Under this situation, ice can usually be removed by a mixture of sodium and calcium chloride, or by hydraulic blades at an appropriate pressure.

Although chlorides have been used for many years to de-ice highways and streets during winter months, questions have been raised recently concerning the wisdom of unrestricted spreading of excessive quantities of these chemicals into our natural environment. Because chlorides are readily dissolved in water, and because snow or ice is the solid form of water, any chloride-snow mixture will eventually result in disappearance of the salt into solution. Dissolved chlorides may enter streams, rivers, lakes, and water supplies situated close to the channel and terminal facilities resulting in water pollution. High chloride concentration can cause injury to vegetation, vehicle corrosion, and pavement damage. It is the general opinion of many road maintenance engineers in the Upper Great Lakes Region, however, that the use of deicing chlorides, in combination with mechanical means, is the most practical and economical method of removing snow, ice, and slush from highways and streets. Sensible use of chlorides to maintain bare pavement can also save vehicle operating costs and reduce accidents. The fact that deicing chlorides can be misused and mishandled, culminating in less than satisfactory results is recognized. Consequently, it is generally agreed that these chemicals must be used sparingly in accordance with established rates of application based on local experience and variations in temperature, precipitation, pavement conditions, and other pertinent factors. To insure proper distribution, the spreading equipment must be carefully calibrated individually. Unused chemicals must be covered or enclosed in waterproof sheds and never be allowed to be stored in open fields to protect the environment from chloride contamination.

In current practice, calcium chloride and sodium chloride are not allowed as deicing agents for airport pavements because of their detrimental effects on the bodies and hydraulic systems of aircraft. Some non-corrosive chemicals have been tested in the region, but none has been found entirely satisfactory. Many airports use motor graders for clearing ice on pavements. Heated abrasives are also applied on critical areas to provide traction.

Future Research Needs

The operational systems of snow removal and ice control for ground transportation channels and terminals in the Upper Great Lakes Region have been developed through many years of experience in the field and, in most instances, have been adequate to keep the facilities in serviceable condition during the long winter months. Very little organized research has been conducted, however, to determine the effects of the properties of snow and ice, climatic conditions, terrain, traffic, geometrics, equipment, personnel, and location factors on these operations. From the viewpoint of systems planning, there is a general lack of an analytic approach that would describe and define in quantitative form the factors that affect the formulation and use of the systems for removal of snow and ice from transport channels and terminals in terms of benefits accruing to the users of these facilities. From a detailed evaluation of the input data of this investigation, the following specific areas of research seem to be needed in the development of new techniques and quantitative data for improved systems performance.

1. Establishment of performance and efficiency criteria of various types of equipment commonly used for snow removal in terms of properties of snow and ice, power efficiency, casting distance, volume or weight removed per hour per horsepower for different speeds, and other factors. Possible improvements in design and operation for better performance and higher efficiency should be considered.
2. Re-evaluation of the effectiveness of chloride salts and other chemicals for snow and ice control, as well as their social and environmental consequences in the Upper Great Lakes Region. Investigations should include a study of particular situations where treatment is seemed necessary, the proper amount of application in each case with regard to ambient temperature, pavement condition, snowfall rate, traffic volume, etc., and control procedures to minimize environmental contamination.
3. Development of models and techniques for the analysis of operational systems for maximum effectiveness of snow removal and ice control in the Upper Great Lakes Region. The analysis should be based on considerations on detailed systems characteristics, local climatic and geomorphologic conditions, properties and conditions of snow and ice, types of transportation facilities, volume of traffic, population characteristics, economic conditions, environmental consequences, and cost structure.

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About Snow Drifts

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This article discusses some geomorphological-climatic aspects in snow-drifting control. The growing consciousness about the importance of coping with snow drifting on roads causes highway construction and maintenance engineers to look for systematic, long-term data and more effective methods of snow-drifting control than what is now available that could be used in updating design criteria, for operation of existing roads, or included in a project for a new road alignment. It appears that, besides artificial methods of snow-drifting control, more attention than hitherto should also be paid to the natural ones, such as geomorphology of the terrain. To cope effectively with snow-drifting problems, a comprehensive theoretical and experimental research on geomorphological and climatic factors is suggested in this article. Reliable parameters for practical use, classification of snow drifting, and regional snow-drift maps delineating the regimen of the snow cover, should be the aim in these researches. Such researches should find an important place in the programs of various institutions, agencies, transportation boards and transportation departments, and authorities administering snow-drifting control work of various transportation facilities. With reference to the suggested research, some geomorphological aspects pertaining to snow drifting on roads are discussed in this article.

Need For Snow Drifting Control

Protection of the nation's ground transportation facilities against snow, and the removal of it is an undisputed necessity for unimpeded, year-round vehicular transportation.

Disucssion of snow removal practices by mechanical means is beyond the scope of this article. This topic, as well as the subject of various types of snow fences have been discussed adequately in References 1 through 5. In some regions here and abroad snow fences are being used empirically with some reasonable, practical success in reducing wind velocity and thus protecting roads from snow drifts. However, snow fences cannot and should not be used blindly everywhere. To combat snow drifting on roads effectively, local observations about snow drifting should be supplemented by theoretical and experimental studies on the geomorphology and climatic conditions, and the aerodynamics of snow drifting.

Whereas in recent years the problem of protecting roads against frost action has been given considerable attention, the protection of roads against the winter traffic impediment by drifting snow is still an enormous, unsolved problem of immediate necessity.

At the present time, publications about snow and ice appear in many different journals and conference proceedings. Studies along these lines are pursued in many individual laboratories.

From the hitherto available research results one may also notice that very few researchers have really pursued systematic, deeply scientific-technical studies on snow drifting for practical, immediate applications. All that has been studied so far was aimed at learning only about certain properties of snow, or those of a snow cover, and ice.

Another regrettable lack in disseminating knowledge about snow drifting is the episodic nature of research along these lines.

All the knowledge on snow and snow drifting so far available needs a comprehensive synthesis for building up and fusion of the engineering discipline called snow mechanics.

The nation's transportation depends to a great extent upon a complex network of highways that require constant grooming by maintenance crews to keep the system functioning all year round - and free of snow. In our contemporary economy, wheels must turn, freight and people must move. Therefore, prompt removal of snow from transportation facilities is a recognized necessity. Coping with snow drifts and snow removal, however, is an expensive, multimillion dollar enterprise: hundreds of thousands of tons of snow must be removed to keep the roads open to traffic. Added to this is the cost of ice control. Besides, the drifting control by portable snow fencing structures requires a lot of manual work, and is difficult to mechanize. Economy in snow removal usually results in snow piling up, snow which then freezes, and many traffic arteries become nothing else but continuously rutted pitfalls and treacherous tracks for motor vehicles and their users. All this means a traffic hazard to safety.

The growing consciousness of the importance of coping with snow drifting on roads has caused highway construction and maintenance engineers to look for systematic, long-term data and more effective means of snow-drifting control than now available. This information can be used in updating design criteria for construction and operation of existing roads, or included in the project of a new road alignment. It appears that besides artificial methods of snow-drifting control, also the natural ones, such as the geomorphology of the terrain, should be paid more attention than hitherto.

About Snow Drifts

All existing methods of coping with snow drifting on roads are based on the principle of protecting the road from the deposition of snow masses, carried by wind, on the road.

In snow, viz., water resources management, the functional intent of a snow fence is not the prevention of drifting of snow. Rather, its function is to facilitate purposive drifting and deposition of snow in the catchment basin. Also, in agronomy, in conserving the treasure of the "white gold," the principle of snow-drift control is the spreading out of the drifted snow over the field (catch basin) in a uniform layer facilitating vegetal growth. This means approximately equal thawing time in the spring; otherwise, ponding in some places may occur; crops may become damaged; the soil may become eroded, and slides may occur. Thawed, undrained water from accumulated masses of drift snow may also endanger stability of earthworks. On the other hand, the snow cover protects the soil from deep frost penetration. Thus, one realizes here the importance of the snow cover to engineering, traffic, and farming.

Snow

Snow is a familiar phenomenon. Most of us have tramped through it, revelled in it, admired it and even cursed it. Yet, what do we really know about snow?

A considerable amount of precipitation on our planet Earth is in the form of snow. Winter snow falls have occasionally occurred even in the far south of the United States.

Snow is a precipitate of porous, unstable aggregate mixture of ice particles and air, - a material of bewildering complexity difficult to study and to work with. Snow is formed directly from the water vapor of the air at a temperature less than 0°C. It is not a frozen rain.

A very dry, fluffy layer of snow may contain as much at 97% air. Therefore it has a very small coefficient of thermal conductivity. This porous quality of a new snow makes it efficient insulating material against frost penetration into soil. A newly fallen snow consists of hexagonally crystallized ice crystals whose form depends upon the condition of their crystallization.

Fresh snow has a definite but low strength depending partly on "cogging" between the branched ice crystals and partly on real grain bonds. Essentially, snow is an unconsolidated sediment. During and after its deposition, snow undergoes its metamorphosis, i.e., changes in its character. During the course of time, wind may shake and densify the snow, whereupon it settles, becoming more dense. Thus heavy snow drifts may become greatly densified. It is the weight and inertia of deep and/or dense, heavy snow that brings vehicles, trains, and aircraft to a halt. Hence, removal of dense snow drifts costs considerably more than removal of fresh, loose snow drifts.

The physical, mechanical and thermal properties of the snow are important factors in the snow drifting problem in particular, and in snow mechanics in general. Snow mechanics is a complex engineering-science discipline, and its research results for practical application do not come easily. Hence, the snow mechanics aspects of snow drifting and snow removal problems are very complex, too. An appraisal of the major difficulties in snow mechanics was made by Melor (6).

Information about physics of ice and snow may be found in Reference 7. The properties of snow were discussed by Mellor (8). A discussion about the metamorphosis of snow can be found in Reference 9 and 10. The physical characteristics of the snow cover is dealt with in Reference 11. Reference 12 pertains to an interdisciplinary symposium about advanced concepts and techniques in the study of snow and ice resources.

Snow Drifting

Coping with snow drifting on roads is now merely a problem of snow removal and using snow fences. It is based on the theory of snow drifting (13, 14). Aerodynamically, a drifting or blowing snow is a two-phase flow containing ice and air, arising on the interface of wind stream and snow cover. If snow transport by wind takes place only up to about 20 cm above the ground (viz., snow surface), one usually speaks about a snow drift.

At a certain intensity, the wind is able to pick up, lift up from the interface of the wind stream and the snow cover, and whirl up loose, powder-fine surface snow flakes, ejecting them into the wind stream, which gain momentum from their motion, and to carry them away over and along the snow or ground surface to considerably long distances.

A snow particle can be removed from the surface of snow cover

a. By a direct drag of the wind, and
b. By the impact of a snow particle on the interface flying down the wind.

Depending upon the air-stream velocity, the movement of the snow particles in an airstream can basically take place by suspension, or by saltation, or by creeping along the surface. These modes of motion may be operative singly, or in any variety of combination together.

Some of the basic conditions conducive to snow drifting are:

1. There must be enough snow on the ground; drifting will occur to a large scale after all irregularities on the ground surface have been smoothed out;
2. The air temperature must be below 0°C, and the snow should be dry, although drifting may set in even at air temperature of 0°C;
3. The lowest wind speed for bringing about drifting is usually regarded as approximately 15 km/h. At wind velocities higher than 15 km/h, more snow particles are ejected into the wind stream, gain momentum, and are drifted away. If the wind that drifts the snow is swift, great volumes of snow will be carried over and far beyond a level terrain. Great, thick drifts can thus be built up, and deep gullies can thus be packed to the brim.

The amount of snow deposited depends also upon the quantity and physical properties of the snow; velocity of the wind and its direction; the nature of the topography of the terrain and its relief; exposure of the protected area to the wind, as well as upon the areal extent over which the drifting snow is transported. The area may be situated in relation to its surroundings in such a way that the vertical profile of the ground surface is streamlined. Lack of ground surface relief affords extensive snow transport by drifting.

When the snow-laden wind stream encounters natural and/or artificial obstacles, snow whirls or eddies in the wind stream are formed, and a local reduction in wind velocity takes place. Upon decrease in wind velocity, the snow particles are deposited out of the wind stream into these zones of relative calm to form a drift. The large snow particles tend to collide with each other, and with the obstacle. Collision among snow crystals decreases their velocity, and upon colliding with an obstacle they rebound and settle at a short distance from the obstacle. This process continues for as long as an obstacle is effective in reducing the velocity of the wind (15). Such obstacles may be vegetation, fences of all kinds, built-up areas, changes in the relief of the terrain, and various geomorphological landforms encountered in a region prone to snow drifting. In glaciated regions, such landforms may be ground moraines, terminal moraines, drumlins (long, egg-shaped oval hills whose long axis is parallel to the glacial ice movement), eskers (long, meandering ridges), kames (low, cone-shaped mounds), and other landforms (16). Thus, under certain combinations of climate, meteorology, topographical terrain features, and the velocity of wind blowing across the various landforms and the road may cause snow to drift and pile up where it is not wanted. Areas which seem to be prone to accumulation of drifting snow are usually encountered around knolls, mounds, hills, ridges, and peaks and at point of low elevation, and depressions in the ground surface. Shallow trenches, borrow pits and quarries become quickly filled up with snow. Therefore, snow drifting on a road is very much influenced by its position in the terrain, and by the direction and intensity of the wind. Usually the amount of drift is greater at perpendicular winds than at longitudinal ones. The filling up of cuts with snow is slower when their slopes are gentler. Here a considerable amount of snow is carried across the cut. For a complete picture about snow drifts in cuts, it is necessary to know the geometric dimensions of the whirl (eddy) zones which are formed in the depressions.

From the above discussion one may get the notion that the environmental parameters such as landforms and climatic conditions influence the formation of snow drifts. Also, one becomes cognizant that transportation alignments and their facilities such as parking areas, fuel stations, maintenance centers, and the like, as well as housing developments must fit properly, purposely, geomorphologically, climatologically, aerodynamically, and aesthetically in the landscape with respect to wind, snow drifting control, drainage, and appearance. It is believed that geomorphological and aerodynamical considerations in engineering design will help to cope with undesirable chronic winds from being a nuisance where snow drifting is concerned.

It is for the reasons discussed above that a comprehensive theoretical and experimental geomorphological research on snow drifting in drift-prone regions is advocated herewith, namely;

1. Geomorphological-climatic (and microclimatic) studies,
2. Aerodynamics of various landforms,
3. Aerodynamics and snow mechanics of snow drifting,
4. Climate and hydrology of drift-prone regions,
5. Soil mechanics, and
6. Thermal soil mechanics in connection with snow drift problems.

Such studies should include the proper tracing of traffic routes through the given climatic spaces, which, as is known, may vary considerably from place to place on a small areal extent. They should also include studies on climatic weather zones and weather trends; "detours" of the prevailing wind and snow drifting paths; the study of plantation effects such as woods, trees, shrubs; wind gaps; jet streams; sunny and shady positions; fog zones; run-off; drainage, and other pertinent factors. Especially, it is necessary to obtain information about the casual connection between geomorphology and the wind-streaming regimen, as well as the snow-drifting processes in mountainous, hilly, flat terrain and other landforms.

The above described phenomena and criteria also bring to the fore the question whether wind protection is always necessary, or desirable, or even advisable. Sometimes there may be cases where the relocation of a road section is justified in order to avoid excessive snow drifts. Thus, one sees that there are no simple, general solutions to snow-drifting control. Until more knowledge becomes available, one resorts only to making intelligent choices.

Some Geomorphological Aspects Pertaining to Drifting of Snow

In practical alignment work of a road, it so often happens that a great deal of thought is given to balancing favorably soil masses in cuts and fills. The question whether a mere lateral shift of the alignment of the road might be beneficial relative to snow drifting control is being paid very little attention. Available information about the causes and control of snow drifting points first to highway design factors such as placing of highways in locations free of snow drifting; alignment of the highway with exposure to prevailing winds; slope of the terrain; elevation of the road grade line above the average snow level;flattening both cut and fill slopes to or below the air flow line; avoiding obstructions which cause drifting, and providing for areas of catchment for storage of snow. Avoiding high fills with steep slopes may be helpful. At a high dam, the snow first fills in the toe (Fig. 1). Then the snow-laden wind, moving upward along the slope, increases in velocity so that the suspended snow in the windstream, too, is carried upward. Because the upward-directed wind at the top of the dam cannot change its direction suddenly, there forms above the crest of the dam a wind-calm space where the wind loses part of its velocity. Hence snow particles settle out and deposit a drift. The crest of the dam becomes covered with snow.

On not too high, gentle slopes the snow is swept across the crown of the road. Therefore, flatten out slopes, or make curved slopes of cuts and fills. Also, rounding up junctions with terrain and top of the fill (top and bottom of the cut) facilitates streamlined drifting. To avoid excessive snow removal, roads should be elevated above the natural ground surface.

Avoid shallow cuts. Unprotected excavations, trenches, borrow pits, and quarries can be drifted full of snow quickly during a period of one single drifting. Fig. 2 illustrates the concept of snow drifting in a cut made in a sloped ground. Because of the cut, the cross-section of the blowing windstream across the cut increases. This brings about fall-out of snow from the windstream and sedimentation of snow. The cut is drifted full quickly. The drift continues until the effect of the opposite slope of the cut makes itself felt, and the cut is drifted full.

Figures 3a and 3b show snow drifts at various obstacles. Figure 4 illustrates a wind gap between two hills. Figure 5 illustrates a road section along the windward slope of a hillside prone to snow drifting. The hillside is exposed to a broad, level expanse of an open fore-field. Figure 6 shows a good position of a road protected against the wind by trees.

Conclusions

1. Coping with snow drifts on ground transportation facilities is of national importance.
2. Snow-drifting control is also of utmost importance in planning of housing developments, as

Figure 1. Snow drifting at a high dam.

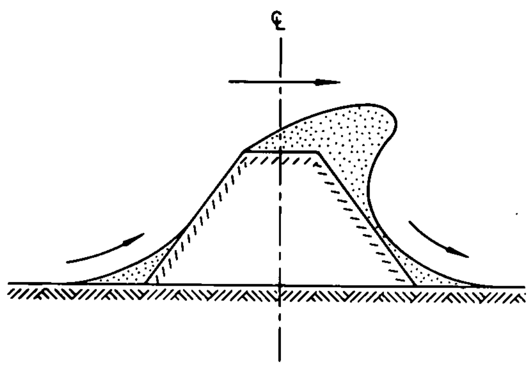
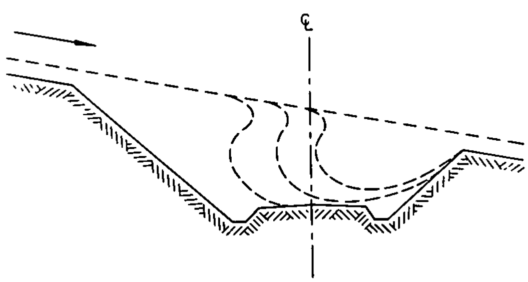


Figure 2. Snow drifts in a cut made in sloped ground.



Figures 3a and 3b. Snow drifts at various obstacles.

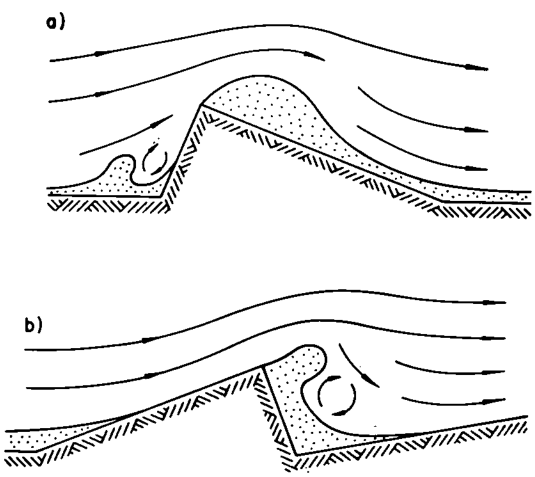


Figure 4. Wind gap between two hills.

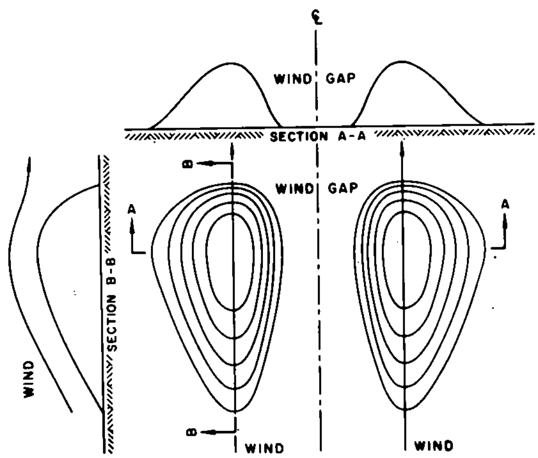


Figure 5. Road section along the windward slope of a hillside prone to snow drifting.

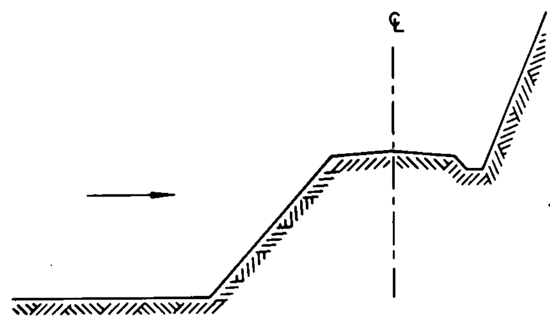
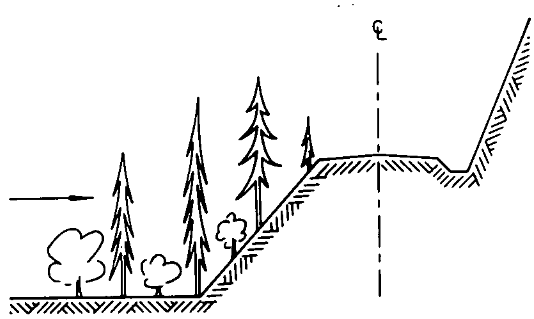


Figure 6. Good position of a road protected from wind by trees.



well as in solving problems of snow retention and conservation for agricultural use and as a water supply resource.

3. The physical, mechanical and thermal properties of the snow and the soil are important factors in snow-drifting processes. Therefore, it is necessary to understand the snow-drifting processes in a geomorphological environment under various climatic conditions.

4. To cope effectively with snow-drifting problems, a comprehensive theoretical and experimental research on geomorphological and climatic factors is suggested in this article. Reliable parameters for practical use, classification of snow drifting, and regional snow drift maps delineating the regimen of the snow cover, are aimed at in these researches. Such research should find an important place in the programs of various institutions, agencies, and transportation boards, authorities and departments administering snow-drifting control work on roads, as it deserves.

5. With reference to the suggested research as outlined above, some geomorphological aspects pertaining to snow drifting on roads are discussed in this article.

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Deicing Chemical Rates on Open-Graded Pavements*

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Introduction

During the 1976 - 1977 winter season, the Federal Highway Administration's Implementation Division sponsored four studies which were designed to determine if more salt (sodium chloride) is needed to clear open-graded asphalt friction courses during winter storms than is needed to clear conventional asphalt pavements. Four State organizations conducted the studies:

1. Maine Department of Transportation
2. Michigan Department of State Highways
3. Utah Department of Transportation
4. Vermont Department of Transportation

The work plans for the four studies were similar. During winter storms, Maine, Michigan, and Utah were to observe the snow and ice-clearing rates of two open-graded pavement sections and two dense-graded control sections--one control section to be paired with one open-graded section. Vermont was to observe the clearing rates of one open-graded section and a single control section. For each observed storm, the condition of each pavement section was to be recorded at the beginning of snow-clearing operations, at approximately 30-minute intervals after each salt application or plow passage, and at the end of the storm. Timely photographs were to be taken. Traffic information and weather conditions were to be noted. Any unusual conditions that were observed throughout the storm or on the day following the storm were to be reported.

Between five and twelve storms were observed by each State. With the exception of Vermont, the salt quantities applied to the open-graded and control sections during each storm were the same. Vermont used less salt on its open-graded section.

The following section of this report summarizes the information recorded by the four States. Since the purpose of this report is to succinctly report the findings of the four States, the extensive data collected by each State has not been published. However, interested individuals may schedule a review of the unpublished data until January 1, 1981, by contacting the Federal Highway Administration's Implementation Division.

Summary of Four Studies

The conclusions drawn by each of the four States that participated in the four related studies were not identical. Maine estimated that the amount of salt needed to effectively clear an open-graded pavement was about the same as that needed to clear a conventional asphalt pavement. Michigan agreed but added that slightly less salt per storm would be needed on an open-graded pavement than needed on a very fine-graded asphalt pavement with a tight, fine texture.

Vermont went a step further. They concluded that less salt--and also less sand--was needed to keep open-graded asphalt pavements in as safe a condition as dense-graded asphalt pavements. As proof, they not only adduced the evidence gathered in this FHWA-sponsored study, but also produced evidence gathered during a concurrent State-sponsored study. In the latter study, Vermont used less salt per lane mile on 32 miles of open-graded pavement than was used on dense-graded control pavements during the 1976 - 1977 winter season while attempting to maintain equal levels-of-service on all pavements.

Utah's findings were different. Utah observed that more salt was needed to clear open-graded pavements. They indicated that during their study, the "dense-graded surface * * * [cleared] to a wet and clear condition before the open-graded."

In an attempt to determine the prevailing behavior of the open-graded pavements observed by the four States, the contract manager from the FHWA's Implementation Division analyzed all recorded data, photographs, and comments submitted to him by these States. His views are expressed in the paragraphs below. It should be noted that Utah was unable to furnish documentation which compared the condition of the open-graded and dense-graded (control) pavement sections at measured intervals. They were also unable to provide photographs that portrayed the observed differences between pavement sections.

*This is a summary of the Federal Highway Administration Report FHWA-TS-77-216, published in October 1977.

"While the data submitted was not refined enough to accurately compare the amount of salt (NaCl) needed to clear open-graded pavements with that needed to clear dense-graded pavements, it was comprehensive enough to support the view that more salt is not needed to maintain an equal level-of-service on open-graded pavements during a winter season than is needed on dense-graded asphalt pavements. This does not mean that both pavements react identically during snow-clearing operations. At times a dense-graded pavement will be "clear and wet" or "clear and dry" while slush remains on an open-graded pavement. But State observations of traffic behavior and braking tests with State vehicles suggest that the skid-resistant characteristics of open-graded pavements are regularly superior to those of dense-graded pavements throughout winter storms. Furthermore, the submitted data shows that an open-graded pavement will either clear faster than a conventional pavement or be "mealy" while a conventional pavement is "icey" as often as the reverse.

"During most storms, however, the clearing rates of open-graded and conventional pavements are about the same. Although the snow-filled voids of an open-graded pavement may create a slippery appearance, the protruding aggregates provide a skid-resistant surface.

"In summary, the data shows that the clearing rates and appearance of open-graded and dense-graded pavements are not identical. While a dense-graded pavement will occasionally clear faster than an open-graded pavement, the opposite is also true. Regardless of the clearing rates, an open-graded pavement seems to provide a superior skid-resistant surface during most storms. More salt is not needed to maintain this superior surface."

Alternative Highway Deicing Chemicals*

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A search has been made for road deicing chemicals to replace sodium chloride (NaCl). The impetus for this search stems from the numerous drawbacks associated with the current extensive use of NaCl as a road deicer. All classes of chemical compounds were reviewed. Deletions from the sum total were made on the basis of pertinent criteria such as water solubility and freezing point lowering, corrosion, toxicity, relative cost or cost potential, effect on soils and plants, on water supplies, flammability, etc. Low molecular weight and high solubility were primary qualifications. Waste products were considered as possible raw material sources. Two candidate deicers have been selected which, if used, **might** result in total costs about one-half those associated with the use of NaCl. Both materials can operate at temperatures below that at which NaCl becomes ineffective. Both can be made from waste cellulose. Neither is corrosive. One of them, methanol, reacts almost immediately upon contact with snow and ice but is less persistent than the other candidate or than NaCl. The other candidate, calcium magnesium acetate (CMA) acts at about the same rate as NaCl in the temperature range of common activity and shows about the same persistence. By strong contrast with NaCl, CMA is a corrosion inhibitor, is beneficial to most soils and has no potential for harming drinking supplies.

The well known corrosive effect of sodium chloride (NaCl) upon metals has long begged for replacement of this chemical as a road deicer. It has been demonstrated that this obvious defect is but one of many undesirable results attendant upon the use of NaCl for deicing purposes (1). Accordingly, the present search for viable alternates was initiated.

Chemical deicing depends upon the general effect of solutes on the melting point of the solvent in which they are dissolved. The effect is always to lower the melting point. The amount of lowering is almost solely dependent upon the number of molecules or ions present in solution, roughly proportional to this number and almost entirely independent of the nature, size or weight of these solute particles. Thus, low molecular weight materials produce the most freezing point lowering for a given weight dissolved in the solvent. Also, the solubility of the solute determines the degree of lowering it can exert on the melting point of the solvent in which it is dissolved.

* Based on Federal Highway Administration Report No FHWA-RD-78-67.

Preliminary Elimination of Chemical Deicer Possibilities

Since the primary requisite for a deicing chemical is water solubility, there are many substances to choose from. Selection of the best deicing chemical then becomes a process of elimination. There are a number of criteria by which to judge and eliminate candidate deicers. These were applied repeatedly each time additional information became available upon which to form a judgement.

The first round of judgements was based upon general knowledge of the elements in the Periodic Table, their scarcities, costs, and hazards of various kinds. The following groups were excluded:

1. Transuranum elements.
2. Actinide series.
3. Lanthanide series.
4. Elements in Periods 4,5, and 6, excepting potassium (K), calcium (Ca), barium (Ba), manganese (Mn), iron (Fe), zinc (Zn), and bromine (Br).
5. The noble gases Group VIIIA.
6. The miscellaneous group, beryllium (Be), fluorine (F), and sulfur (S in the sulfide form).

The remaining chemical elements were then considered under the two headings, Inorganic Salts and Organic Compounds. Organic chemistry is concerned primarily with the chemistry of carbon (C) and includes most of its compounds, the most notable exception being the carbonates characterized by the carbonate anion $CO_3^{=}$. Inorganic chemistry includes the carbonates and most of everything that is not organic. For chemicals of deicing interest, namely water soluble ones, attention is centered upon the neutral ionic inorganic compounds or salts.

In making an evaluation of deicing potential, whether organic or inorganic, a formula was developed which takes into account the unit weight cost of the material in relation to sodium chloride, as well as its effectiveness per unit weight related to sodium chloride. In nearly all cases, the unit weight costs were derived from the July 1976 issue of the Chemical Marketing Reporter. In a few instances, it was necessary to obtain quotations from suppliers for materials which were not covered in the Chemical Marketing Reporter. For the first round cost evaluations, the effectiveness of the various deicing candidates was calculated on the basis of freezing point depression theory, assuming a figure of 1.86° C for the freezing point depression of water per unit molal concentration of solute. The osmotic effects of ions and of molecular solutes were assumed to be equivalent. Osmotic theory teaches that this is approximately so in that freezing point depression by a solute is a function of the number of particles in solution primarily, rather than a function of their nature. With the final cost comparisons, however, actual performance data was substituted for this type of approximation.

This cost effective comparison of a candidate deicer to sodium chloride, or ratio of cost effectiveness, is defined by the following equation:

$$R = \frac{MC}{N} \times \frac{N_o}{M_oC_o} \quad (1)$$

where M = molecular weight of the candidate.
C = cost of the candidate.
N = the numbers of particles or ions into which a molecule of candidate breaks up upon going into solution.
Subscript o = the same quantities for NaCl.

To illustrate the quantity N, a solute such as methanol will have an N=1 because a molecule of methanol CH_3OH exists as such without splitting up when put in aqueous solution. On the other hand, a salt like sodium chloride, for example, breaks up into two parts or ions when it is put into solution. The two ions are oppositely charged, Na^+ and Cl^-. As already mentioned, each of them behaves much like a separate molecule insofar as freezing point depression is concerned. Accordingly, the value for N in this case is 2. Both calcium acetate and magnesium acetate are ionic materials like sodium chloride. They differ from it, however, in that the positive ion or cation is doubly instead of singly charged. Consequently, to satisfy the demands of electric neutrality, there must be two singly charged acetate ions or anions. In other words, when calcium acetate or magnesium acetate dissolves in water each molecule, as it were, splits up into three charged particles, one doubly charged positive ion and two singly charged negative ions. The value of N in these cases is 3 accordingly.

Evaluation of Individual Deicer Candidates

Inorganic Salts

Using the R-Value system and a criterion of R equal to 20 or less, several more chemical elements were eliminated as constituents of deicers to replace sodium chloride. These were barium, manganese and zinc. Partly for reasons of cost and partly for reasons of corrosion, chlorine and bromine, the last two members of Group VIIA, were eliminated as components of inorganic deicers. Sulfur was eliminated as a component for reasons of toxicity (sulfide) and corrosion (sulfate, the only other stable form). Several elements were eliminated because they required excessively high or low acidities to be soluble. Silicon, as silicate, and iron and aluminum fell into this category. Lithium was found to be much too expensive. Boron, in the form of the borates, appeared to be too costly and too toxic to consider. The nitrate combination of nitrogen and oxygen was found to be intolerably corrosive. It appeared that even the ammonium ion might be unacceptable under conditions where trace nitrates might be formed by bacterial action.

Thus, only nine elements were left for serious consideration as constituents of inorganic deicers (Table 1).

The three elements in the left hand column combine in inorganic salts as positive singly charged ions or cations, i.e., H^+, Na^+, and K^+, H forming with N an additional singly charged cation, NH_4^+, the ammonium ion. The only inorganic negatively charged ions or anions to go with these cations are formed by various combinations of the four elements to the right, -C, N, O, and P.

There are several possibilities. The combination of O and H to give OH^- is severely caustic and cannot be used. The anions, $CO_3^=$ (carbonate), $PO_4^{\equiv}$ (phosphate), $P_2O_7^{\equiv}$ (pyrophosphate) though less so, are still too caustic for consideration unless they are partially neutralized to form appropriate amounts of HCO_3^-, $H_2PO_4^=$ and $H_2P_2O_7^=$ respectively. The various viable salt combinations are tabulated together with some pertinent properties (Table 2). The freezing point data, in this case, were obtained from the literature or experimentally determined rather than calculated from theory.

Sodium Bicarbonate-Sodium Carbonate. Working from the top of the table downward NaCl is included as a reference point, it being the currently most used chemical deicer. Neither sodium bicarbonate nor sodium carbonate has sufficient solubility to be an effective deicer, having eutectics (temperatures at which all mixtures freeze solid) with water of -2°C and -3°C respectively. These salts, thus, are ruled out of consideration.

Sodium Monohydrogen Phosphate-Sodium Dihydrogen Phosphate. Of the three sodium salts of orthophosphoric acid (H_3PO_4) none could be used alone as a deicer for different reasons. The dihydrogen phosphate salt (NaH_2PO_4) produces aqueous solutions which are too acid, pH = 3 to 4. The monohydrogen phosphate salt (Na_2HPO_4) is too insoluble and the tribasic salt (Na_3PO_4), as already mentioned, is too strongly alkaline, pH $\cong$ 13.

The composition of the triple eutectic of water NaH_2PO_4-Na_2HPO_4 is perhaps still too acidic, pH $\cong$ 4. The eutectic temperature of this salt combination is -9.9°C, which is certainly borderline from the point of view of utility (2). Its cost to produce an equal deicing effect at -10°C is 26 times that of sodium chloride. The damage inflicted on plants and animals by sodium ion, as well as the hypertension in human beings have been well documented (3, 4). All of these factors combined make the sodium salts of phosphoric acid, as a group, a poor candidate as a road deicer.

Potassium Bicarbonate-Potassium Carbonate. The mixture of potassium bicarbonate ($KHCO_3$) and potassium carbonate (K_2CO_3) looked promising at first, since the substitution of K for Na not only brought about lower eutectics with water but overcame most of the environmental objections associated with Na. The system was finally rejected, however, when it was found that the proportion of $KHCO_3$ required to temper the caustic nature of K_2CO_3 resulted in too low a solubility, i.e., too high a eutectic.

The Environmental Protection Agency (EPA) has established pH 6.5 to 9.0 as optimum conditions for aquatic biota (5) with a somewhat wider range (pH 5.5 to 9.5) as the maximum tolerable pH range (6). Water pH is maintained by buffering capacity, which is primarily due to the bicarbonate-carbonate system. Alkalinity resulting from the presence of carbonates appears to have little harmful effect on aquatic life as long as it does not increase the pH above the optimum pH. Such a system is, of necessity, predominately a bicarbonate (as opposed to a

Table 1. Elements Remaining for Consideration as Constituents of Chemical Deicers Arranged in their Order in the Periodic Table.

Period \ Group	IA	IIA	IIIA	IVA	VA	VIA	Etc.
1	H (Hydrogen)						
2	--	--	--	C (Carbon)	N (Nitrogen)	O (Oxygen)	
3	Na (Sodium)	Mg (Magnesium)	--	--	P (Phosphorus)	--	
4	K (Potassium)	Ca (Calcium)					
Etc.							

Table 2. Deicing Performance Data for Inorganic Deicer Candidates.

Candidate Deicer	Eutectic with Water: Composition (wt.% Deicer)	Eutectic with Water: Temperature (°C)	Cost ($/Lb[a])	Deicer Needed to Liquify Ice at -10°C: Lb/100 Lb of Ice	Deicer Needed to Liquify Ice at -10°C: Cost Relative to that of NaCl	Approximate pH of Aqueous Solutions
NaCl	23.3	-21.1	.014	16.0	1.0	Neutral
$NaHCO_3$	> 6.	~- 2.	.08	b		8
Na_2CO_3	7.	- 3.	.024	b		12
NaH_2PO_4	35.6	- 9.7	.107[c]	~55.	26.4	3-4
Na_2HPO_4	1.56	- .5	.101[c]	b		9
$KHCO_3$	19	- 8.8	.14	b		8
K_2CO_3	41	-36.	.10	~19.	8.5	12
KH_2PO_4	11.6	- 2.7	.134[c]	b		4-5
K_2HPO_4	36.8	-13.7	.145[c]	47.0	30.4	9
$K_4P_2O_7$	~60.	~-39.	.35	37.4	58.4	10-11
$NH_4H_2PO_4$	18.5	- 6.	.08	b		4-5
$(NH_4)_2HPO_4$	35.	-14.	.067	32.5	9.7	8-9
NH_4HCO_3	10.6	- 9.5	.03[d]	11.9	1.6	8
$(NH_4)_2CO_3$	30.	-14.6	.04[d]	31.6	5.6	9
NH_3	<20.	<-77.	.09	8.1	3.3	12

[a] All prices are bulk and derived from the 7.5.76 issue of Chemical Marketing Reporter except that for CO_2 which was obtained 10/6/76 from an Airco representative in Chicago.
[b] No liquid phase at -10°C.
[c] From H_3PO_4 and the carbonate.
[d] Mixed gases CO_2 and NH_3.

carbonate) system (7).

Potassium Monohydrogen Phosphate-Potassium Dihydrogen Phosphate. Of the potassium salts of H_3PO_4 only one salt could be used alone as a deicer, K_2HPO_4. However, its eutectic is barely acceptable, -13.7°C, its cost for equal effect is thirty times that of sodium chloride and its pH is high, though perhaps acceptable. On the other hand, the tribasic salt is too caustic and the monobasic one too insoluble.

A mixture of the mono and dibasic salts in the weight ratio 27.3:72.7 produces a respectable eutectic, -16.7°C and a very desirable pH range of 7 to 8 (2); the cost for equal effect compared to sodium chloride at -10°C is 37 times. Environmentally, the potassium ion is fairly acceptable. Phosphate is a mixed bag. Far from being toxic to plants and animals, it can cause problems in lakes and rivers associated with overgrowth of unwanted species. On the other hand, it is an important constituent of many corrosion inhibitors (8).

The temperature of the water eutectic of the KH_2PO_4/K_2HPO_4 mixture can be lowered by 0.5°C and the cost for equal effect can be reduced from 37 to 36 times that for sodium chloride by inclusions of 2% of Na_2HPO_4 (2).

The modest eutectic and undesirable environmental factors balanced by a rather high cost factor make the KH_2PO_4:K_2HPO_4::27.3:72.7 system a borderline case for further consideration. Nevertheless, this appears to be the best combination of the several possibilities involving the potassium salts of the orthophosphoric acid.

Tetrapotassium Pyrophosphate (TKPP). Though there may be some question as to the precise figure, there is little doubt that TKPP has a very satisfactory eutectic temperature with water. Its pH is high, 10-11, but this probably could be tempered by admixture with one of the less basic salts of pyrophosphoric acid. It possesses essentially the same environmental merits and drawbacks as the potassium salts of orthophosphoric acid, discussed above. It suffers from a high cost factor, however, nearly twice that of the potassium orthophosphate system -- borderline -- the much better eutectic offsetting the higher cost.

Ammonium Monohydrogen Phosphate-Ammonium Dihydrogen Phosphate. The respective ammonium and potassium orthophosphates are similar to each other in regard to water eutectic and aqueous pH. In both cases the monobasic salts are too insoluble and a little bit too acidic. The tribasic salts are too alkaline. In both cases, the dibasic salts show tolerable and nearly identical eutectics with water. The dibasic ammonium analogue shows a slightly more favorable pH range, 8-9, as opposed to approximately 9.

Probably the mono and dibasic ammonium salts would prove to exhibit a combined eutectic comparable to or possibly below that of the corresponding potassium salts, with a similarly favorable pH range. The biggest differences between the corresponding ammonium and potassium systems would appear to be in the environmental and cost factors.

Like the phosphates, the ammonium ion can serve as a nutrient to the point of causing unwanted proliferation in streams and lakes. In some circumstances, as already mentioned, it can be converted to nitrate with adverse corrosion effects (9). In addition, NH_3 is extremely toxic to fish (see below). These potential adverse effects of ammonium phosphates, compared to the potassium salts, are offset to some degree by their much lower cost -- one-third to one-fourth or about ten times the cost of equivalent treatment with sodium chloride. Thus, depending upon priorities, the ammonium phosphate system would appear to be comparable to the preferred potassium phosphates and pyrophosphates, namely of borderline importance for further work.

Ammonium Bicarbonate-Ammonium Carbonate. On the basis of their water eutectics, NH_4HCO_3 and $(NH_4)_2CO_3$ are comparable though slightly better than the respective mono and dibasic ammonium and potassium phosphates. Similarly, they might be expected to exhibit a combined eutectic which is lower than that of either component, though this is yet to be determined. They exhibit similar near neutral solutions. Environmentally, they would be slightly superior to the ammonium phosphates and perhaps comparable to the potassium phosphates. They might trail the latter in this respect because of the absence of the generally beneficial potassium ion. On the other hand, the negative environmental aspects of the ammonium carbonates are lessened by virtue of their volatility.

The ammonium carbonates are far cheaper than either of these two phosphate salt systems on the basis of the weight to produce a liquidus of a given temperature (e.g., -10°C). However, they are amenable to a unique method of dispensing which is capable of providing additional deicing benefits among which are more rapid and additional melting through heat of reaction.

The ammonium carbonates can be formed by reaction between two liquids in the presence of ice or liquid water:

$$NH_{3\ liq.} + CO_{2\ liq.} + H_2O_{ice} = NH_4HCO_{3\ aq.sol'n}$$
$$\Delta H = -14.2\ \text{kcal/gm.mol.} \qquad (2)$$

$$2NH_{3\ liq.} + CO_{2\ liq} + H_2O_{ice} = (NH_4)_2CO_{3 aq.sol'n}$$
$$\Delta H = -26.6\ \text{kcal/gm.mol.} \qquad (3)$$

The second reaction consumes 0.23 pounds of ice for each pound of the combined liquid reactants and the heat evolved is enough to melt 6.2 pounds of ice per pound of combined reactants. This ratio of weights corresponds to the liquidus at -5°C. At lower temperatures, of course, the liquidus contains higher proportions of ammonium carbonate and consequently, the heat of reaction is in excess of that necessary to melt the ice for the liquids. At -10° C this excess heat amounts to 65%.

The technology for pumping, accurately metering and mixing reacting liquids is well known and the equipment is inexpensive and reliable. A considerable cost advantage accrues from making $(NH_4)_2CO_3$ from liquid NH_3 and liquid CO_2 rather than purchasing it as the crystalline salt. In effect, the costs associated with crystallization, drying and sizing are eliminated.

Although both NH_3 and CO_2 have low boiling points (-33.4° and -79°C [sublimination] respectively) and therefore require pressurized storage, storage and handling techniques are convenient and economical due to well established large volume markets in both cases. The danger of freezing in the contiguous United States is nil since the freezing points are -78°C for NH_3 and -57°C for CO_2. The manner of storage precludes the inconveniences sometimes associated with salt storage: caking, spillage, pollution of water supplies from runoff, corrosion of equipment, etc. Although ammonia is flammable, its flammability limits are narrow (from 16 to 27 volume percent in air) and its vapor density is one-half that of air. These, together with its manner of storage and handling, virtually eliminate the risk of fire. Leaks are detected by the pungent odor long before flammable concentrations are approached.

An important feature of forming the ammonium carbonates on the highway site is the fact that the ratio of the two reactant gases can be varied to suit the conditions. Thus, after a snow at the freezing point, where temperatures are not expected to drop below -5°C, a bicarbonate mix would be preferred, i.e., equimolar NH_3 and CO_2 or 17 parts to 44 parts by weight respectively. For these temperatures the bicarbonate is the more economical, being only 1.5 times the cost of an equal performance application of sodium chloride. By the same token, in uninhabited regions when temperatures of -20°C or below may be encountered, a ratio of ammonia in excess of that to produce $(NH_4)_2CO_3$ might be employed. Ammonia is one of the most weight efficient freezing point depressants for water. Although its unit cost is higher than that of the stoichiometric $(NH_4)_2CO_3$, the resultant cost would be slightly less on account of the greater weight efficiency of the ammonia.

Even for a tenfold excess of NH_3, the pH would be raised only to about 10; this would then drop back to 9 as the excess NH_3 gradually evaporated. The evaporation rate is too slow to produce a flammable concentration. With equipment adapted from the agricultural applicators for injecting NH_3 directly into the soil and with the avidity of NH_3 for water, including an appreciable heat of solution, there should be little difficulty in making it dissolve in road ice and snow.

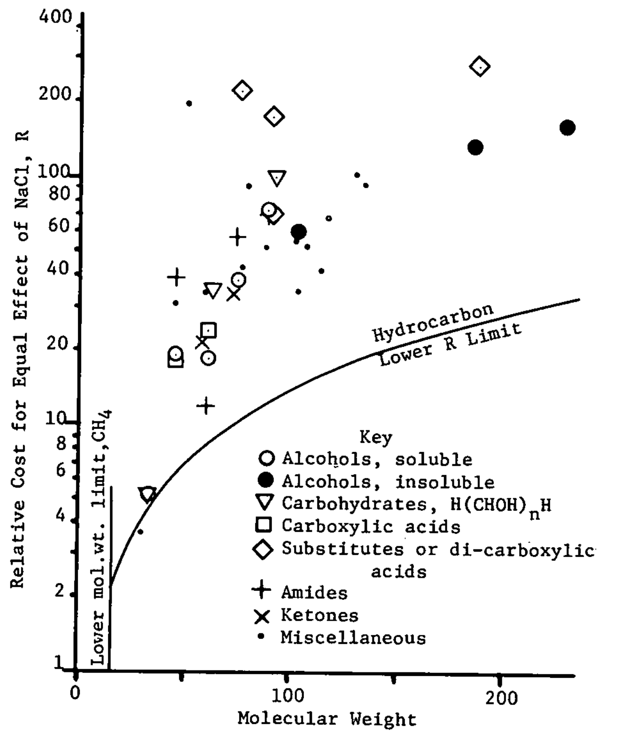
Subsequent to the above findings, an additional serious drawback to the use of ammonium based systems was discovered. Actually, it is not the ammonium cation itself that causes the problem but rather the un-ionized ammonia which occurs when an ammonium salt dissolves in water of moderate to high pH. Waters containing as little as 0.2 ppm of un-ionized ammonia (NH_3) have proved toxic to aquatic biota (5). The proportion of un-ionized ammonia varies with pH from about 0.04% at pH 6 (20°C) to 28% at pH 9.0 and increases even further with additional pH increases. Thus, at pH 6.0 a concentration of 500 ppm NH_4CO_3 would produce a toxic concentration of ammonia. Since the pH of natural waters tends to be more alkaline than pH 6.0, the toxicity will generally occur at concentrations of 100 ppm of $(NH_4)_2CO_3$ or less.

EPA has recommended a maximum level of 0.020 ppm un-ionized ammonia for surface water, one-tenth of the concentration deemed toxic to aquatic life. This would be impossible to maintain with extensive use of the ammonium carbonate-bicarbonate system as a deicer. Nevertheless, in arid regions where the well being of aquatic biota are not a consideration, the ammonium carbonate system has unique and attractive features which merit its consideration.

Organic Compounds

The prices of organic chemicals with molecular weights up to 248 were obtained from July and August issues (1976) of Chemical Marketing Reporter. Values of R were calculated and plotted versus molecular weight on semilog coordinates (Fig. 1). This figure helps to illustrate several constraints on the use of organic chemicals as deicer substitutes for NaCl. Although a plot on linear coordinates would illustrate more clearly the fact that R value tends to increase linearly with molecular weight, the semilog plot is more useful in making out distinctions in R values.

Figure 1. Relative Cost R of Organic Deicers versus Molecular Weight.



The price per unit weight of nearly all organic chemicals is higher than that of petroleum hydrocarbons for the simple reason that the latter are the cheapest source of carbon-hydrogen moieties for organic synthesis. Accordingly, although unsuited by water solutility and other reasons as deicing chemicals, hydrocarbons were included in Fig. 1 to illustrate the molecular weight and relative price limitations on organic chemicals to replace NaCl. It is seen that there is little hope of obtaining such a substitute having a molecular weight as high as 200 for less than 30 times the cost of NaCl to give equivalent performance. Synthesis costs must be considered and the maximum molecular weight for R=30 would appear from the examples to be closer to 100. This corresponds to a maximum of seven or eight carbon atoms in the molecule. Methane, the hydrocarbon with only one carbon atom, has the lowest R value, and that is over two.

The question of solubility can only be resolved by the inclusion of oxygen, nitrogen or other polar atoms in the organic molecule. The simplest such modification of the hydrocarbon structure is the alcohol series, $C_nH_{2n-1}OH$, represented by the circles in Fig. 1. A single hydroxyl group in the molecule will provide the requisite solubility only up to molecular weight 100. If the cost factor corresponding to R=30 is applied, it is seen that only the three lowest alcohols fit, methanol, ethanol and i-propanol.

Solubility can be assured by attaching one oxygen to the molecule for each carbon atom, $H(CHOH)_nH$, the triangles in Fig. 1. Methanol is the first member of this series as well, then ethylene glycol and glycerol or glycerin. The cost factor rises with molecular weight, if anything even more rapidly than it does with the alcohols. It is already R=35 with ethylene glycol and R=99 with glycerol.

It is not always necessary to have one hydroxyl group for each carbon atom. The solubility can be improved over the alcohols by incorporating two hydroxyls per molecule, the glycols. Ethylene glycol is the simplest of this class and, as already mentioned, has an R=35. Both it and propylene glycol are infinitely miscible with water, the R value for the latter, 43, is larger as expected. Of the four butylene glycol isomers, molecular weight = 90.1, only the 1, 4 and 2, 3 isomers are completely miscible in water and the 1, 2 isomer is only slightly soluble. There is no reason to expect the butylene glycol R values to be anything but higher than that for propylene glycol.

Another type of oxygen linkage which might serve in an organic deicer is the ketone. The simplest of this class is acetone with R=21. The next higher homologue, methyl ethyl ketone, has an R=33. Higher homologues are insufficiently soluble for consideration.

Aldehydes can be ruled out on account of their chemical reactivity and particularly the irritant and toxic character of the more interesting lower molecular weight homologues. Were it not for these factors, the lowest member of the series, formaldehyde, would be of special interest because it appears to be the organic chemical with the lowest R value, 3.7.

The oxygen in ethers does not impart sufficient water solubility for this class of compounds to be considered as freezing point depressants. Esters are of no use for the same reason. Organic halogens are disadvantageous, since they add weight without imparting water solubility among other things.

Only a limited number of carboxylic acids are candidates and these only as their salts, on account of their corrosive power as free acids. Acetic acid with a molecular weight of 60 and an R of 23 is probably the most likely candidate. Propionic acid, whose R value is undoubtedly higher, is another possibility. The butyric acids would probably be unsuitable because of the powerful and objectionable odor of the free acid, which could not help but form from hydrolysis during actual usage conditions. Higher homologues would be ruled out because of excessive R values. Anhydrides are simply a precursor of the acids in the presence of water, with which they react only slowly and in which they are only slightly soluble. These and considerations based upon them make it difficult to see how the anhydrides can be of much use as deicers. Even considering the formation of two mols of acetic acid from one of the anhydride the R value for the lowest molecular weight homologue acetic anhydride is 27.

The amines are unsuitable because of their unpleasant powerful odor. Even as salts, this smell would be objectionable due to hydrolysis. The quaternary ammonium compounds are stable, very soluble and odorless, but too expensive for consideration. Amides, like the quaternary ammonium compounds, get around the malodor problem and are generally quite stable. Formamide, the simplest, has an R=38. Dimethylformamide has a much larger R=57. The most economical of the amides is the diamide of carbonic acid, urea. Its R=11.8 and is the next most economical of the organic compounds discussed, being second to methanol at R=5.1.

The nitriles are generally insoluble and too toxic and accordingly, unsuitable.

It must be noted and emphasized that all of the R values determined thus far are based upon prices for compounds of technical purity, at least. The price usually includes an appreciable cost for purification and isolation as well as a base cost for raw material. Considerably lower R values, approaching those of the hydrocarbons, might conceivably be achieved where a reaction mixture can be used as is without further treatment. This possibility is, of course, open to the usage for deicing since, pecularly to this purpose, the identity of the molecules and ions is not important, only their number.

The possibility of lowering the R cost ratio below those of the hydrocarbons and even below unity, the R value of NaCl, also exists in the usage of waste products whose value approaches or falls below zero. Solid waste, nitrogeneous sewage sludge, nitrogeneous tankage, and other waste materials were examined as possible raw material sources for these reasons.

The more cost efficient organic deicers shown on Fig. 1 were examined in greater depth and compared with NaCl (Table 3).

course, even higher than 60°F. The density of methanol vapor is only slightly above, while that of gasoline is several times that of air. Fires can be extinguished with water, by contrast to gasoline, because methanol and water are miscible in all proportions.

As with all substances, it has toxic limits. But these limits are relatively high, methanol having been cleared as a food additive (11). No ill effects have been found upon prolonged exposure to low concentrations or to short intermittent exposures to high concentrations of its vapors (12).

The cost of methanol is one of the lowest of the candidate deicers, being 5.5 times that of an aqual effect application of sodium chloride at -10° C. If the cost of the harm caused by sodium chloride were included, the cost ratio of methanol could well be less (1). The methods of handling and dispensing liquids such as methanol are simpler than those for solids and subject to much finer control. Methanol appears to be the most promising of the simple organic compounds as a deicing substance.

Ethanol and Isopropanol. Ethanol and isopropanol are like methanol in nearly all respects; very low eutectics, neutral, noncorrosive, no nitrogen or phosphorus, volatile and flammable in nearly the same degrees, completely miscible with water and

Table 3. Deicing Performance Data for Organic Deicer Candidates.

Candidate Deicer	Eutectic With Water: Composition (wt. % Deicer)	Eutectic With Water: Temperature (°C)	Cost ($/Lb[a])	Deicer Needed to Liquify Ice at -10°C (Lb/100 Lb of Ice)	Deicer Needed to Liquify Ice at -10°C: Cost Relative to that of NaCl	Approximate pH of Aqueous Solutions	Flammibility, Tagliabue Open Cup: Pure Compound (°C)	Pure Compound (°F)	-10°C Liquidus with Ice (°C)	(°C)
Methanol	83	-125	.065	19	5.5	Neutral	15.6	60	43	109
Ethanol	93	-131	.17	23.5	17.8	Neutral	12.8	55[c]	35	95
Isopropanol	$\geqslant$80	$\leqslant$ -42	.127	29.9	16.9	Neutral	15.6	60	30	86
Acetone	> 60	$\ll$ -27	.15	50	33.5	Neutral	- 9.6	15	- 3	27
Urea	33	-13	.08	34	12.5	Neutral	> 100	> 212	>100	> 212
Formamide	65	-45	.35	34	53.5	Neutral	~100	~212	>100	> 212
Dimethyl-Sulfoxide	> 50	<-50	.47	35.1	73.7	Neutral	95	203	>100	> 212
Ethyl Carbamate (Urethane)	60	- 6	.32	b		Neutral			b	

[a] All prices are bulk and are derived from the 7/5/76 issue of Chemical Marketing Reporter except as noted otherwise.
[b] No liquid phase at -10°C.
[c] Closed cup.

Methanol. Methanol exhibits a eutectic with water far below that of sodium chloride or any other inorganic deicer candidate. It is neutral and noncorrosive. It contains no nitrogen or phosphorus, thus contributes nothing to eutrophication problems. It has been used as an antifreeze for gasoline engines, but was replaced by the glycols because of its relatively high evaporation rate. At snow and ice temperatures volatility is much reduced. The remaining volatility, however, serves to minimize the concentration of methanol in the runoff and correspondingly, its contribution to BOD. It also facilitates housecleaning, since spills are self removing.

The flash point of methanol, 60°F, is nearly thirty degrees F above the freezing point of water while that of gasoline is fifty degrees below 0°F (10). The flash point of its aqueous solution is, of

only moderately toxic. Ethanol is probably the least toxic of the three alcohols. However, its apparent reaction with chlorine in water supplies to produce chloroform is a potentially serious drawback to its use wherever it might enter water supplies through runoff (13).

Both of these alcohols differ from methanol in having vapor densities appreciably heavier than air and each is approximately three times the cost of methanol. If anything, methanol is slightly superior to either of these two candidates and it is, of course, much cheaper.

Acetone. Acetone is similar to the above three alcohols in nearly all respects but flammability and cost. It is considerably more flammable in the pure state, though less so than gasoline and in water solution still less so. It is double the cost of ethanol or isopropanol, six times that of methanol. It would not be purchased outright over any of the alcohols but would be acceptable as a constituent of a deicing mixture, as for example, one generated from waste products.

Urea. The water eutectic of urea is modest by comparison with those of the alcohols. It is comparable to but not quite, as low as that of $(NH_4)_2CO_3$. It is neutral but there is disagreement as to its corrosive effects (14, 15). The variable results may occur due to the tendency for urea to decompose and the resulting ammonia to be oxidized to nitrate which is, of course, corrosive. On the other hand, it is reported to adsorb tenaceously onto steel which, if not accompanied by decomposition and bacterial oxidation, might give rise to some corrosion inhibitory action. Its nitrogen content is a drawback from a eutrophication standpoint. It is nonvolatile, hence the full concentration is carried in runoff waters. On the other hand, it is nonflammable. Its cost, on an equal performance basis at -10°C, is a little over double that of methanol and twelve and one-half times that of sodium chloride, not counting the cost of the latter's deleterious effects.

Urea:Ammonium Carbonate::52.4:47.6. The triple eutectic between water, urea and $(NH_4)_2CO_3$ is a degree below that of sodium chloride with water (16). Neither component nor the mixture is flammable. The nitrogen content of the urea is more of a drawback than that of $(NH_4)_2CO_3$ because of its lack of volatility. Although both compounds are solids, the one sublimes. Thus, storage of the already prepared solid mix might be difficult to achieve without some degree of disproportion due to thermal gradients, within the storage bin. On the other hand, mixing and dispensing solid urea along with the two liquid components of $(NH_4)_2CO_3$ directly from truck to road is cumbersome and negates the convenience of liquid-liquid mixing and dispensing. Material cost was calculated nevertheless, on the latter basis. Preparations of the solid mix would be higher for the reasons already stated.

Despite the tempting lower eutectic it would seem that the added complications, cost and other disadvantages outweigh this combination system as compared to the ammonia and carbon dioxide system alone.

Formamide. Formamide has an excellent eutectic with water. It is neutral, nonflammable and its aqueous solution, corresponding to the -10°C liquidus with ice, has the lowest viscosity of those tested. Its melting point, +2.6°C, is disadvantageous, virtually assuring the necessity of dealing with it both as a liquid and as a solid, unless incorporated in solution with another ingredient.

It is an organic compound and so would increase BOD. It contains nitrogen which, on hydrolysis produces ammonia, with its attendant environmental problems. Its hydrolysis in aqueous solution, though very slow, probably accounts for its designation as a hazardous compound, since formic acid is also produced on hydrolysis. Acidic conditions such as occur on the skin surface tend to accelerate the hydrolysis, so skin irritation and perhaps even "burns" can be expected to occur if it is used in areas with foot traffic.

Its cost for equivalent treatment is ten times higher than that of methanol and 54 times that of sodium chloride. It would appear much less promising as a candidate deicer than methanol.

Dimethyl Sulfoxide (DMSO). DMSO, like formamide, has a very low eutectic with water, is neutral, nonflammable below 200°F and has a melting point between room and water freezing temperature, namely 18.6°C. For an equal effect, it is even more costly than formamide, being over a dozen times more costly than methanol and 74 times more so than sodium chloride.

The compound contains no nitrogen or phosphorus and thus is free of the environmental liabilities associated with those elements. DMSO is considered to be relatively low in toxicity. It does dry and remove lipids from the skin when in contact at high concentrations. A more serious problem is its very high solubilization and penetration properties. DMSO solubilizes a wide spectrum of organic and inorganic substances, and it tends to carry them through the skin as it penetrates. The crude DMSO could itself contain impurities of questionable desirability, but it would certainly tend to solubilize other pollutants and carry them into whatever plant, animal or human it came in contact with (17, 18). This raises serious question as to the desirability of this material as a road deicer.

Considering its high cost and its possible toxic complications DMSO, like formamide, appears to be much less likely as a candidate deicing chemical than methanol.

Metal Organic Salts

All of the four metals picked in the initial screening, Na, K, Mg, and Ca and ammonium ion, form soluble salts with the lower organic acids mentioned above as candidate deicers. Of these possibilities, the Ca and Mg are preferred for several reasons, e.g., they are the cheapest when accepted as the naturally occuring mixture in dolomitic limestone (K is the most expensive); they are harmless to flora and fauna, by contrast to ammonium ion and they are beneficial to soils, in contrast to Na.

It has been shown that cellulosic solid waste can be converted to alkaline earth salts of lower carboxylic acids, predominantly acetic, by relatively simple technology and in yields sufficiently large to be interesting (see below). Most of these salts show sufficient water solubility to function as deicing agents. Other features of these compounds are attractive for this application.

A conservative cost estimate for producing these salts was based upon the process involving alkaline fusion of cellulosic waste. A more refined calculation will almost certainly yield a lower cost per unit weight. This same unit weight cost was used also for some of the other fatty acid salts produced by the same process in evaluating their respective costs for equivalent deicing effect (Table 4).

The water eutectics of the two primary products, calcium and magnesium acetates, are good and excellent respectively. Calcium propionate also shows a good eutectic. Although that of magnesium lactate is quite high, that of calcium formate is acceptable. It should be kept in mind that a combined eutectic such as would be encountered in a mixture will probably be lower than the lowest of the individual compounds.

The costs for an equivalent deicing effect are on the average about the same as that of methanol, around five times that for sodium chloride.

The aqueous solutions of these salts are not only neutral they exhibit pronounced inhibition of corrosion. In five month corrosion tests, the calcium and magnesium acetate solutions produced corrosion rates on iron strips an order of magnitude lower than rates in distilled water. None of these salts is flammable.

These salts do not contribute significantly to eutrophication. The anion decomposes to carbon dioxide and water.Usage as a deicer however results in minimal BOD stress because of the low temperatures. The calcium and magnesium cations are precipitated as the carbonates and thereby removed from solution where their presence might otherwise influence water density and interfere with the turnover of the lakes.

Soils in the eastern half of the United States, where most deicing is done, are deficient in calcium and magnesium. Restoration of these ions to the soil in these areas as through a road deicer could be beneficial (19, 20). These divalent cations tend to improve the structure of the soil where, by comparison, sodium and to a lesser degree other monovalent cations (e.g., potassium and ammonium) tend to cause the breakdown of soil structure. Such breakdown results in a decreased permeability for both water and air, often a serious agricultural problem (21, 22).

Calcium and magnesium acetates and similar salts of other low molecular weight organic acids appear to be among the deicers which are ecologically the most desirable. On two counts, corrosion inhibition and soil building, far from being detrimental they are beneficial. For this reason, it is hardly accurate to compare these salts with sodium chloride on the basis of materials cost alone for the equivalent deicing performance. A proper comparison must include as well the attendant cost (or benefit) to the taxpayer's person and property (including that which he owns through the state) resulting from the application of the respective deicers. On this basis, the calcium and magnesium salts of the lower organic acids, instead of five times as costly, may prove to be half as costly as sodium chloride on an equivalent deicing basis.

This family of compounds would appear to be a primary candidate for further investigation as deicer substitutes for sodium chloride.

Deicers from Waste Materials

Alkaline Earth Organic Salts from Cellulose Waste. There are several processes for producing calcium and magnesium salts of organic acids, largely acetates from solid wastes and dolomitic limestone. These raw materials are of interest in part because one has a negative value and the other is one of the cheapest chemicals available. Four such processes are briefly described and evaluated below.

Enzymatic hydrolysis, involving fermentation steps through glucose and ethanol to acetic acid, suffers at present from low efficiency in breaking down the cellulose into glucose. Also considerable technological know-how is required to operate the process and then there is always a danger of enzyme poisoning from the very heterogeneous feed stock.

Destructive distillation of cellulosic solid waste at 400-1000°C in the absence of air produces, in addition to charcoal, a gaseous mixture containing about 2-6% acetic acid mixed with methanol, acetone, etc. Additional complex technology is required to convert the byproducts to acetic acid.

Oxidative pyrolysis involves heating in a limited supply of air to make producer gas which, in turn, can be converted to methanol, then acetic acid. Again, rather complex technology is required and very large plants are necessary (greater than 1000 tons solid waste per day) for economical operation. In this, as in the other two schemes above, the acetic acid and acetate production is in competition with other products of potentially greater value, e.g., methanol or ammonia.

Alkaline fusion is 19th Century technology which involves heating solid wastes in an excess of alkali (e.g., calcium, magnesium hydroxides) at a temperature of about 200-300°C for from one-half to three hours. The reaction produces a rather high yield of calcium magnesium acetate, which can then be extracted. The reaction is exothermic. Among its byproducts are methanol and acetone, either or both of which could be used as deicer or burned for process energy. The insoluble byproducts, calcium and magnesium oxalates and carbonates could be allowed to remain or separated out by extraction. In the latter case they would be combined with makeup limestone and recycled in a kiln to produce the oxides and hydroxides with which to repeat the process.

While the literature on alkaline fusion of cellulosic wastes is old, none of it goes into as much detail as one could desire. Nevertheless, in preliminary experiments conversions up to 15% were obtained and there is every reason to believe that yields up to 20-40% acetic acid can be obtained, as claimed in 1895 by Cross and Bevan (23). Indeed, in 1892 Cross et al. had reported yields as high as 42% acetic acid from complex, largely cellulosic materials (24). Mahood and Cable reported yields of acetic acid -- up to 30% under optimum conditions -- with either calcium hydroxide or sodium hydroxide as the alkaline agent (1919) (25).

The alkaline fusion technology is simple, requiring only atmospheric pressure, relatively simple equipment and few steps. In these respects the process could serve the needs of smaller communities which could not afford the more sophisticated equipment or provide the trained personnel for the alternate methods of converting waste into deicing materials.

Approximately one-half of the United States population lives in communities too small to generate 200 tons of solid waste per day. If one-half of these, or 50-million people, live in the colder parts of the country, and if we assume solid waste production of two pounds per person per day, they generate 1×10^5 tons of solid waste per day, or 3.65×10^7 tons/year. If the production of acetic acid were approximately 30%, we would then be able to produce approximately 1.4×10^7 tons of calcium magnesium acetates annually, as compared to 0.9×10^7 tons of sodium chloride currently used on roads. The ratio of the weights is approximately that to produce equivalent ice melting effects. Thus, the deicer production capability via alkaline fusion of solid waste in the communities wherein it would most likely be employed is roughly equal to the current need for deicer of the nation as a whole.

Evaluation of Breakdown of Proteinaceous Wastes by Enzymes

Laboratory studies on this type of process were not carried out because initial evaluation appeared too negative.

It is assumed that proteinaceous wastes can, indeed, be broken down with enzymes into amino acids, and probably further treated to deaminate them. However, in light of the high value of proteinaceous feed and food supplements, it appears that edible usages would command a premium price which would make deicing usage economically unattractive.

In addition, a combination of nitrogen and carbon sources under conditions where bacteria can grow almost assures vigorous microbial growth -- and anaerobic growth produces putrefacation with all of the unpleasant odors implied by the term. Furthermore, nitrogen is usually a limiting nutrient for algal growth in lakes and streams, which means that a deicing chemical made from a protein source might have to be used with caution in some areas.

Prime Candidate Chemical Deicers

From the foregoing discussion it appears that the two best deicing candidates are methanol and CMA. CMA refers to the alkaline earth salts of the assorted low molecular weight organic acids derived from cellulosic materials (waste) by alkaline fusion.

Both of these deicer candidates have been and are still being tested. An elaborate program of corrosion testing is under way and preparations have been made for an additional road test. Heat of solution determinations revealed that by contrast with NaCl, which absorbs heat and gets colder as it dissolves, both methanol and CMA liberate heat upon going into water solution. This heating effect should speed up the melting process. Whether the effect on melting rate is appreciable is yet to be determined.

Preliminary sidewalk and road salting experiments reveal that CMA behaves very similarly to NaCl, the equiosmolar quantity producing about the same deicing effect and at about the same rate. By contrast to both of these, methanol acts immediately, producing its maximum effect within minutes after application. Again, by contrast its persistence is measured in only a few hours.

Some dynamic traction tests have been run on flat ice surfaces. These indicate as anticipated that if the deicer fails to bore through the sheet of ice to permit wheel contact with the pavement, the effect of applying either NaCl or purified CMA is to reduce traction. However, with CMA taken straight from the alkaline fusion reaction mixture without purification, the wheel traction on the ice appears to improve. This effect is probably due to the presence of insoluble byproducts of the reaction. The implication is that a purification step is not needed and that a superior CMA deicer may be produced without it at an even lower cost than anticipated.

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The Effect of Chloride Concentration on Automobile Stopping Distance

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The objective of this study was to determine the relationship between chloride concentrations and stopping distances for various driving speeds on snow-covered asphalt pavement. Fields tests were conducted from January to March, 1978 at the Rochester Institute of Technology campus in Rochester, N.Y. Artificial trafficking was done by one driver with a single automobile, so that the factors in stopping distance measurement were minimized. Snow samples were collected at various points across the road profile after artificial trafficking. Approximately 250ml of snow was collected for each sample. The mercuric nitrate method was used in the determination of chloride concentration. The data were used to fit a mathematical model which relates the stopping distance and chloride concentration. Two of the most important observations of the study were: for an asphalt pavement covered with 5 cm (2 in) or less of packed snow and for for driving speeds of 48 km/hr (30 mi/hr) or less, there is no significant reduction of stopping distance when the chloride concentration in greater than 1,000 mg/l; also, the mathematical model developed may be used to determine the required chloride concentration based on the desired stopping distance at a given driving speed.

The current rates of application of sodium chloride for road deicing purposes is generally considered excessive and environmental stress may result. This study measured the response of snow-covered pavement to chloride concentrations under conditions similar to those encountered on residential streets. The intent was to optimize the application rate of deicing chemicals.

Two testing sites, approximately 0.32 m (0.2 mi) of Ward Road, and Parking lot B on the Rochester Institute of Technology (RIT) campus, were used. Both sites are essentially level. Data were collected from January to March, 1978. Results of test were used to determine the relationship between various driving speeds under artificial trafficking conditions at pavement temperatures ranging from -6.1° C to 0° C (21°F to 32°F).

Salt Application Practice at RIT

The RIT Campus Services Department uses a converted dump truck with snow plow in the front and salt hopper mounted on the back for winter operation. The hopper has an effective capacity of 4 tons with a sluice-gate-opening of approximately 5 cm by 30 cm (2 in by 12 in). During salting operations, the slot is always set at this opening size. The salt is fed to the slot by a conveyor belt operated with an independent engine. The application rate may be controlled by a throttle. A spreading disc is attached near the slot to spread the salt, and its distribution may be somewhat adjusted by a clutch. The normal practice is to spread the salt at full throttle, with one pass on 6.71 m (22 ft) of road width. A field test at RIT demonstrated that the actual spread pattern covered a width of 7.92 m (26 ft). This results in deicing chemicals being cast beyond the edge of the road and landing on grass and planting areas.

Campus Services indicated that an average of 4 tons of rock salt are spread on the 21 km (13 mi) of campus roads for each application. This rate is equivalent to 85 kg/3.35 m-lane-km (300 lbs/11 ft-lane-mi). An actual measurement of the salt flow with full throttle in a one minute time interval was 84 kg (185.5 lbs). This is equivalent to 79 kg/3.35 m-lane-km (280 lbs/11 ft-lane-mi), when the salt truck is driving at the usual operating speed of 32 km/hr (20 mi/hr). A salt application rate at 141 kg/lane-km (500 lbs/lane-mi) is roughly equivalent to 5,000 mg/l of chloride concentration as shown in a field test.

The rock salt used on the RIT campus is stored in a heated garage. Laboratory analysis showed a stockpile moisture content of 1.47%. Also, two sieve analyses were performed, one on an oven-dried sample, and the other at stockpile moisture content. The gradation for both oven-dried and stockpile samples was rather uniform as indicated in Figure 1. The chloride content of the rock salt was analyzed to be 58.82% compared with a chemical reagent sodium salt of 60.65% chloride. The difference can be attributed to impurities and additives.

Field Study

Approximately 0.32 km (0.2 mi) of Ward Road was selected as Testing Site No. 1, because of its flatness. The road consists of two 3.35 m (11 ft) lanes of dense-graded asphalt concrete pavement with a 1/48 (¼ in/ft) crown slope, and it was blocked and remained closed during the testing period. The data collected at this site were used to develop a mathematical model. Parking Lot B (Testing Site No. 2) is also a dense-graded asphalt concrete pavement. Data collected at this site were used to test the mathematical model developed for site 1.

Field Test

Stopping Distance. In order to minimize the factors in stopping distance measurement, only one driver with a single automobile was used in the test. The car used was an 8-cylinder Dodge Dart with studded rear snow tires. The driving speeds were 32, 40, 48, 56, and 64 km/hr (20, 25, 30, 35, and 40 mi/hr). During each test, artificial trafficking was made and recorded; then brakes were applied as if emergency stops were being made; that is, with wheels locked. Also, the car was allowed to stop without steering correction. The distance was then measured from the point of initial braking, marked by a road cone, to the point of stopping.

Snow Sampling. Snow samples were collected at various points across the road profile after artificial trafficking. The samples were collected by completely removing the snow on the pavement. Approximately 250 ml of snow was taken for each sample. The packed snow thickness during the testing period ranged from 1 to 5 cm (½ to 2 in).

Laboratory Determination of Chloride Concentration

The mercuric nitrate method was used in the determination of chloride concentration. The procedure described in "Standard Methods for Examination of Water and Wastewater", 14th Ed., 1975, was followed.

Study of Test Results

The field study results at Testing Site No. 1 are summarized in Table 1. As observed, not enough data were collected for driving speeds of 56 and 64 km/hr (35 and 40 mi/hr). The stopping distances for driving speeds of 32, 40 and 48 km/hr (20, 25, and 30 mi/hr) were plotted against the chloride concentrations, as shown in Figure 2, 3, and 4, respectively. The data suggested that they might fit an assumed mathematical model, which was developed and is presented below:

For SI units:

$$S = \frac{V^2}{2g}\left(\frac{1}{C_1 \log Cl^- + C_2}\right)$$

$$S = \frac{V^2}{254.2}\left(\frac{1}{C_1 \log Cl^- + C_2}\right) \qquad (1)$$

where,

S = stopping distance in m
V = driving speed in km/hr
C_1 = friction coefficient associated with chloride concentration
C_2 = friction coefficient for snow or ice covered pavement without chloride application, herein assumed in the range of 0 to 0.10
Cl^- = average chloride concentration in mg/l/lane

For English units:

$$S = \frac{V^2}{30}\left(\frac{1}{C_1 \log Cl^- + C_2}\right)$$

where,

S = stopping distance in ft
V = driving speed in mi/hr

Equation 1 is valid when chloride concentration is equal to or larger than 1 mg/l.

The method used in developing the parameter C_1 is mathematically described as:

$$C_1 = \frac{\sum_{i=1}^{n} C_{1,i}}{n}$$

$$C_1 = \frac{\sum_{i=1}^{n}\left(\frac{V^2}{254.2S_i} - C_2\right) \Big/ \log Cl_i^-}{n} \qquad (2)$$

In which, S_i and Cl_i^- are field data as shown in Table 1 (attached). For a given driving speed and an assumed C_2 value, the value of C_1 can be generated from Equation 2. Once parameter C_1 is established a series of chloride concentrations for a given driving speed is assumed, and the corresponding stopping distances are calculated from Equation 1. (The RIT computer facilities were used for this algorithm). The calculated stopping distances and their corresponding chloride concentrations are also plotted in Figure 2 through 4, and the best fit curves are thus generated. The coefficients developed are summarized in Table 2.

As observed from the 3 figures, the data fit fairly well with the computer calculated curves. With a driving speed of 48 km/hr (30 mi/hr) on snow-covered pavement and a desired maximum stopping distance of 21 m (70 ft), the salt application rate equivalent to a chloride concentration of 1,000 mg/l is adequate. Also, for a driving speed of 40 km/hr (25 mi/hr), a chloride concentration of 1,000 mg/l is enough if the desired stopping distance is 20 m (65 ft) or less. For a driving speed os 32 km/hr (20 mi/hr), it is reasonable to say that a stopping distance of 15 m (50 ft) or less can be obtained with a chloride concentration of no more than 1,000 mg/l. For driving speeds of 56 and 64 km/hr (35 and 40 mi/hr), it is believed that the general trend is similar to those driving speeds of 32, 40, and 48 km/hr (20, 30 and 40 mi/hr), except that the stopping distance would be greatly increased. In any event, it is not recommended to drive more than 48 km/hr (30 mi/hr) in residential area on snow-covered pavements.

It is further observed that increases in chloride concentration are more efficient for the higher speeds relative to the reduction in stopping distance as indicated by the relative slopes of the curves for various driving speeds. However, considering the driving safety together with the environmental impact of chloride pollution, the preferred method of reducing stopping distance is to reduce driving speed on snow-covered pavement rather than to increase the chloride concentration.

The same field tests were conducted at another location in order to observe the reproducibility of the developed model. RIT Campus Parking Lot B was selected because it is the same kind of pavement as that of Testing Site No. 1, and there was accumulated dense packed snow left while the snow on other campus roads was already melted. The field test results are summarized in Table 3. Data collected at Testing Site No. 2 are also plotted on Figure 3. It shows that the stopping distance and chloride concentration correlate fairly well. Although the stopping distances were slightly longer than the model, it is due to the fact that the snow was left on this testing site for quite a long time without plowing and it was densely packed with about 1.27 cm (½ in) of ice formation.

Conclusions

On the basis of the findings from this investigation, the following conclusions are drawn:

1. It has been demonstrated that the chloride concentration is related to stopping distance and driving speed on snow-covered pavement.
2. No significant reduction of stopping distance is obtained when the chloride concentration is higher than 1,000 mg/l/lane at a driving speed of 48 km/hr (30 mi/hr) or less on a pavement covered with packed snow of 5 cm (2 in) or less.
3. There is no significant effect on the established relationship between the chloride concentration and stopping distance when the pavement temperature is between -6.1°C and 0°C (21°F and 32°F).
4. The required salt application rate expressed as an equivalent of chloride concentration should be dictated by the desired stopping distance for a certain driving speed.
5. From inspection of Figures 2, 3 and 4, it is obvious that the most efficient manner to reduce stopping distance on snow-covered pavements is a reduction in driving speed rather than an increase in chloride concentration.

Recommendations

Based on the results of this investigation, the following future studies are recommended:

1. The study, under the same controlled conditions, should be repeated in the coming winter to improve the established mathematical model.
2. Snowtires without studs should also be used, to determine their effect.
3. The friction measurement device, developed by the U.S. Army Cold Regions Research and Engineering laboratory, should also be used for correlation in the above mentioned studies.
4. If possible, pavement temperatures between -6.6°C and -17.7°C (20°F and 0°F) should be studied separately in order to establish the temperature effect. The van't Hoff - Arrehenius model can be tried in simulation of the temperature effect.

Table 1. Summary of field test results at testing site No. 1 - Ward Road.

V Driving Speed		S_i Average Stopping Distance		Cl^-_i Average Cl^- Concentration per 3.35 m-lane (11 ft) mg/l
km/hr	mi/hr	m	ft	
32	20	8.2	27.0	5523
32	20	9.1	30.0	979
32	20	8.8	29.0	454
32	20	11.6	38.0	73
32	20	14.9	49.0	49
40	25	12.8	42.0	2776
40	25	11.9	39.0	5523
40	25	10.1	33.0	2656
40	25	7.9	25.7	705
40	25	13.6	44.5	890
40	25	14.8	48.5	1792
40	25	18.9	62.0	467
40	25	19.5	64.5	580
40	25	15.9	52.0	49
40	25	18.9	62.0	96
48	30	16.5	54.0	2776
48	30	16.5	54.0	5523
48	30	16.3	53.3	2656
48	30	14.0	46.0	705
48	30	20.3	66.5	489
48	30	20.3	66.5	550
48	30	20.7	68.0	491
48	30	18.8	61.5	644
48	30	19.7	64.5	49
48	30	21.0	69.0	96
56	35	23.3	76.5	2776
56	35	25.3	83.0	73
56	35	26.7	87.5	49
64	40	26.8	88.0	5523
64	40	18.9	62.0	2656
64	40	19.8	65.0	705

Table 2. Friction coefficients at various driving speeds.

C_1			
V = 32 km/hr (20 mi/hr)	V = 40 km/hr (25 mi/hr)	V = 48 km/hr (30 mi/hr)	C_2
0.161	0.170	0.187	0.00
0.140	0.152	0.168	0.05
0.119	0.133	0.150	0.10

Table 3. Summary of field test results at testing site No. 2 - Parking Lot B.

Driving Speed		Average Stopping Distance		Average Cl^- Concentration per 3.35m-lane (11 ft), mg/l
km/hr	mi/hr	m	ft	
40	25	11.6	38.0	5094
40	25	11.6	38.0	5094
40	25	11.3	37.0	2744
40	25	12.8	42.0	2744
40	25	13.7	45.0	3924
40	25	11.0	36.0	3924
40	25	14.0	46.0	3924

Figure 1. Sieve analysis of rock salt.

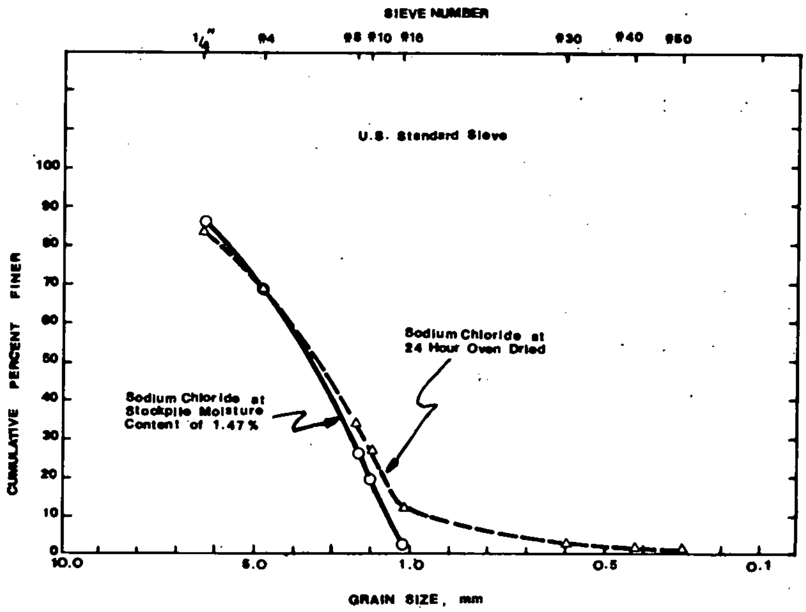


Figure 2. Relationship between average chloride concentration per 3.35 m-lane (11 ft) and stopping distance at driving speed of 32 km/hr (20 mi/hr).

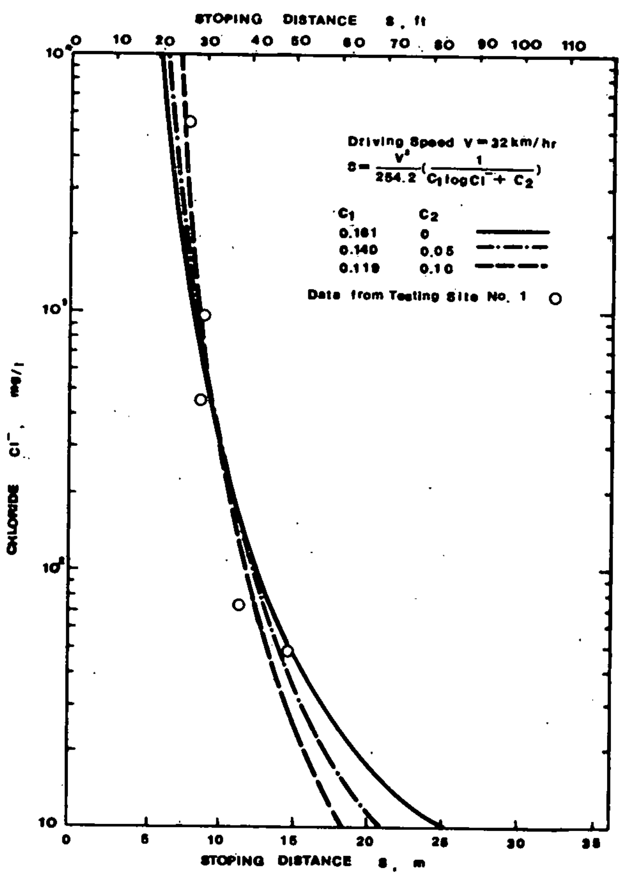


Figure 3. Relationship between average chloride concentration per 3.35 m-lane (11 ft) and stopping distance at driving speed of 40 km/hr (25 mi/hr).

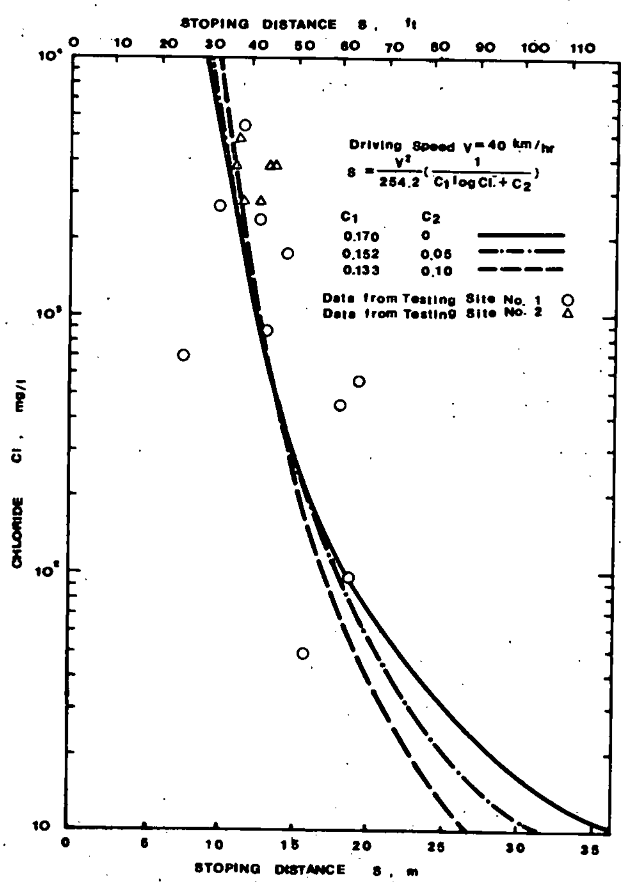
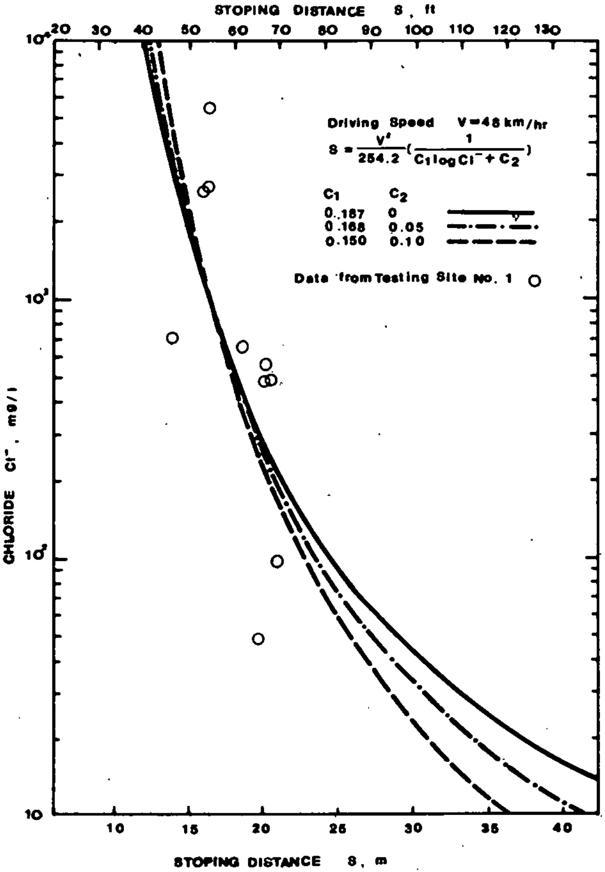


Figure 4. Relationship between average chloride concentration per 3.35 m-lane (11 ft) and stopping distance at driving speed of 48 km/hr (30 mi/hr).



5. The salt application rates, their distribution pattern as affected by wind, and the chloride concentration should be studied in as much detail as possible so that the optimum range of application rates can be narrowed.

6. Winter driving speed in residential areas on snow-covered pavement is recommended to be no more than 48 km/hr (30 mi/hr).

Acknowledgements

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Evaluation of the Use of Salt Brine for Deicing Purposes

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Connecticut Department of Transportation

The formation of snowpack and ice on roadways is of major concern during snow removal operations. The use of conventional methods requires substantial use of deicing chemicals and equipment. A new method for destroying snowpack and ice, which utilizes high-speed sodium chloride brine jet streams, is discussed herein. This report describes the prototype unit, its calibration and stationary facilities for making the brine solution. Data obtained from field testing the unit on Interstate 84 in Connecticut during the winters of 1977-78 and 1976-77 is contained herein. Application rate data are compared for conventional methods and the salt brine concept for the past two winter seasons. Use of the prototype for special icing situations is also discussed.

Background

Environmental movements and tight operating budgets are compelling personnel responsible for highway ice and snow control to minimize the use of chloride deicers.

Plowing is the primary method of removing loose bulk snow from a pavement. The snow remainin after plowing is usually in a state of compaction and, on high-volume roadways is rapidly coated with an ice glaze caused by moving traffic. To reduce the formation of ice glaze and further snow adhesio to a pavement, chemical deicers are used.

A deicer applied in the dry form is embedded into the cover in either the solid or liquid form. The former is embedded for the most part by passing vehicles, whereas the latter is embedded as a brine which is formed on solution of the salt crystals. Regardless of which way the material enters the pavement cover, its transformation into an active deicer is time-consuming and dependent on both temperature and available moisture. The prime objective during ice and snow control operations, therefore, is to maintain or obtain an acceptable level of service by destroying an existing snow pack or ice glaze.

Prior to 1970, the Connecticut Department of Transportation, in keeping with a bare-pavement policy, called for application rates of 700 pounds of crystalline salt per two-lane mile. However, the 1970's have witnessed the rate of application drop from 700 pounds to the present 430 pounds per two-lane mile per application. During this time, a project was instituted to evaluate a unique concept involving the use of sodium chloride brine for pavement deicing. The use of both sodium and calcium brines in itself is not new./1,2&3/ Brine has been used successfully in many areas.

Although the use of brine is not new, the method of applying it does differ from existing methods of application. The Department's first experience with brine occurred during the winter of 1971-72, when it was applied using a road oiler. During this period, it was reasoned that better results would ensue if certain modifications were made in the method of application. It was hypothesized that a 0-degree nozzle deployed at a very shallow angle to the pavement would destroy a portion of the pack or ice by mechanical action. Once the forward momentum of the jet had diminished, the solution would immediately initiate a chemical melt.

Prototype Design Considerations

The first consideration in advancing this hypothesis was to establish optimum nozzle parameters. It was reasoned that maximum mechanical efficiency would result if the nozzles were positioned as close to the pavement as possible and angled such that the path of the flow would be within a few degrees of being parallel to the pavement (See Fig.'s 1 and 2). With the nozzles positioned in this manner, the energy in the fluid stream, plus the forward speed of the truck would be better utilized. Also, it was hypothesized that with the nozzles deployed in this position, the fluid would destroy a portion of the pavement cover mechanically by a high-velocity stream directed at the packed snow or ice. It was reasoned that immediately after an application, the snow cover would be either partially or completely destroyed and the cover remaining on the pavement loosened sufficiently to allow removal by plowing. The remaining cover, permeated with an active deicer would either be destroyed chemically or would remain a mealy state. Under these conditions, the likelihood of the cover adhering to the pavement would also be substantially reduced.

Prior to constructing a full-scale prototype, laboratory tests were performed to determine the most suitable type of nozzle, spray angle, and fluid pressure to be used under field conditions/4/. Commercially manufactured flat, narrow 15° (0.26 rad) and 20° (0.35 rad) fan nozzles seemed to be the most promising and were used during the initial tests. The tests indicated that because of air resistance, the fan nozzles were unable to maintain a flat, narrow configuration at a test pressure of 150 psi (10.5 kg/cm^2).

Fig. 1 Schematic Showing Proposed Design of Full Scale Prototype (Valve, Piping, Gages, Etc. Not Shown)

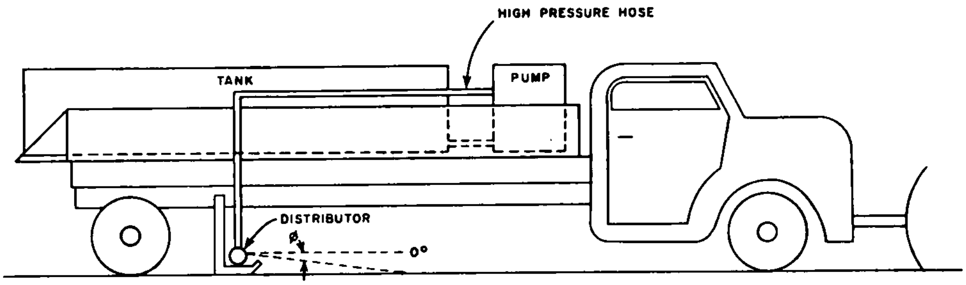
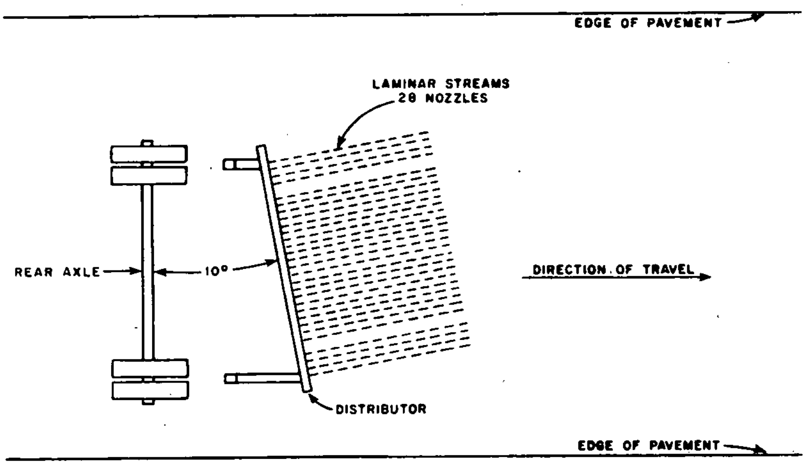


Fig. 2 Schematic Showing Direction of Fluid Stream in Relation to Trucks Direction of Travel



Tests performed using straight or 0° fan nozzles showed that this type of nozzle produced a stream that was not substantially affected by air resistance. The resulting high-velocity stream had the ability to cut into the surface of the ice specimen on contact. Since the streams were cutting the ice at point locations, i.e., in the path of the flow, a corduroy effect resulted on the specimen surface. This problem was overcome by simply rotating the nozzles horizontally 10° (0.17 rad). This orientation change used the jet's abrasive qualities in a planing manner on the ice and the corduroy texture was substantially reduced.

A second project objective was to utilize the available energy in the jet stream to the maximum; therefore, it was required to optimize the incident angle of the jet stream to the pavement. The laboratory tests indicated that although an angle of less than 12° (0.21 rad) did not adversely alter the path of the stream, the optimum angle would have to be set in the field.

Prototype Brine Applicator

The full-scale prototype design was based on data obtained in the laboratory and from maintenance-operation requirements. Sufficient capacity was built into the unit to apply brine for ten miles at a rate of 75 gals (283.9 l) per minute at 300 psi (21.1 kg/cm^2) using a fully saturated solution; this amount is equivalent to 400 pounds (181.6 kg) per two-lane mile when applied at a travel speed of 30 mph (48.3 km/hr.).

The prototype was fabricated and mounted on a standard maintenance nine-ton truck chassis (Fig. 3). The main components in the system consist of a positive-displacement pump, 25-horsepower engine, 1500-gallon (5,677 l) fiberglass tank, nozzle bar and necessary hoses, valves and fittings.

The distributor bar assembly (Fig. 4) consists of a 3-inch (7.6 cm) pipe 8 ft (2.4 m) long mounted on steel pads, 28 nozzles having an orifice diameter of .080 inch (2.0 mm), a pair of telescoping box beams, two 12-inch (30.5 cm) casters, and a pneumatic piston with necessary cables and pulleys for raising or lowering the unit.

The upper ends of the telescoping units are attached to the chassis directly in front of the rear wheels. The lower end of this unit was fabricated with slots through which the I-bars supporting the distributor bar are passed. The end of the I-bars passing through the slots is attached to the box beam which is designed to lift the distributor bar off the pavement should an obstruction be encountered. When in the down or spray position, the nozzle elevation is fixed and maintained with respect to the pavement by

Fig. 3 Completed unit mounted on truck

Fig. 4 Distributor-bar assembly

the casters on which the unit rides. When the distributor bar is not in use, the entire assembly is raised pneumatically to approximately 9 inches (22.8 cm) above the pavement.

The piping system was designed to use the unit's pump for the dual role of filling the fiberglass tank and applying the brine to the roadway surface; therefore, auxiliary equipment is not required at the brine-making and storage facility.

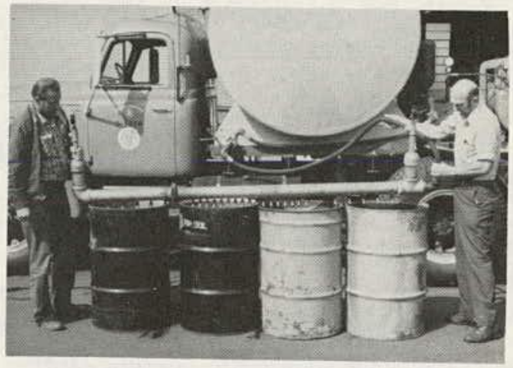
The high-pressure system, which is used to apply the fluid, consists of high-pressure hoses, a pressure-relief valve, a 3-way valve, a distributor and an auxiliary by-pass line. In the spraying mode, the auxiliary by-pass is closed and the unit is pressurized to 300 psi (21.1 kg/cm^2). When the system is operating, but not spraying, the auxiliary by-pass is open and a pressure of 230 psi (16.2 kg/cm^2) is maintained.

The unit contains two safety devices consisting of a pressure-relief valve and fail-safe device capable of shutting off the system should pressure failure occur.

Calibration of the unit is easily performed by collecting and measuring a volume of water dispensed over a given period of time and at an observed pressure. Two methods have been used for collecting the water. One method, shown in Fig. 5, involves the use of four 55-gal. (208 l) drums in which all the water is collected and measured. The second method consists of collecting the water by placing four 2.5-gal. (9.5 l) containers under individual nozzles and again measuring the volume collected. The sequence is twice repeated using four different nozzles each time. The recirculation pressure prior to calibration and application pressure are noted. Of the two methods, the second is preferred mainly because of ease in handling and measuring the fluid.

This method of calibration has its advantages over conventional techniques in that volume and not weight of material (which can vary with moisture content) is the basis of the calibration.

Fig. 5 Calibration of unit using 55 gal. drums



Brine Making Facilities

The stationary facilities consist of two steel tanks containing a total of 7,000 gal. (26,500 l), a fiberglass tank in which the salt is dissolved and an overhead hopper in which the crystalline salt is stored prior to entering the dissolver (Fig. 6&7). Although loose, free-flowing salt provides fully

Fig. 6 Brine-Making apparatus (front view)

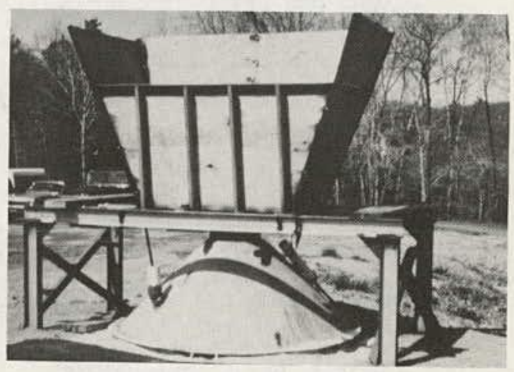


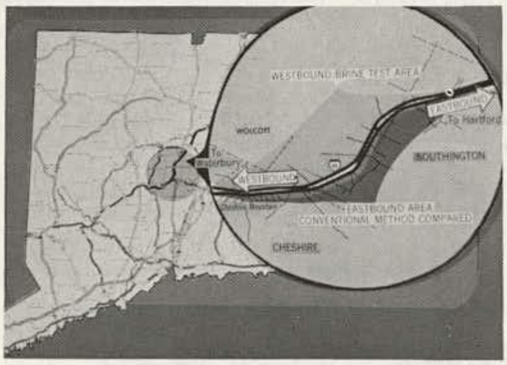
Fig. 7 Tanks used to store brine with brine-making unit in background

saturated solutions (100 percent saturation), caked salt can be efficiently disposed of in the dissolver when due care is exercised; in the latter case, however, saturation drops off to approximately 90 percent, and on occasion, to as low as 85 percent. An 85 percent solution has a freezing point of minus 3.7°F (-19.8C); therefore, with ambient storm temperatures normally ranging in the high teens and twenties, there is no need to increase the saturation to 100 percent.

Description of Experimental Section

The experimental section was located on I-84 in the Towns of Southington and Cheshire. It was selected so as to include a long continuous grade over Southington mountain; here, the road rises 320 ft (97.5 m) over a distance of 1.8 miles (2.9 km). In terms of elevation, this area is the highest of the entire run, and was considered by Maintenance personnel to be the most severe problem location under their jurisdiction (See Fig. 8 and 9).

Fig. 8 Map of Connecticut showing location of test site



In the final layout, the test section on which the brine was applied ran from Rt 229 (West St) in Southington to Rt 70 in Cheshire and included only the westbound roadway; the entire test section encompassed approximately 15.9 lane-miles (25.6 lane-km), including the truck-climbing lane. The control section in the eastbound roadway not only ran concurrent with the westbound test section, but also continued beyond it in both roadways for approximately 47.8 lane-miles (76.9 lane-km). To facilitate record keeping for amounts of crystalline salt applied, however, the remaining section of I-84 from Rt 229 to Rt 72 in New Britain (both roadways) was incorporated into the control section, since the trucks spreading the salt were responsible for the entire run from Rt 70 to Rt 72, and metering of the output of salt would be less complex if it were done over the entire run. In this case, the total lane-miles monitored for amounts of salt used was 61.9 lane-miles (99.7 lane-km).

All operations involving the experimental brine program operations originated from the Southington Maintenance garage where the brine-making apparatus and prototype unit were housed. This garage is also responsible for the maintenance of the entire experimental and control sections on I-84 from Rt 72 to Rt 70.

Storm Description for Winter 1977-78

Maintenance personnel were called out for storm duty a total of eighteen times. The following is a description of all storms experienced during the winter season:

No. of storms	Snow Accumulation
9	1" or less (5 with a trace)
5	1.25" - 3"
2	3.125 - 6"
2	over 6"

No. of Storms	Average Storm Temperatures
1	20F or less
6	21F - 25F
3	26F - 30F
8	over 30

Of the eighteen storms, nine did not warrant the prototype's use. The nine storms in question either lacked an appreciable amount of snow or occurred during warm (above 30F) temperatures. During five of the remaining eight storms, difficulties were experienced with the truck or pump engine.

Field Operations

Prior to the winter of 1977-78, the prototype was fully operational. During the first storm it was noted that the nozzle bar tended to rotate downward to an angle of 7.75 degrees (0.14 rad) to the pavement from the desired angle of 3 degrees (0.05 rad). It was determined that since the casters, which set the height of the nozzles, act independently, a torque is developed in the bar as each caster attempts to conform to the snow-covered pavement surface. This nonuniform vertical movement caused the bar to rotate. The bar's clamping system was redesigned to overcome the rotation problem.

Since it was not known to what degree the concept would meet with success, the prototype was mounted on an older truck. Also, the engine for driving the pump was one used previously on a salt spreader. The truck and pump engines required many hours of repair, therefore, the prototype was not used for the duration of a number of storms making comparisons impossible. Tables 1 and 2 summarize the results of tests not only for the winter of 1977-78, but also for the previous snow season.

Under normal operating procedures, a plow mounted on the prototype would remove the bulk of the loose snow on the pavement to expose compacted snow or ice glaze. When ice glaze exists on a pavement, it is removed on contact by the high-velocity jet streams. Any compacted snow remaining on the road surface after passage of the plow will be penetrated and loosened to some extent by the mechanical action of the high-velocity brine jet, and will be converted to a mealy mass. Compacted snow covers of 0.25 inches (0.6 cm) or less in depth are readily penetrated by the brine and can be immediately removed by a trailing plow. Where the depth of the residual cover exceeds 1/4 inch (0.6 cm), however, the mechanical action of the brine is insufficient to loosen the entire pack, but penetration of the brine will precipitate an immediate chemical action that continues to destroy the pack, and ultimately the bond at the pack-pavement interface.

Table 1 Summary of Test Results for Two Winters

Storm No.	Total Precipitation	Roadway Cover	Brine Applied (Gal.)	Results
		1976-77		
10	3" Snow	Mealy Snow Thin Pack	2,250	Pavement Wetted Pack Broken
11	1" Snow	Thin Pack	1,350	Pavement Wet with Slush
14	8.8" Snow	Mealy Snow	2,250[a]	Pavement Wet and Clean
23	0	Ice	750[b]	Ice removed on contact
11A[e]	0.4" Snow	Thin Pack	2,250	Pavement Wet with Slush
18[e]	18" Snow	.25" Pack	3,700[c]	Pack Loosened
21[e]	6.0" Snow	Thin Pack	800[d]	Wet

(a) 85% Brine Solution
(b) 65% Brine Solution
(c) Deicers used only for cleanup operations
(d) 90% Brine Solution
(e) Winter of 1977-78

Table 2 Comparison of Crystalline Salt vs Brine Used for Two Winters in ton per lane mile per storm

Storm No.	Crystalline Salt	Salt Brine
10[a]	0.89	0.19
11[a]	0.73	0.11
14[a]	0.89	0.16
23[a]	----	0.12
11A[b]	0.61	0.21
18[b]	1.19	0.35
21[b]	0.98	0.17

(a) Winter of 1976-1977
(b) Winter of 1977-1978

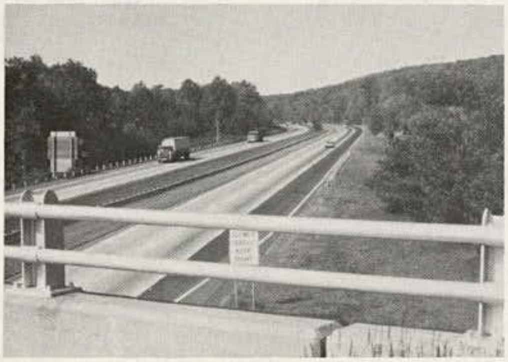
On January 9, (Storm 11A) two applications of brine were made on dry, dense, thin pack. After each application, the pack was coverted to a light slush cover. During this storm, a total of 2250 gallons (8516 l) of 96.5 percent saturated solution equivalent to 2.87 tons (2.61 mt) of crystalline salt was used. On a per lane-mile basis, this amounted to 0.21 ton (0.19 mt) of salt for the brine application, and 0.61 ton (0.55 mt) for the dry crystalline application. The storm temperature was 22F (-6C) with a total 0.4 inches (1.0 cm) of snow.

During the blizzard of February 6 and 7th, (Storm 18) deicers were not used. On February 8th after the blizzard had stopped, maintenance personnel made a brine application, which removed the still remaining snow cover consisting of 1/4 in. (0.6 cm) of extremely tight pack. Approximately 48 hours of snowplowing had elapsed since the beginning of the storm. Personnel at the site stated that "immediately after application of the brine, either bare pavement resulted or the pack was loosened sufficiently to permit removal by plowing." A total of 3700 gallons were used for clean-up operations. On a per lane-mile basis, 0.35 ton (0.32 mt) of salt as brine was used compared to 1.19 tons (1.08 mt) of crystalline salt. Total snowfall prior to deicer applications amounted to 18.0 inches (45.7 cm). During the brine application, the ambient temperature was 21F (-6C).

During the storm of March 3 (storm 21), brine was applied only to the grade ascending Southington

Mountain (Fig. 9). This section of roadway is 1.8 miles (2.9 km) long and consists of two travel lanes plus a truck-climbing lane. On two occasions, this section

Fig. 9 Portion of test site entering long uphill grade.



was covered with a thin, extremely slippery, wet, compacted snow. The pavement surface receiving the brine was immediately exposed after the application (Figs. 10,11,12). A total of 800 gallons (3028 l) of 90% saturated solution equivalent to 0.17 ton (0.15 mt) per lane-mile was used. A total of 60 tons, or 0.98 ton (0.89 mt) per lane-mile of salt were used outside the test section. The storm temperature was 24F (-4C) with a total of 4.4 inches (11.2 cm) of snow.

Fig. 10 Pavement prior to brine application

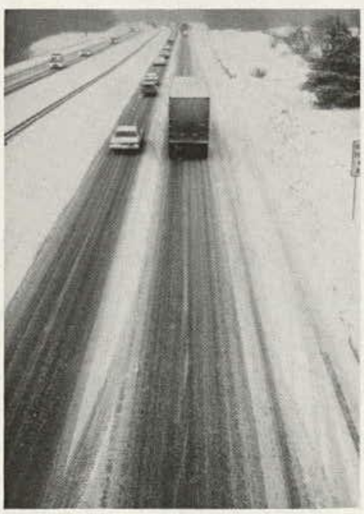


Fig. 11 Brine being applied to pavement

Fig. 12 Pavement 5 minutes after brine application

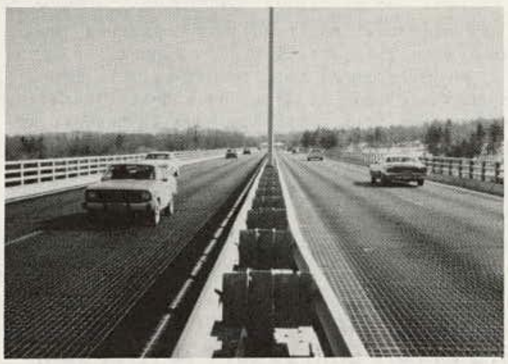
Special Icing Situations

Bridges having open steel grid decks, especially when coated with ice, are extremely hazardous to the motorist and are a difficult problem to maintenance personnel. Application of either deicers or abrasives are of little or no value on bridge decks of this type. Since the grid has steel studs which protrude above the grid's surface, plowing is both difficult and ineffective (Figs. 13 and 14).

An icing condition occurred on such a bridge deck over 1800 ft (546.6 m) in length during the winter of 1977-78. Having spent approximately two hours attempting to remove an ice accumulation from the four-lane divided deck and having exhausted all other avenues, maintenance personnel requested the services of the prototype brine truck. An application of a 90% brine solution was made in each of the four lanes at a speed of approximately 10 mph (16 kmph) and a pressure of 300 psi (21.1 kg/cm^2). This amounted to approximately 1460 pounds (662. 8 kg) of crystalline salt. Once the applications were completed, the deck, except for a few isolated spots, was bare of ice. The ice remaining on the deck had been weakened sufficiently to allow removal by traffic. The film of brine remaining on the deck acted as an anti-icing agent, preventing further ice formation.

Fig. 13 Close-up view of open steel grid bridge deck showing studs

Fig. 14 Overall view of open steel grid bridge decks



Ice formation often occurs on shoulders especially under overpasses. Since the ice is shaded from sunlight, it can remain in these locations for extended periods of time. Crystalline salt frequently embeds itself into the ice forming deep narrow cavities where the crystals come to rest leaving the remainder of the ice intact. Brine applied on ice of this type fills the existing cavities resulting in a rapid breakdown of the ice.

CONCLUSIONS

The second year's testing of the prototype produced results similar to those obtained during the preceding year. The high-velocity jet streams combined with the brine's deicing characteristics were capable of destroying packed snow normally encountered during snow removal operations. Sufficient melting had occurred in the path of the brine applications within moments of application, during most storms, to cause splash up by passing vehicles. The lowest ambient temperature during a brine application was 21F (-6C).

The prototype proved its ability to overcome difficult icing situations such as bridges having steel open-grid bridge decks.

All operational problems encountered during the winter season can be assigned to mechanical difficulties with the pump and truck engines. All components of the prototype functioned as designed.

ACKNOWLEDGEMENTS

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Enhancing Ice-Melting Action of Rock Salt by Prewetting with Calcium Chloride

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This investigation was prompted by the interest in liquid calcium chloride ($CaCl_2$) for prewetting rock salt and abrasives used for snow and ice control. The findings demonstrate that prewetting can increase the effectiveness of rock salt and abrasives and thus reduce application rates and costs and may result in decreased damage to nearby salt sensitive vegetation and reduced infiltration into ground water. Both field and laboratory information are included, and both substantiate the increased efficiency of rock salt and abrasives; data indicates that salt use may be reduced by 25-50% and that rock salt may be effectively used at temperatures as low as -17.8°C (0°F).

Almost every maintenance engineer in the snow-belt states has been faced with the problem of removing snow or ice at temperatures lower than -6.7°C (20°F), where the effectiveness of rock salt is greatly reduced. According to literature data, at temperatures below -3.9°C (25°F), salt will melt less than 30% of the amount of ice it would melt at -1.1°C (30°F) or above (1).

A method recently introduced to combat this low temperature effectiveness problem is the concept of prewetting rock salt with liquid calcium chloride brine (8-12 gallons 30-32% $CaCl_2$ per ton salt) to reduce bounce-off (Fig. 1) and loss due to traffic,

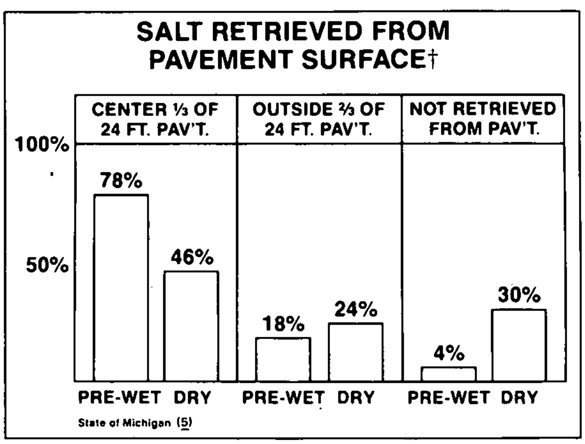

FIGURE 1

extend its effective application temperature, and increase ice melting action (14). Reductions in salt use per mile of 25-50%, resulting in more miles spread per load of salt, have been claimed by various agencies (2,3,4,5,6,7,8) due to prewetting which decreases both costs and adverse environmental effects of deicing chemical use (Fig. 2). Respreading and overspreading are also reported to be reduced by prewetting rock salt.

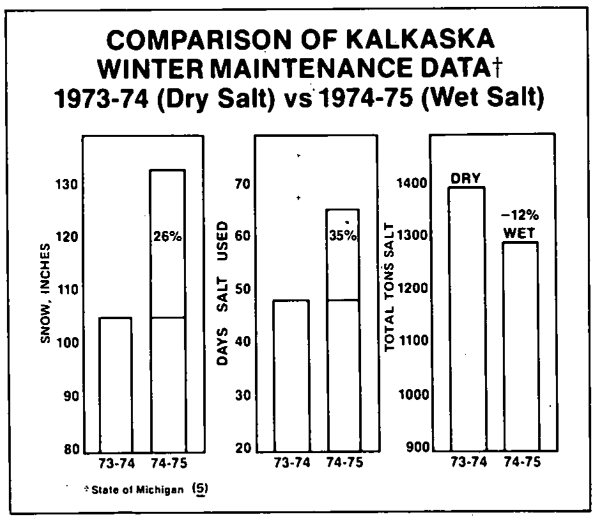

FIGURE 2

Field Experience

Background

The first field test of rock salt prewet with liquid calcium chloride at the rate of 10 gal. 32% $CaCl_2$/ton salt was conducted in Clayton County, Iowa during the 1968-1969 winter and successfully demonstrated that prewetting substantially increased the melting action of rock salt and reduced loss due to salt bouncing off the pavement.

In the years since that date, many other cities, counties, and states have experimented with liquid calcium chloride, proven its effectiveness with field tests, and outfitted their maintenance yards with a variety of equipment to accomplish the prewetting. The most notable experimenters are the states of Iowa, Michigan, and Ohio (2,4,5,6,9) who have conducted closely monitored field trials and presented their findings.

Calcium Chloride Properties

Calcium chloride, chemical formula $CaCl_2$, is the salt of a strong acid and a strong base. Commercially, calcium chloride is obtained either from natural brines or as a by-product of the reaction between lime and ammonium chloride. It is extremely soluble in water and forms many hydrates.

Although calcium chloride is highly soluble in water at ordinary temperatures, solid phase separation will occur under certain temperature-concentration conditions as shown in the phase diagram in Figure 3. Although this figure is comprised of data for pure $CaCl_2$, brines made from commercially available calcium chloride closely approximate the heavy black line in the diagram. The eutectic point is 30.2% $CaCl_2$ and -50°C (-58°F).

PHASE DIAGRAM FOR THE $CaCl_2$–H_2O SYSTEM

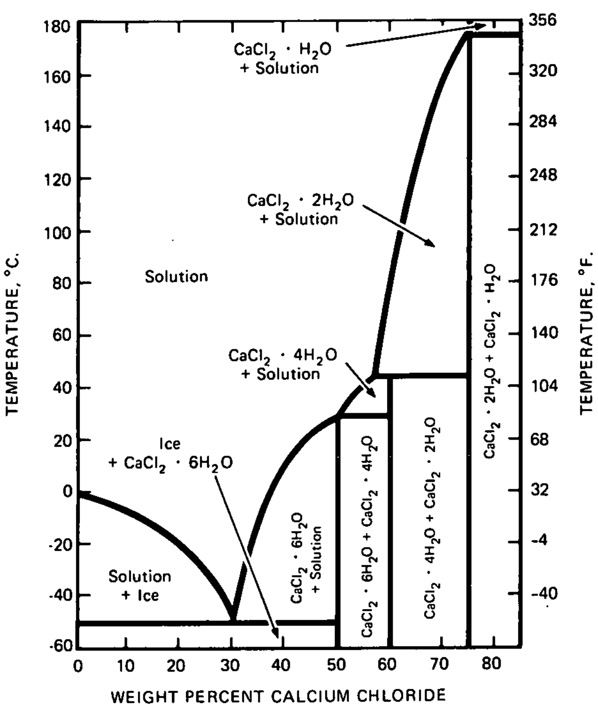

FIGURE 3

Calcium chloride is both strongly hygroscopic (attracts water) and deliquescent (the solid can dissolve by absorbing atmospheric water). Calcium chloride also has a highly exothermic heat of solution. These properties, among others, make it effective in dust control, deicing, concrete acceleration, road stabilization, and oil well drilling applications. It is commercially available in anhydrous and dihydrate solid forms or in liquid form in various concentrations.

Benefits Cited

Prewetting with liquid calcium chloride extends the effective temperature range of salt to 0°F, and reduces the total amount of deicer required through faster action per unit of chemical applied and reduction of loss due to scattering and bouncing of salt from the road (14) (Figure 1).

The faster penetration and undercutting action will also reduce salt use, since operators can see melting action earlier and are less inclined to overspread or respread treated areas.

Users of the prewet salt have reported savings of 25% (and more) of their total salt usage in comparison with dry rock salt (Figure 2).

This reduction in the amount of salt used, in addition to decreasing the cost of a maintenance program, reduces the potential effect of such deicers upon the environment.

APPLICATION FACTS

PREWET	DRY
Holds in close pattern. No dust.	Some segregation. Large particles spread wide. Dust evident.
Stays in place, little sliding on thick ice.	Stays in place on loose slush, slides wide on thick ice.
Inbeds in ice cover immediately.	Dormant when applied. Inbeds in 3-5 minutes @ 30°F, 19 minutes @ 25°F, much greater time below 20°F.
Minimal early loss caused by whipping of traffic.	Loss variable: High temperatures: minimal; Low temperatures: considerable

MELTING ACTION

Starts immediately	28°–32°F	Minor delay
Starts immediately	25°–28°F	10-20 minute delay
Minor delay	Below 20°F	30 minutes or greater delay

Melting Action Comparison

Winter testing at eight separate district maintenance unit headquarters in the State of Michigan (3) was conducted to determine comparative advantages of prewet salt vs. dry salt. The following section is a composite summary of observation reports received from these headquarters.

Melting Action

Starts immediately	28°-32°F	Minor delay
Starts immediately	25°-28°F	10-20 minute delay
Minor delay	Below 20°F	30 minutes or greater delay

Limitations

It must be remembered that prewetting with liquid calcium chloride is not the total solution for snow and ice control. For the most accelerated deicing action at lower temperatures, dry calcium chloride alone or in mixtures with salt, must be applied. At lower temperatures (as illustrated in Figure 4), dry calcium chloride is much more effective than salt or salt prewetted with liquid calcium chloride.

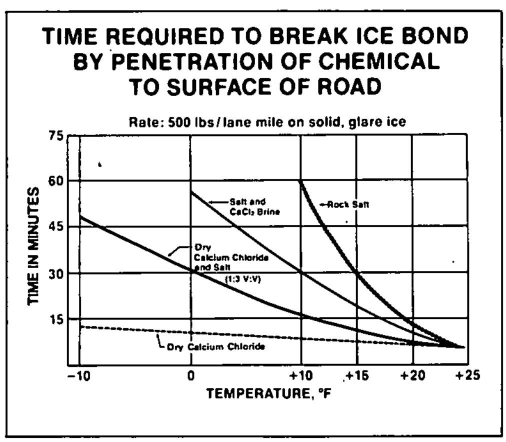

FIGURE 4

If speed of action is critical under low temperature conditions, then dry calcium chloride is the answer to the problem. The use of pre-wetting or dry calcium chloride must be tailored to the user's operations, concerns, and weather conditions.

Application Systems

Field application systems have ranged from equipment as simple as a bucket and sprinkler can for trials to a sophisticated, electronic device with logic circuitry.

The basic components for all permanent systems are a tank, a pump, and the associated piping and electrical equipment (Figure 5).

Figure 6 shows a simple system which consists of a garden hose water nozzle or a gasoline pump-type nozzle which can be attached through a rubber hose to a valve, meter, and pump and used to spray liquid calcium chloride over rock salt already loaded into a truck. Nozzle material may be either brass or steel. The City of Indianapolis, Indiana, among others, uses this system.

Figure 7 is a simple hand wand which has been used in place of the nozzles in the above system. This is made of standard steel pipe.

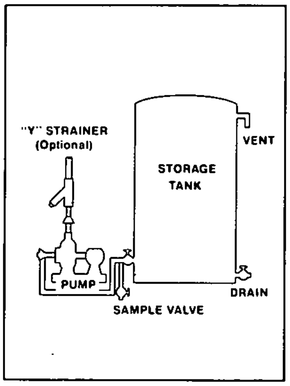

FIGURE 5 Basic Components

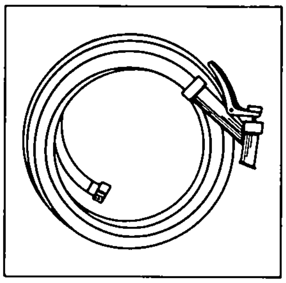
FIGURE 6 Simple System

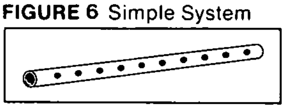
FIGURE 7 Hand Wand

District No. 3 of the State of Ohio Department of Transportation is using a more sophisticated system which is shown in Figure 8. A truck with a load of salt drives into the stall, the truck driver hits the timer control, and the liquid calcium chloride is sprayed over the rock salt in the truck.

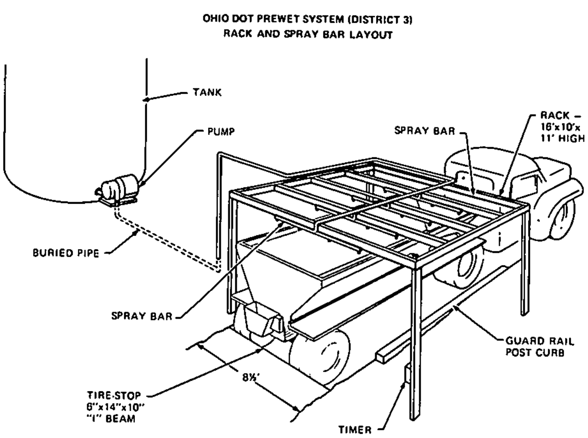

FIGURE 8

The system devised by the Iowa State Highway Commission, and depicted in Figure 9, is also more complex. It involves a truck mounted set of components. Liquid calcium chloride is placed in a fiberglass tank mounted along the side of the truck bed. A pump which is belt-driven from the spreader drive shaft applies the liquid to two 50-degree fan nozzles drilled at a given spacing in a spray bar. This is inserted into the spreader discharge chute immediately above the spinner assembly.

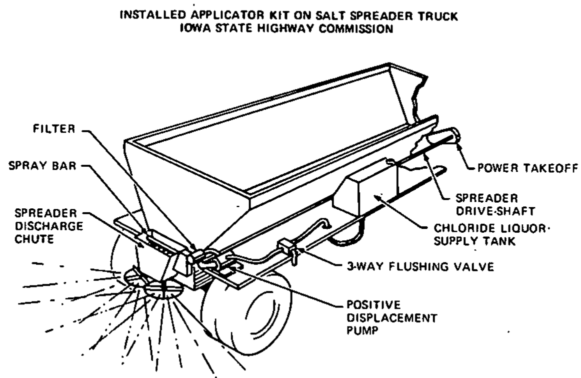

FIGURE 9

The Michigan Department of State Highways and Transportation also uses a truck-mounted system similar to that used by Iowa (Figure 10). Liquid calcium chloride is pumped from a fiberglass tank on the side of the truck to a nozzle set just below the discharge chute. Prewet salt can then be applied through the spinner assembly or to an auger feed which applies it just above the roadbed.

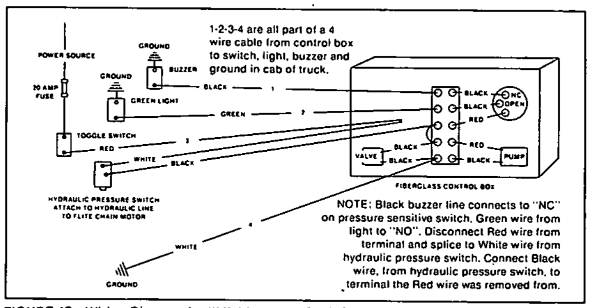

FIGURE 10 Wiring Diagram for "Michigan Wet Salt" Control Box

The most complex system currently on the market today, and used in Evanston, Illinois and Kettering, Ohio, consists of a radio-controlled wetting arm which applies liquid calcium chloride to salt in the end loader bucket before it is placed in the truck (Fig. 11).

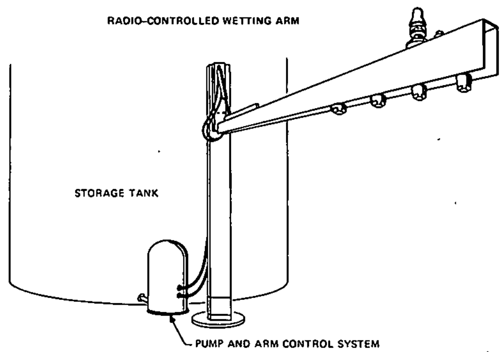

FIGURE 11

Laboratory Experimentation

Although field data demonstrated an increase in effectiveness, there were still questions which needed to be answered by controlled experimentation. The principal question was whether the 1:57 (by weight) ratio of $CaCl_2$ to rock salt used in prewetting was actually producing increased effectiveness since most dry premixes are 1:3 to 1:5, calcium chloride:rock salt, vol:vol (10), or if the trial results were due to other variables present in field experimentation.

The effective temperature range of prewet salt was also being questioned since some users were claiming effectiveness down to -28.9°C (-20°F) although the eutectic temperature for rock salt, which comprises approximately 98% of the mixture, is -21.1°C (-6°F) at best (4). The answers to these questions could be obtained by well-controlled laboratory studies of the penetration and undercutting action of untreated rock salt compared with salt prewet with various agents which depress the freezing point of water.

In this study the method used and reported by Sinke and Mossner (11) in their comparison of calcium chloride and rock salt was modified and used as the basis for comparison of prewet with untreated rock salt. The prewetting agents chosen to be studied were 30% calcium chloride, 59% propylene glycol, 56% ethylene glycol, and water (all concentrations on a weight basis). Each prewetting agent was applied, as commonly practiced with calcium chloride in the field, at the rate of 0.04 liters per kilogram of rock salt (10 gallons/ton). Two effects were studied: time to undercut a sheet of ice and time to penetrate a block of ice.

Undercutting Studies

To study the effects of prewet rock salt on undercutting, an adaptation of the experimental method developed by G. C. Sinke and E. H. Mossner (11) was used. The following is an excerpt from their report:

> In this study a laboratory method for continuous observation of ice melting action in a situation simulating an ice covered concrete highway has been used. A particle of chemical when dropped on the ice will melt down through the ice and the brine will then spread out underneath the ice as illustrated in Figure 12a. This bond breaking action is the most significant effect of deicing chemicals, since calculations show that it would be prohibitively expensive to melt all the ice. In these experiments, a 0.3175 cm (1/8") layer of clear ice was built up on a concrete block and the block was placed in a commercial deep freeze unit held at the desired temperature (see Figure 12b). A small fan in the freezer circulated the cold air to eliminate temperature gradients. Weighed particles of chemical were lightly dusted with a dye, the sodium salt of fluorescein, and loaded into a dispenser in which the particles were isolated in individual compartments. The dispenser was placed over the ice covered concrete block and the system allowed to come to a uniform temperature as measured by thermocouples or thermometers.

ICE BOND-BREAKING AT INTERFACE WITH PAVEMENT (11)

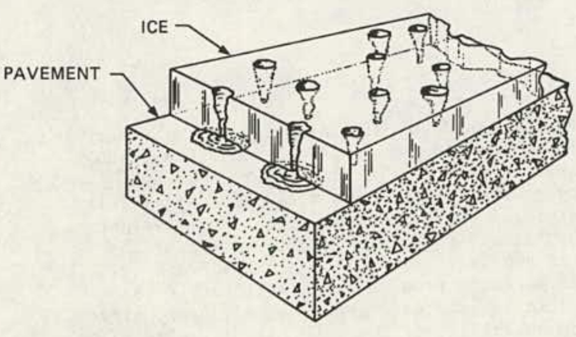

FIGURE 12a

PREWET STUDY EQUIPMENT

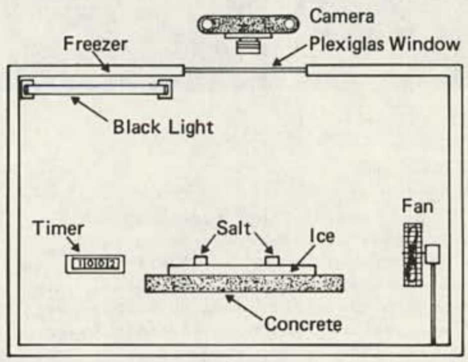

FIGURE 12b

In our experiment, salt was treated with the various "freeze-proof" wetting agents first and the system was then allowed to return to the chosen temperature. Prewetting with water was done just prior to application of the rock salt to the ice surface. Continuing with Sinke's and Mossner's (11) technique:

> The dispenser was then actuated by pulling cords passing through the freezer lid. The particles were thus dropped on the ice and the dispenser drawn out of the way. As melting action began, the dye dissolved and fluoresced due to an interior ultraviolet light source. The fluorescent brine clearly outlined the extent to which the bond between the ice and the concrete was dissolved. Color photographs of the melting action were taken through a plastic window in the freezer lid at appropriate intervals.

Selected photographs from an experiment at -12.2°C (10°F) are shown in black and white in Figures 13a & b. Continuing to quote from Sinke

SELECTED PHOTOGRAPHS SHOWING TECHNIQUE USED IN UNDERCUTTING STUDY

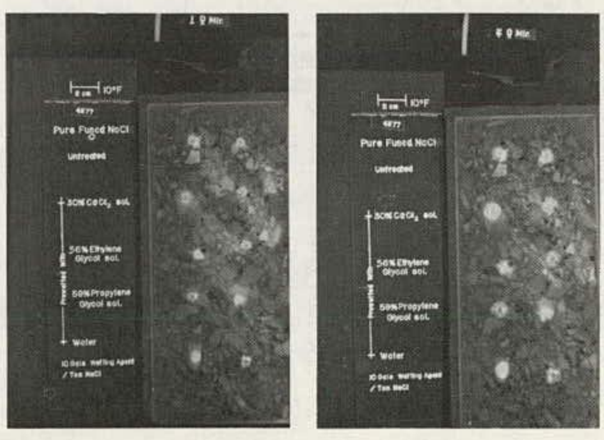

FIGURE 13a

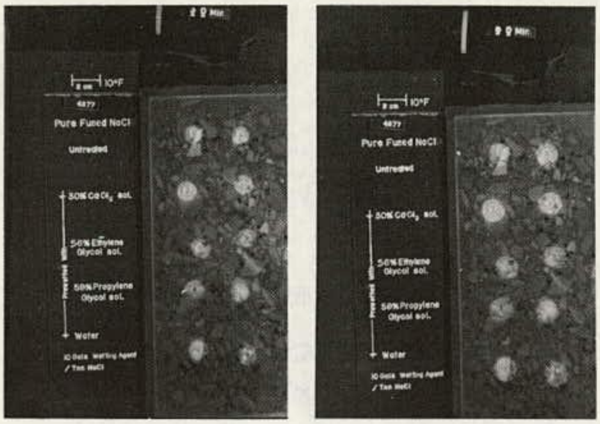

FIGURE 13 b

and Mossner (11):

> Unfortunately, the distinctiveness in melting and undercutting action evidenced in the colored photographs is not as clearly shown in the black and white copies. The initial hole melted through the ice becomes surrounded by a lighter colored area which is the thin layer of brine between the ice and concrete. The area "undercut" by each chemical particle is determined by comparison with the 2 cm standard length in each picture. The rate of ice melting as well as the ultimate area of undercutting can be determined in one experiment at a given temperature.

Penetration Studies

In this study a laboratory method for continuous observation of ice penetration was used. A block of ice approximately 2 cm x 2 cm x 8 cm was polished and the top surface branded with a linear grid design of four 2 cm x 2 cm squares. This effectively formed gutters and isolated each salt particle from its neighbors. The block was then placed into a commercial deep freeze. A mirror mounted at an angle of 45° was placed in front of the ice so that penetration could be viewed from above. The dispenser was then placed over the ice and the system described above allowed to attain steady-state at the desired temperature. The equipment was arranged as depicted in Figure 14 .

SKETCH OF PENETRATION STUDY EQUIPMENT

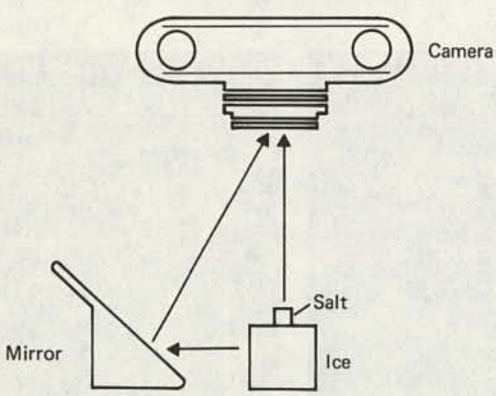

FIGURE 14

Two small fans circulated the air in the freezer to minimize temperature gradients and improve freezer efficiency. The salt particles were lightly dusted with the sodium salt of fluorescein and loaded into the dispenser. After the system reached the desired temperature, the salt was treated with the various "freeze-proof" wetting agents and the system returned to steady state. Prewetting with water was performed just prior to application of the salt to the ice surface. The dispenser was then actuated and drawn out of the way. As penetration proceeded, the sodium fluorescein dissolved and fluoresced underneath internally-mounted black lights. Color photographs of the progressing experiment were taken at appropriate intervals through the plexiglass window mounted in the freezer lid. Photographs from an experiment at -12.2°C (10°F) are shown in black and white in Figure 15.

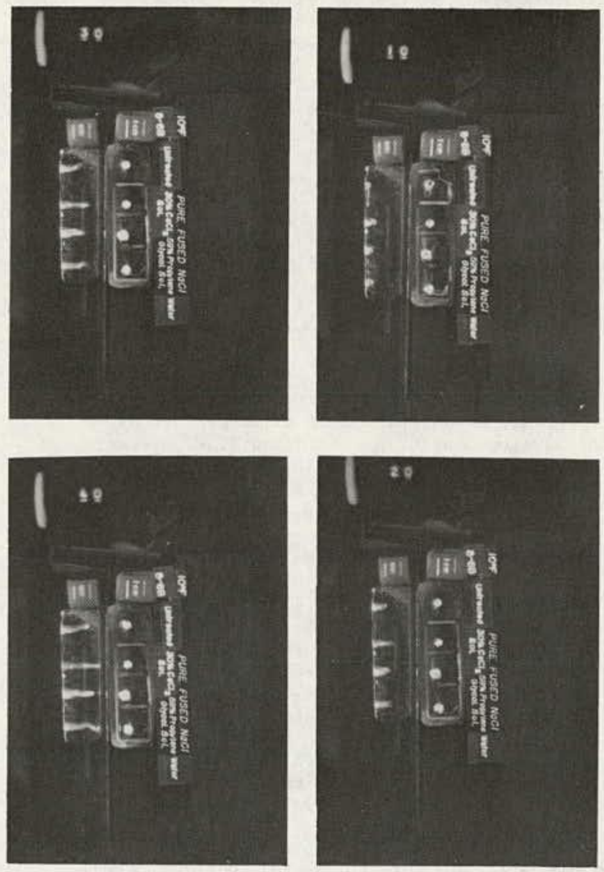

FIGURE 15

Preparation

Pure fused sodium chloride was used to reduce the number of random variables to a minimum ($CaSO_4$ concentration variance in particular, a common impurity present in Michigan rock salt (11)). All salt particles were cut to 60 mg ± 1 mg, a weight found by Sinke and Mossner (11) to represent the weight of approximately 60% of Michigan rock salt. Care was taken to produce cubic salt particles since variations in salt shape can adversely affect the reproducibility of the results. All prewet particles were treated with 2.5 microliter (µl) of wetting agent using a 10 µl syringe. The application rate of 2.5 µl/60 mg is equivalent to 10 gal/ton of rock salt.

Prewetting agent concentrations were adjusted so that each solution had a freezing point of -47.8°C (-54°F). Deionized water was used when water prewetting was studied.

Results

Undercutting Studies. A graph of the area undercut as a function of melting time and temperature is shown in Figure 16. An average of the results of all of the prewet salts is shown for convenience since all prewet salt results were very similar. In all cases, prewet salts were better than the dry salts with respect to the onset and extent of undercutting. The prewet curves are comprised of data from salts treated with 30% $CaCl_2$, the glycols, and water for the -6.7°C (20°F) and -12.2°C (10°F) runs, and only 30% $CaCl_2$ and the glycols for the -15.0°C (5°F) and -17.8°C (0°F) runs. Water was not used at -15°C (5°F) and -17.8°C (0°F) due to freezing problems.

AREA UNDERCUT BY PREWET AND UNTREATED NaCl AS A FUNCTION OF TIME AND TEMPERATURE

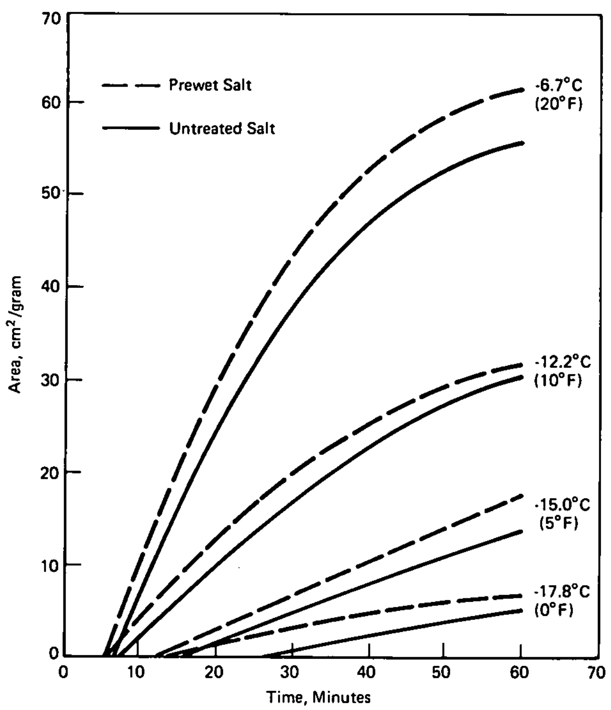

FIGURE 16

Penetration Studies. A graph of the depth of penetration as a function of melting time and temperature is shown in Figure 17. Due to the high rate of penetration shown by the salt at -12.2°C (10°F), the decision was made not to study the effects of prewetting at higher temperatures. An average of the results of all prewet salts is shown for convenience since all prewet salt results were very similar. The prewet curve at -12.2°C (10°F) is comprised of data from salts treated with 30% CaCl, 59% propylene glycol, and water. Water was not used at -15.0°C (5°F) and -17.8°C (0°F) due to freezing problems. The prewet salts have a higher initial penetration rate than the untreated salts. This initial rate soon decays to the rate of untreated salt since the prewetting agent is diluted and flushed away with the salt brine formed during penetration.

PENETRATION OF PREWET AND UNTREATED NaCl AS A FUNCTION OF TIME AND TEMPERATURE

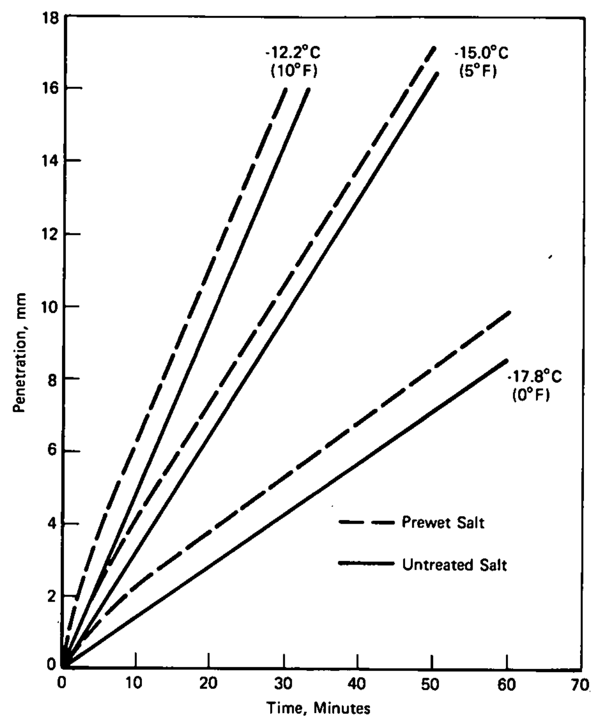

FIGURE 17

Discussion

From this research, it is shown that prewetting of pure fused NaCl increases the effectiveness of NaCl in both undercutting of a sheet of ice bonded to pavement and penetration of a block of ice.

The prewet data was generally in very good agreement for each run except at -15.0°C (5°F). Scatter was increased for both undercutting and penetration. It would appear that -15.0°C (5°F) is near the transition point from relatively fast reaction rates at -6.7°C (20°F) and -12.2°C (10°F) to the slow rates experienced at -17.8°C (0°F).

Results shown here may represent the minimum advantage that may be realized by prewetting rock salt since the pure fused NaCl contained none of the $CaSO_4$ found in regular highway rock salt. $CaSO_4$ was found by Sinke and Mossner (11) to reduce the melting action of regular rock salt. The increased ability of the prewet rock salt to form brine may overcome to some degree the slower reactivity of rock salt containing $CaSO_4$ because once a brine is formed, the NaCl around the $CaSO_4$ particle can be dissolved.

Also of great advantage is the reduction in the amount of prewet salt necessary to treat a given portion of roadway. This advantage is reflected not only in dollar savings due to reduced salt use, but also in a decreased burden of NaCl on the environment. Environmental damage could be reduced due to the lower rate of salt application and the significant reduction in salt bounce off and scatter (8). Figure 16 should be helpful in optimizing deicing operations. Water as a prewetting agent was considered for the sake of completeness. Its use in the field, however, is impractical, because rock salt prewet with water will freeze and clump.

Economic Analysis

Since all prewetting agents examined in this study were effective in increasing melting action of rock salt, an economic analysis of market prices of the various agents was conducted. The results of this analysis are shown in Figure 18. Calcium chloride prewetting is about one-fourteenth the cost of either glycol.

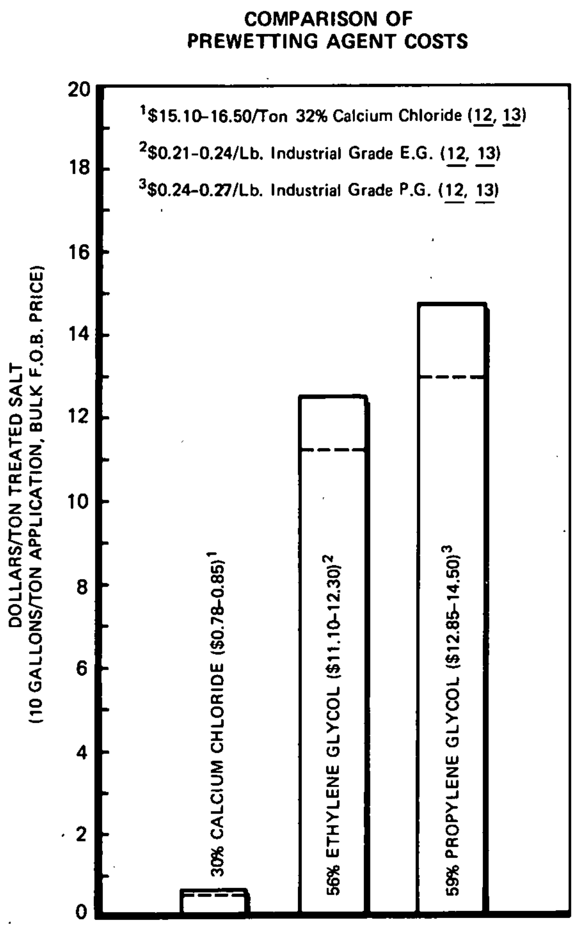

FIGURE 18

Conclusions

On the basis of the data obtained, the following conclusions may be drawn:

1. The use of rock salt with prewetting agents offers several advantages over untreated rock salt. Among these are increased melting action and decreased salt usage per mile which results in lower costs, greater productivity, and a probable reduction in NaCl damage to the surrounding environment.
2. Liquid calcium chloride is the most economical agent to use in prewetting of rock salt as shown by the cost data in Figure 18.
3. Liquid calcium chloride prewet salt provides a more efficient use of deicing chemicals, equipment and winter road maintenance budget when both performance and economics are considered.

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Detachment of Ice From Surfaces by Application of High Intensity Light

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A novel approach to the problem of detaching ice layers from surfaces is described. The primary problem is one of disrupting the bond of the frozen coating to the surface, at which point removal of the layer is a relatively simple matter. Some of the early methods that were examined at B. C. Research are described to show the progression which led finally to the subject technique. The use of high intensity light as the source of energy parallels the effect seen on a sunny winter's day, whereby, an ice coating exposed to the sun's rays experiences melting at the interface with the pavement surface. The advent of improved gas plasma arc lamps has provided the light intensity necessary to make this approach feasible for de-icing applications. A vehicle-mounted prototype de-icing unit that was field tested during the winter of 1977/78 is described and a brief discussion of the results and future prospects is presented.

De-icing Background

Our organization began working in the field of de-icing technology in 1969 in response to a request from the British Columbia Ministry of Highways and Public Works to investigate methods of removing ice layers from paved road surfaces. More specifically, the problem was defined as that of determining the best method of removing a frozen layer of 13 mm (½ inch) maximum thickness - this being the residual coating which could not be readily removed by conventional plowing without damage to the pavement surface. No chemical means were to be considered.

A program involving both theoretical and experimental studies was initiated and several different approaches were condidered in the early work, viz.

Simple Melting of the Layer

Technically, it would be possible to melt the entire coating using, perhaps, a gas-or oil-fired burner; however, the energy requirements would be enormous. A calculation was made to determine the fuel requirement, based on a maximum heat transfer efficiency of forty percent (40%), for 1 km (0.6 mi.) of a 3.66 m. (12 ft.) lane width and having a 13 mm (½ inch) coating of ice at $-10^{\circ}C$ ($+ 14^{\circ}F$.) ambient temperature. A minimum of 1200 ℓ. (317 U.S. gal.) of fuel oil per kilometer would be required. Also, the resulting volume of melt water would be over 42,000 ℓ. (11,000 U.S. gal.) per km., which would present a formidable disposal problem.

This approach, then, was rejected for three main reasons; (1) high fuel consumption, (2) low traverse speeds, and (3) flooding and/or refreezing complications resulting from the melt water.

Mechanical Detachment of the Coating

The work required to fracture ice is relatively little, so it is very tempting to try mechanical detachment methods. Our calculations showed that 75 watts (0.1 hp) would be needed to fracture a 13 mm (½ inch) thick ice layer along a 3.66 m. (12 ft.) lane width at a traverse speed of 24 km/h (15 mph). The fracturing was assumed to occur in 3 mm (1/8 inch) thick layers down to the interface with the road, but without separating the last thin film of ice residue from the base.

Other researchers[1,2] have shown that the physical strength of ice is often less than its adhesive force to other materials. In the case of an ice layer on pavement it has been found that using mechanical force on the ice coating will result in fracturing the ice, but not in separating it completely from the surface to which it is bonded.

Laboratory tests using a jack hammer with a spade tool and various narrower chisel-shaped tools showed that these were capable of chipping the ice away but, as predicted by theory, always left a thin film on the pavement surface. Over-enthusiastic use of the jack hammer removed the entire ice coating but not without damaging the underlying pavement. A compressive force applied normal to the ice surface through a blunt tool resulted in shattering of the ice in a flaking mode, but again left a thin layer of ice adhering to the pavement.

Because our tests indicated that the mechanical approaches were not completely effective in removing the ice coating from the road surface, we turned our efforts in new directions.

Other Methods

Next, a number of more exotic techniques were considered and some tested experimentally; viz.,

Microwave Power. The possibility that microwave power would be effective in detaching the ice was examined. However, the known dielectric constants and very low loss coefficients of both ice and asphalt pavement showed clearly that a very high voltage gradient and very large displacement current would be needed to produce the desired effect. Under such conditions the efficiency of power transfer would be very low and the service life of the equipment would be very short. No experimental verification was attempted.

Electrical Discharge. Sudden electrical discharges are known to exert disruptive forces on many insulation materials. In a laboratory test a ½ μf capacitor was charged to 25,000 volts and discharged against the surface of an ice-coated block of asphalt pavement material. Even a thin ice coating (3 mm/ 1/8 inch) was sufficient to resist penetration - the discharge was dissipated over the ice surface without causing any observable effect.

Vibration/Ultrasonics. Vibrations originating from a jack hammer had been tried and found ineffective. Vibrations from an ultrasonic source at approximately 22,000 Hz frequency were applied through a conventional acoustic transformer to the surface of an ice-coated pavement specimen. For low contact pressures flaking occurred at the surface. However, there was no indication of any disruptive effect at the ice/pavement interface.

Infrared Heating. A considerable amount of work was carried out in utilizing various forms of infrared heating as possible means of removing ice. Examination of the radiation absorption characteristics of the ice/water system, however, indicates that radiation in this wavelength region (2-50 microns) will be almost totally absorbed at the ice surface and, as such, amounts to no more than a variation of the simple melting methods tried (and rejected) in earlier work.

Visible and Near-Visible Radiation. Published data[3,4] on the properties of ice suggested that electromagnetic radiation in the visible and near-visible regions of the spectrum could pass through ice relatively unimpeded, but would be absorbed strongly by pavement materials. The implication was that the interface between the ice and the pavement might be heated selectively by such radiant energy. If the energy could be supplied to the interface at a faster rate than it was conducted away, then the interfacial temperature would rise to the melting point of ice, resulting in disruption of the ice/pavement bond.

Several laboratory experiments were conducted on ice-coated pavement sections and these confirmed that the bond disruption occurred as predicted.

In view of the promising aspects of this latter approach, subsequent work (1970 and onwards) was aimed at studying and developing this method of de-icing.

Visible Light Experimentation

A program was begun to measure parameters and, hopefully, to optimize efficiency and rate of ice removal for an ice detachment system using visible light energy. The early phase of the program began with both theoretical and experimental procedures.

An initial mathematical model was created to represent a static condition, wherein radiation incident onto an ice-coated surface and the rate of temperature rise was expressed in terms of energy input, thermal conductivity of ice, and the interface temperature. The expression had the form,

$$Q = \frac{W}{t} = \frac{a\Delta T}{\sqrt{t}}$$

, where W is amount of energy input to the ice/ pavement interface required to raise the temperature to the melting point of ice,
a is a constant,
ΔT is the difference between the initial temperature at the interface and the melting temperature of ice,
Q is the rate of energy input to the interface, and
t is the time required to reach the melting point of ice.

The important aspect of this relationship was, that if good efficiency was to be achieved, then a high rate of energy input to the interface would be essential.

Later, a second and more complex model was conceived to introduce the effect of motion of the energy source over the surface of the ice and to incorporate a term for the energy required to melt a thin film of ice at the interface (latent heat). The relationship derived was,

$$Q = bV + c\ \Delta T\sqrt{Vx}$$

, where Q is the rate of energy input to the interface per unit length of source,
b and c are constants,
V is the traverse velocity of the energy source,
ΔT is the difference between the interface temperature and the melting point of ice, and
x is the distance travelled in the traverse direction.

From this model, calculations were made to obtain a range of values relating energy input rate at various interface temperatures and traverse velocities to thicknesses of ice melted at the interface. Up to a limiting energy input rate, we were able to verify these calculations in laboratory and field experiments using very high intensity quartz/halogen lamps.

A series of experiments was carried out to measure the energy transmitted through an ice or snow layer for visible energy sources and therefore determine what fraction of the energy would be effective in producing heat at the interface. These tests showed that the optical transmission of clear ice peaked at about 0.47 microns wavelength and was high throughout the wavelength range 0.3 - 1.0 microns. Other experiments were conducted to verify theoretical relationships; such as, that the required input energy rate was a function of the square root of the traverse velocity. Still other tests showed that an ice coating was dependably detached from a pavement specimen when a 130 micron (0.005 inch) thick film of ice was melted at the interface and, also, that refreezing required more than five seconds after passage of the energy source for an ambient temperature of $-15^{\circ}C$ ($+5^{\circ}F$). Gradually, the data were accumulated that allowed us to design an ice-removal process. At this stage patent protection was sought (1974) and received[5].

During the course of these experiments it became evident that even the most intense light sources of the day did not have sufficient output energy density to enable our proposed machine to de-ice pavement at a high enough speed to be practical. Our prediction showed that 115 kw. of radiation was needed to reach the interface for each 30 cm. (1 ft.) of lane width in order to melt a 130 micron (0.005 inch) film of ice at 24 km/h (15 mph) traverse velocity and an ambient temperature of $-15^{\circ}C$ ($+ 5^{\circ}F$). An extensive search for a suitable high intensity source failed to uncover anything that looked promising, so the project was temporarily shelved.

Within a few months hope was suddenly revived by the publication of data on a potentially very high intensity light, based on the principle used in plasma arc welding. Groups of workers in several physics laboratories had been developing gas plasmas - highly ionized gases that are electrically conductive and, in many respects, behave as metallic resistance heaters. An electric current passing through such a plasma will heat it up to a steady-state temperature which is dependent on the balance between heat input and heat removal. Temperatures beyond $30,000^{\circ}C$ ($54,000^{\circ}F$) have been reached in reported laboratory tests. The elimination of the tungsten filament and its replacement by a gas plasma; such as, ionized argon, has led to a many fold increase in the radiant energy that could be produced heretofore. We followed the progress in plasma arc lamps with eager anticipation and, in fact, we worked in cooperation with one group at the University of British Columbia to conduct initial de-icing tests in their laboratory. Important developments were made in stabilizing the light output and prolonging electrode life until, by 1976, at least two companies were offering gas plasma arc lamps for sale commercially. Finally, we were able to organize the funding for a program to field test the concept of de-icing pavement using a vehicle-mounted plasma arc lamp.

A Prototype De-icing Equipment

During 1977 the construction of a prototype de-icing unit was completed in order to run field trials during the winter of 1977/78. The main components of the unit were, (1) the gas plasma arc lamp, (2) the downward facing water-cooled reflector, (3) the water-to-air heat exchanger, (4) the diesel-generator power supply and (5) the transporting vehicle. The lamp was specially modified for cold weather use and for transportability. The lamp length was 20 cm (8 inches) and required 100 kw of input power. The typical energy level emitting from the reflector was 20 kw approx. The reflector was contoured to focus the radiant energy in a line about 1 cm. (0.4 in.) wide at the road surface. The vehicle was a dump truck modified to operate at low speeds and to carry the arc lamp (with its heat exchanger) cantilevered out in front (see figure 1). The power supply was mounted in the dump box. A test site in central B.C. was selected and prepared for testing in the fall of 1977. Thermocouple wires were imbedded in the asphalt with the measuring junctions positioned half-buried at the surface.

Despite some initial difficulties, several test runs were made over the thermocouples at a variety of ambient temperatures with different coatings on the road surface for a range of traverse speeds. In each test run the temperature variations versus time were recorded.

Figure 1. Photograph of the vehicle-mounted prototype de-icing unit.

A comparison of measured and theoretical results revealed good correlation for clear ice coatings. Snow coatings, as expected, presented a more serious problem because of their inherently high reflectivity. A high percentage of the energy incident on the coating never reached the road surface, consequently the temperature rises recorded, even at very slow traverse speeds, were quite small (typically 20% of of those for a similar thickness of clear ice at the same traverse speed and temperature).

Conclusions

If the correlation between theoretical and actual results holds for higher power levels incident onto the coating, then to detach clear ice from pavement at 24 km/hr (15 mph) would require at least 120 kw per 30 cm (1 ft.) of lane width. The lamp used in the prototype de-icer produced approx. 30 kw per 30 cm (1 ft.) width. It is expected, however, that this could be at least doubled merely through improvements in (a) reflector contour and (b) the reflectivity of the reflector surface. Increases in lamp emission can be expected as the techniques of electrode cooling improve and conversion to other gases (e.g. xenon) or gas mixtures for the plasma is made. Other possibilities for increasing the radiant energy onto the road surface involve the use of multiple lamps.

The need for an environmentally acceptable and energy conserving technique for de-icing surfaces; such as, roads, airport runways, ships decks, etc., makes the future of the subject method appear very bright (no pun intended).

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Computer Simulation of Urban Snow Removal

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A general computer model to simulate urban snow removal has been developed. One part of the package includes several programs which assist in the routing of snow removal vehicles using computer graphics. The primary element, however, is a program which, once specific vehicle routes are input, allows the simulation of any particular snow removal scenario. Parameters that can be varied include both truck and snowstorm characteristics. This simulation program is tested using truck routes and storm data from Newington, Connecticut. Results indicate that the simulation predicts plowing times quite reasonably. Using the simulation model, the sensitivity of plowing time to storm length, accumulation rate and plowing start depth is examined. The plowing time exhibits a nonlinear relationship with accumulation rate, varying inversely with it, while the dependence on starting depth and storm length is linear for both. A route designed by the authors is tested against the actual route used in Newington, demonstrating a near-optimum configuration for the current Newington route with regard to the present resolution capabilities of the simulation program.

The winters of 1977 and 1978 demonstrated to much of the U.S. that snow and ice control on streets and highways is indeed a serious problem. Many midwestern and northeastern metropolitan areas were brought to catastrophic standstills for periods of several days. Numerous urban communities tremendously overspent their winter road maintenance budgets. All too often municipal budget planning, snow control included, takes place in the summer when winter road maintenance is conveniently out of mind. Annual expenditures for snow removal operations on state-maintained roads alone are 334 million dollars (1), and total urban expenditures are probably at least this high. Without a substantial improvement in the technology of snow removal, these costs are likely to continue to require a disproportionate amount of municipal budgets.

Optimum usage of a fleet of equipment owned by a municipality could trim these costs considerably as well as preparing it for more difficult winters. "Optimum equipment usage" is more than a phrase, and actual practice or experimentation is necessary. A snow removal emergency is no time for such testing, as critical situations call for only proven techniques (i.e. the way the streets were cleaned last year and the years before). These types of problems, however, lend themselves to computer simulation. A realistic snow removal simulation would allow many of the variables involved in the process to be assessed any time of the year in a rather convenient manner.

Simulations for snow removal have been attempted previously. Brown (2) developed a simulator called AID, designed specifically for the small town. Unfortunately, the program was too large for the computers to which most small towns have access. Experimentally it is a fine laboratory tool once an operator is trained to use it, as it contains practically every conceivable variable involved in the snow removal operation. Alprin (3) also simulated snow control (actually only salting and sanding) for the city of Tulsa, Oklahoma. This simulation has been used successfully for assessing truck routing and relocation of sand piles around the city (4). Snow plowing, including multiple passes to clear a street, overlapping routes, etc., was not considered in this model, however.

Our concern here was to develop a simulation package, usable by nearly any municipality, that will allow the important variables in that municipality's operations to be evaluated and new procedures to be tested before implementing them "on the road." This dictates having a straightforward simulation program that has a minimum of inputs, yet is able to handle the complex issues involved in snow removal. Our effort was aimed at only the snowplowing portion of road maintenance, but we see no obvious reason why the simulator, with some minor changes, cannot be applied to salting and sanding as well.

The snow removal simulation package was created in various program modules. First, a routing module was created that uses sophisticated computer graphics (certainly not available everywhere) to aid in the selection of optimum snowplow routes. (A simpler, yet still useful, version of this module without computer graphics is also available.) The other part of the package is the simulation program, with variable meteorological and equipment characteristics. The preselected routes plus the variable parameters are input, and plowing time for each piece of equipment is calculated. Thus far, both modules operate on a computer system with minimum storage and in fairly rapid execution time.

Snowplow Routing

Snow removal equipment routing is that phase of the operation which can potentially save the most money. Although certain methodology in the fields of graph theory and network analysis could aid in the routing problem (5, 6), the techniques are somewhat difficult to grasp and most city officials are out of touch with this type of technology. In many cases the routes followed are based on the drivers' experience, and these choices often may be close to optimum. Frequently, however, particularly in the larger urban areas where yearly personnel changes can be high, the routes followed are far from optimum. With the exception of a few cities that publish procedural manuals or plans, few attempts at routing improvement are made.

Straightforward routing problems are generally solvable using manual or heuristic methods (7, 8) as mentioned above, but efficient computer solutions to such problems are not available (6). Adding multiple street passes, priority routes and other complexities associated with snow removal to the routing problem makes even manual techniques difficult to implement. In this work, no attempt has been made to solve routing problems numerically, but we have developed techniques for interactive computer assistance to manual routing.

Each street in the network is numerically labeled and stored along with its characteristics (width, length, grade, normal speed) in a computer file. The time T_s required to clear that segment for the static case (no snow falling) is

$$T_s = N \cdot (L/V) + N \cdot C \qquad (1)$$

where: N = Number of passes required (segment width W_i/ effective plow width W_p)

L = Segment length

V = Velocity of the plow along the segment

C = Delay factor for intersection wait time (15 s)

A program has been written which uses equation 1 and accesses the file of segment characteristics. As a segment number is input (simulating a truck progressing along a route), cumulative plowing time is output. Time to plow any combination of segments in the static case can be rapidly determined.

The next logical step was to determine how long a particular vehicle should be plowing. For a given fleet of trucks having the same specifications, minimum plowing time T_{min} to clear the city is given by

$$T_{min} = \frac{1}{M} \sum_{i=1}^{N} \left(\frac{W_i}{W_p}\right) \cdot \left(\frac{L_i}{V}\right) + \left(\frac{W_i}{W_p}\right) \cdot C \qquad (2)$$

where: M = Total number of trucks

L_i = Street length

N = Number of streets

For a fleet of trucks with mixed specifications, a close approximation of the minimum time is

$$T_{min} = \frac{1}{M^2} \sum_{k=1}^{M} \sum_{i=1}^{N} \left(\frac{W_i}{W_k}\right) \cdot \left(\frac{L_i}{V}\right) + \left(\frac{W_i}{W_k}\right) \cdot C \qquad (3)$$

where: W_k = Effective plow width for each of the trucks.

This time is approximate because exactly which streets will be plowed by each truck is unknown at this point.

Knowing the optimum plowing time for a fleet and having the program which handles the bookkeeping (using equation 1), one uses an interactive computer terminal to key in the numbered streets over which the plowing vehicle progresses. An assumption basic to the entire simulation package is that individual vehicle routes are repeatable by that same vehicle. Therefore, when the cumulative plowing time from the interactive program nears the optimum plowing time, the vehicle should be approaching its starting point, establishing the repeatable route. As the route is ended, the keyed-in segment numbers are output to a storage device, saving them for the actual simulations to be made later. While optimum routes in the strictest sense of the word may be difficult to achieve, certainly routes of high efficiency may be constructed rapidly using these techniques.

The laboratory version of this routing module makes use of a cathode ray tube (CRT) interactive graphics terminal to display the network, and routes are keyed in using a lighted cursor on the screen. Contrary to statements made in Tucker (9) concerning the wide availability of such devices, we have learned that most municipalities would have difficulty obtaining a graphics terminal. Most, however, could get access to some sort of more conventional terminal and a time sharing computer system. We also have discovered severe limitations as to the size of the network which may be displayed on the graphics terminal. However, the laboratory model will continue to use the CRT terminal when possible as the keying in of routes is much more rapid on it than on the conventional terminal.

Snow Removal Simulation Model

Once the various repeatable routes for a municipality are established, another computer program allows the simulation of any particular snow removal operation by permitting both meteorological and equipment parameters to be varied. Variable snowstorm parameters are storm length, rate of snowfall, snow density and storm starting time. Truck and route variables are truck weight, plow weight, plow width, normal plowing speed, route starting depth and route starting time. Truck routes are also input to the program and the file containing segment characteristics must be accessible.

Time to clear any network once the number of trucks and their routes are fixed depends on the length of storm, plow width and the velocity that the plows can maintain. Initial velocity over any segment is taken to be the lesser of normal truck plowing speed or normal traffic speed along the segment reduced by a constant amount for hazardous conditions. Additionally, the plowing force available to the truck is calculated to determine if it is adequate to remove the amount of snow in its path at the given velocity. If not, the velocity is reduced until the forces are balanced. Tanaka (10) developed the equation for the force required of a specified truck to remove the given amount of snow.

$$F_R = R_r + R_s + R_p \tag{4}$$

where: R_r = Truck rolling resistance

R_s = Plow sliding resistance

R_p = Plow snow-removing resistance.

R_r, R_s and R_p can be further defined as

$$R_r = W_t\ (0.000123\ V + 0.05) \tag{5}$$

$$R_s = 0.41\ W_p \tag{6}$$

$$R_p = \rho s\ (0.00139\ V^2 + 0.005\ V + 0.331) \tag{7}$$

where W_t = Truck weight

W_p = Plow weight

V = Truck velocity

ρ = Snow density

s = Cross-sectional area of snow being removed

All numerical constants were empirically determined by Tanaka (10). Force available to the truck is given by:

$$F_T = P/V \tag{8}$$

where: P = truck horsepower.

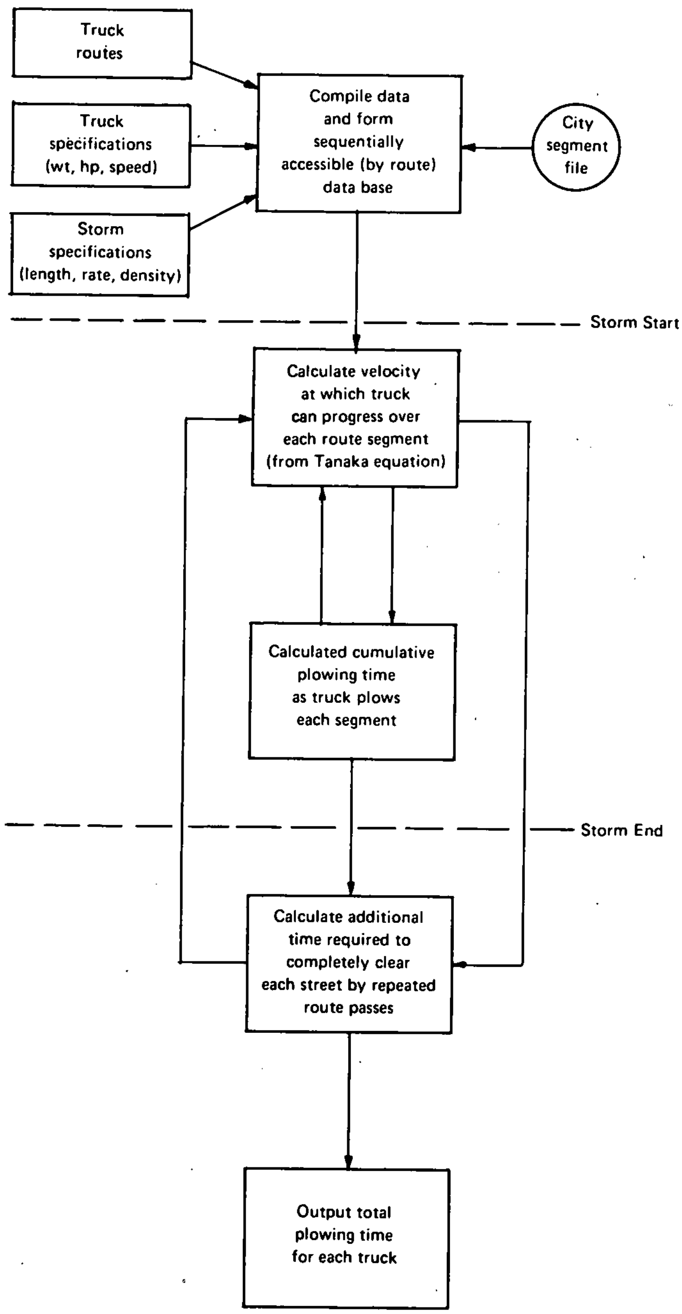
When both forces are calculated, velocity is reduced until $F_T \geq F_R$. As pointed out in Tucker (9), the condition for reduced velocity as dictated by this technique in an urban area is rarely encountered. It is included in the simulation model however, until more applicable relationships are developed.

Time that plowing commences is dictated by two input variables, the minimum depth and the plowing start time. The time for the roads to accumulate the minimum depth is calculated and compared against the specified start time. The earlier of the two times is chosen for plowing on this particular route to commence. This allows the option of either holding out for a certain starting depth or a certain time, for example, very early in the morning prior to rush hour.

Another consideration taken into account by the simulation is plowing windrow - the extra amount of snow which is cast into the next pass lane (to the right). We currently incorporate windrow by adding one-quarter of the depth of snow just plowed to that depth to be plowed on the next pass. This consideration is also marked for modification as soon as empirical data give us better relationships for the effects of windrow on truck velocity.

Summarizing the operation of the simulation program, plowing by a truck begins in time when the designated depth or time first occurs. Each truck progresses through its route, removing one blade width of snow from each segment along the route. Velocity along each segment is calculated, and from this, the time to make the pass is computed and added to the cumulative time of the truck. The width of the uncleared part of the street and depth of snow on it are stored in status registers. At designated constant intervals (presently 7.5 min), these street status registers are examined and new depths are calculated if snow is still falling. The truck continues to make additional passes on its route until the storm has concluded and the streets contain less than a specified depth (1 in.) of snow. A block diagram of the simulation program is presented in Figure 1.

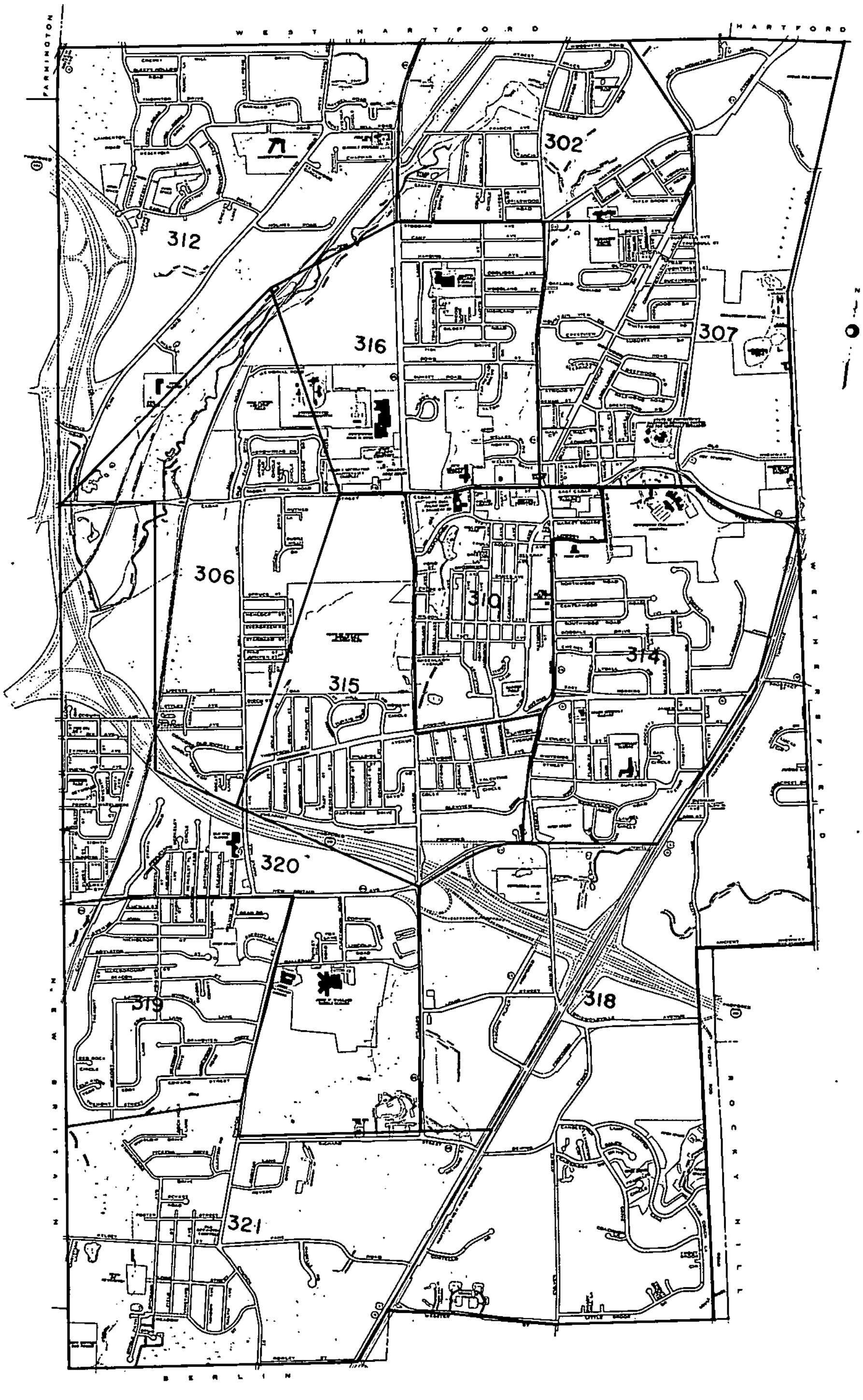
Figure 1. Block diagram of snow removal simulation model.



Validation of the Simulation Model

In previous reports (9, 11), the simulation program was demonstrated using arbitrary data, thought to be representative of actual cases. The results of these earlier tests appeared reasonable, but we had no means of actually assessing the validity of the output. For this study, however, a detailed validation effort has been undertaken using the town of Newington, Connecticut, as a test base. Newington, population 26,000, has a very efficient snow removal program proven by its performance during past severe snowstorms. In addition, highway administration personnel in Newington had an adequate collection of storm and operation data and spent a great deal of time preparing and coding data for the segment file. Newington also has a street layout, topography and problems (parking, etc.) typical of much larger cities. The only apparent disadvantage in working with Newington is that their snow removal operation seemed so efficient that the program, once validated, would be of little use in pointing out possible improvements.

Figure 2. Newington, Connecticut, with assigned truck sections.



The city is divided into 12 sections as shown in Figure 2, with each section assigned to a specific truck. Table 1 gives the equipment specifications for each truck, as represented by the section number that it is responsible for plowing.

Table 1. Truck specifications. (For all trucks the plow weight was taken as 3000 lb (1361 kg), the effective plow width as 8.5 ft (2.6 m) the normal plowing speed as 16 mi/hr (25.7 km/hr).

Section No.	Truck Weight (lb)	(kg)	Horse-power
302	37,000	16783	290
306	29,000	13154	200
307	37,000	16783	290
310	37,000	16783	190
312	29,000	13154	200
314	37,000	16783	210
315	37,000	16783	290
316	29,000	13154	200
318	37,000	16783	210
319	37,000	16783	210
320	37,000	16783	210
321	37,000	16783	210

Highway department personnel also provided the actual routes that the drivers generally follow. It was to our satisfaction to find that the majority of the drivers follow the same general route each storm, and that they repeat that route during an individual storm until all streets on the route are clear. While the findings thus far were consistent with methodology applied within the program, several situations were not. On several major city streets, tandem plowing operations are routinely used. Generally this is handled by the truck in whose section the priority street lies, with the next closest truck coming to assist. This cannot be exactly simulated in the program, but the situation is handled in a sense by having that same segment in both route files. The status of the segment then reflects the operations of both trucks. Where the program fails in this respect is that the times of plowing the segment by the two trucks could be quite different, far from simultaneous. Another problem in the simulation occurs when the storm has ended and all but a few segments are completely clear. The program has the truck continue on its assigned route until these segments are clear. In an actual operation the truck would proceed directly to the unclean segments by the shortest route. The impact of this discrepancy in the Newington case is suspected to be small as the routes are short. For the simulation test runs, no use was made of the routing programs as the routes were provided. Routes were simply taken from maps, coded by segment number and input to a computer file.

Five reasonably large snowstorms were chosen for simulation testing. For each storm, only one clearing time was provided, that supposedly being the average of all trucks. In general, trucks will move to another route and assist if their own route is completed early. Table 2 shows the results of our computer runs for each storm with the calculated plowing time to clear each section presented. Also we show an average calculated plowing time as well as the observed completion time. In all cases the plowing began when the snow reached a depth of 0.5 in (1.27 cm) and the snow density was a constant 12.49 lb/ft^3 (200 kg/m^3).

Table 2. Route plowing times (hr) for various storms.

Route No.	Length (mi)	Storm 1 Length=14.5 hr Rate=0.28 in./hr (0.71 cm/hr)	Storm 2 16.5 hr 0.55 in./hr (1.39 cm/hr)	Storm 3 15.0 hr 0.20 in./hr (0.50 cm/hr)	Storm 4 24.0 hr 0.25 in./hr (0.64 cm/hr)	Storm 5 16.0 hr 0.44 in./hr (1.12 cm/hr)
302	5.56	14.9	18.3	14.9	24.7	17.5
306	6.95	14.1	18.5	13.9	23.4	17.8
307	6.0	17.2	20.5	16.0	26.4	19.3
310	6.4	15.6	19.0	15.7	25.4	18.3
312	8.6	16.4	19.7	16.2	25.9	18.8
314	9.15	14.6	18.8	14.5	24.2	18.0
315	6.1	15.4	18.4	15.3	24.6	17.9
316	5.67	15.1	18.3	14.7	23.9	17.6
318	5.76	15.3	18.8	15.5	24.9	18.3
319	7.71	15.3	18.8	15.5	24.9	18.0
320	6.01	15.4	18.5	15.5	23.9	17.8
321	8.05	14.9	19.0	14.9	24.9	18.3
Average		15.3	18.8	15.2	24.7	18.1
Observed		15.5	17.5	16.0	25.0	17.0

Table 2 shows a wide variability in completion times among different routes for a single storm. Also, upon examination of different storms, a consistent imbalance for some of the routes becomes obvious. For example, route 312 always requires more than the average time for completion. This route could possibly be shortened, giving excess segments to an adjoining route, say 302, that may show less than average completion times. It is our understanding that imbalances such as this are resolved in Newington by distributing the routes according to driver ability.

Another interesting fact is that section plowing times seem to have very little correlation with the overall length of the section. While not obvious, this is to be expected because the plowing time as calculated is a function of the number of intersections and the width of segments as well as the length of the route. In fact, the number of intersections varies from a minimum of 69 (section 318) to a maximum of 224 (section 307) for each route pass. This accounts for a 0.65-hour time difference alone, for each complete traverse of the route, at 15 seconds delay time per intersection. While segment widths are more nearly standard (13 to 14 ft), a few of the main streets are significantly wider, causing more passes of the route to be necessary for complete clearing.

Of major interest in Table 2, however, is the comparison of the calculated completion times with the observed completion times. For storms 1, 3 and 4, the calculated average plowing times are less than the observed, while for storms 2 and 5, the calculated times are significantly longer than the observed times. Examination of storm characteristics shows that storms 2 and 5 had accumulation rates significantly higher than the other storms. The inference here is that at higher accumulation rates near (in time) the storm end, with each traverse of the route the truck is plowing only the leftmost plow width of each segment. This is necessary because the segments at the beginning of the route have accumulated the minimum plowing depth by the time the truck finishes a complete pass and is ready to repeat the route. In the case of the lower accumulation rates, the truck may easily complete a traverse before the depth on the previously cleared leftmost passes of the segments at the beginning of the route is again up to minimum plowing depth. Since the accumulated depth is not up to the specified depth, the truck proceeds to plow the remaining width of each segment (progressing to the right curb). If the storm ends when these leftmost segments contain less than the minimum depth of snow, route completion time is significantly reduced. It is also significant to mention that the observed plowing times are exactly the storm length plus 1 hour for all cases. Here, we tend to believe that the observed data may be in error for the higher accumulation rates. Chapman (Newington assistant highway supervisor, personal communication) confirms that the data are somewhat speculative.

In general the validation results are encouraging. We feel that for a "first order" simulation model, the predictions are reasonable and that the simulation model can be used in its present form with confidence. These tests have also pointed out areas in the program where improvements are most justified; these will be discussed later.

Sensitivity Examination

For evaluation of what appear to be key parameters in the snow removal operation, it was decided to make demonstration runs on only one particular route. Section 321 was chosen as being fairly representative of the average performance of all routes for the five storms. Also, as discussed later in this section, section 321 has what appears to be a near-optimum routing.

Probably the most obvious parameter to examine is storm length. Figure 3 shows plowing time vs. storm length for four accumulation rates. All other parameters remained fixed for the simulation runs. Not surprisingly, the relationship for all rates is linear. For the 0.5-in./hr (1.27 cm/hr) accumulation rate

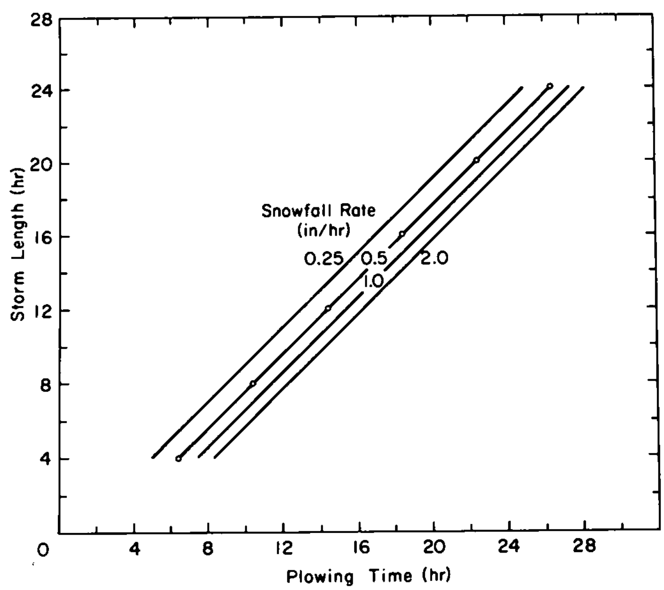
$$T_p = L_s + 2.46 \qquad (9)$$

where: T_p = Plowing time in hours

L_s = Storm length in hours

The numerical constant (2.46) is the time required to completely clear the route after cessation of the snowfall. As Figure 3 shows, only this constant varies with a change in accumulation rate. As mentioned earlier, this variation is a function of the route traverse time and the status of each segment when the storm ends. The implication of this linear relationship is that for a municipality, once these sorts of sensitivity evaluations are conducted, plowing times can be accurately predicted at weather forecast time (depending, of course, on the accuracy of the forecast). For fixed routes, only a few expressions of the form of equation 9 for different accumulation rates need be determined and kept on hand. Newington, for example, presently uses the "storm length plus one hour" rule of thumb to predict plowing times.

Figure 3. Plowing time versus storm length on route 321 for four accumulation rates. The snow density was 12.49 lb/ft^3. (200 kg/m^3) and the starting depth was 0.5 in (1.27 cm).

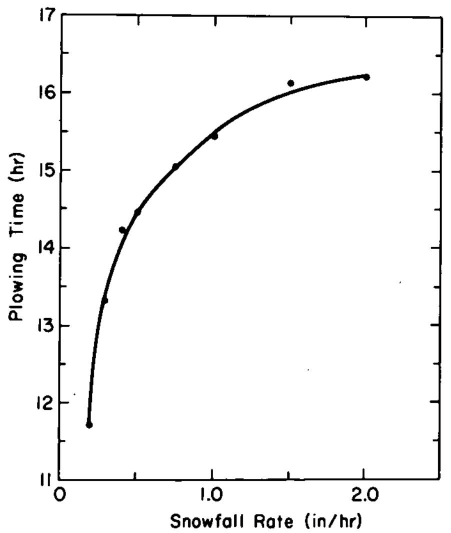


As the simulation shows a great sensitivity to accumulation rate combined with the fact that this seems to be the critical factor in the calculated plowing time discrepancies with Newington, a more detailed examination of this parameter is warranted. Figure 4 shows the sensitivity of plowing time to accumulation rate. Here the rate was varied while holding all other parameters constant for a 12-hour storm. In contrast to the convenient linear relationship that was established with storm length we find a nonlinear dependence which is best fit by a regression line of the form:

$$T_p = 16.57 - 0.983/r \quad (10)$$

where: r = Accumulation rate in inches per hour

Figure 4. Plowing time versus accumulation rate on route 321 for a 12-hour storm. Snow density was 12.49 lb/ft.^{3} (200 kg/m^3) and the starting depth was 0.5 in. (1.27 cm).

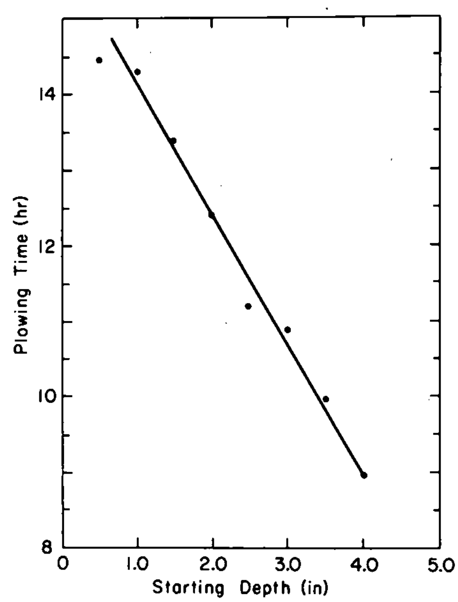


As a result of this inverse relationship, the constants in this case do not represent anything physically meaningful. The significant effect here is that changes in accumulation rate below 1.0 in./hr (2.54 cm/hr) drastically affect total plowing time while at rates greater than 1.0 in./hr (2.54 cm/hr) the curve becomes asymptotic, with very little increase in plowing time. The 1.0 in./hr (2.54 cm/hr) rate appears to be the point above which the entire route must be cleared at storm end. At this high accumulation rate the truck is merely repeating the first pass on each street until snowfall has ceased. Any increase in total plowing time after this point is caused by the fact that the truck must begin plowing earlier, the starting criterion being the 0.5-in. (1.27 cm) snow depth in all cases.

Although the sensitivity to accumulation rate is not reflected in the Newington data, we tend to believe that it is a real effect. Admittedly the variation in observed rates in our validation tests was small (0.20 to 0.55 in./hr), but we feel that if records were more carefully maintained, the effect would be noticeable. It is not advocated, however, that real plowing times would be as sensitive to the rates as the simulation program predicts. In fact, the sensitivity may be somewhat less than that shown by the simulation, due to the fact that a driver can use discretion, and the computer must make a decision based on predetermined criteria.

A municipality has no control over storm length or accumulation rate. But one parameter in a fixed-route, fixed-equipment system that can be varied which significantly impacts total plowing time is the starting depth. Figure 5 shows this impact as calculated by the simulation program. By delaying the starting depth from 1 in. (2.54 cm) to 4 in. (10.2 cm) on a 12-hour storm with a 0.5-in./hr (1.27 cm/hr) accumulation rate, approximately 5 hours of total plowing time is saved. Substantial economic benefits can be derived from this practice, and in fact the technique is well known and used in many Northern New England communities, particularly during storms that occur overnight. On the other hand, larger, more populated areas may have difficulty implementing the technique due to the obvious hazards that may result. It may be possible, however, to delay the plowing of certain low priority routes during nighttime snowfalls. Once again this sort of relationship derived from the simulation is linear, and once it is established for a given route, the time savings can be quickly calculated for any storm length. Only several curves or equations characterizing different accumulation rates need be created.

Figure 5. Plowing time versus starting depth on route 321 for a 12-hour storm. Snow density was 12.49 lb/ft.^{3} (200 kg/m^3) and the accumulation rate was 0.5 in./hr. (1.27 cm).

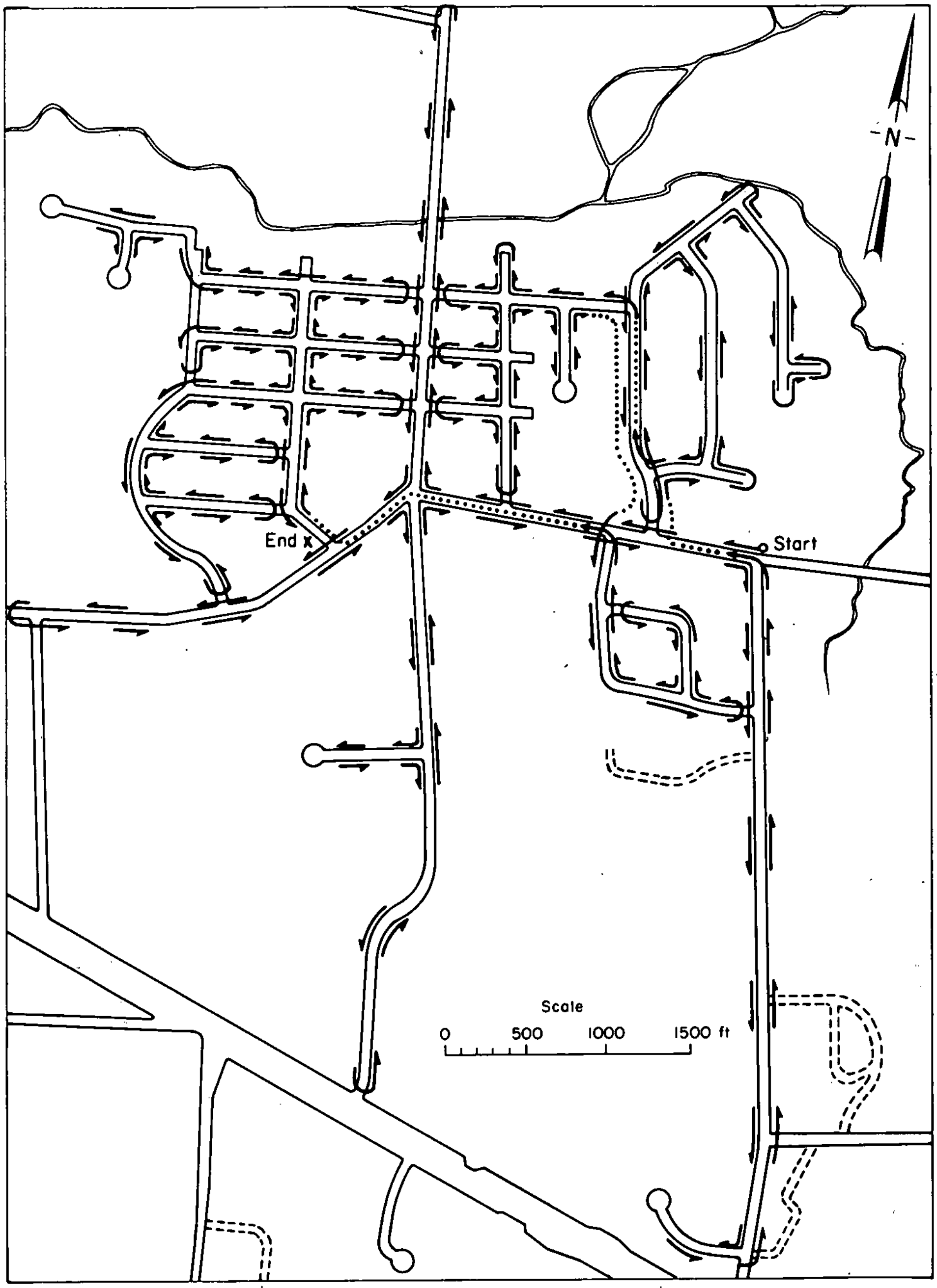


Although the simulation program cannot design optimum routes, it may be used to test different routing strategies. As a test case we attempted to design an optimum route for section 321. Figure 6a shows the route presently followed by the driver on route 321. Figure 6b is our version of what could be a near-optimum route. It is worth mentioning that our routing strategy consisted of the following guidelines:

1. As few intersection U-turns as possible.
2. As few left turns as possible.
3. As little "deadheading" as possible.
4. Completion of plowing at the starting point.

We were able to adhere to all of the above rules fairly rigidly except for left turns. It was found necessary to make left turns often in order to avoid U-turns at intersections. Although the program does not discern types of turns but uses a constant 15-second penalty at intersections, we believed, when the route was designed, that intersection U-turns (or intersection clearing "k-turns") would be costly in time as well as difficult to execute if other vehicles were using the

Figure 6a. Snowplow routing for Newington, section 321. Route currently used.



streets. Studying Figure 6a, apparently the belief in Newington is that these turns are necessary and efficient. As they are used successfully there, our ideas have also since changed, but for demonstration purposes we shall use the route layout previously designed. Table 3 shows the completion times for both routes for the five storms used in earlier tests.

The Newington route is more efficient in 3 of the 5 cases and our route is superior for the other cases; however, all differences are small. Because the completion times are nearly equal for both routing strategies it is difficult to pick an overall superior route based on program results. The differences in times obviously depend on subleties such as the status of the segments and position of the truck when the storm ends. The facts that the priority (also wider) streets are traversed early in the Newington routing and that some of these wider segments are crossed twice in the routing seems to give it some advantage for the storms with lower accumulation rates (1,3,4). On the other hand, our route appears to benefit from having a slightly shorter single traverse time (known from other program output information) for the higher accumulation rate storms (2,5). Considering other factors, one would expect the U-turns in the Newington route to be costly in time if the simulation accounted for them. In

Figure 6b. Snowplow routing for Newington, section 321. Route designed by the authors.

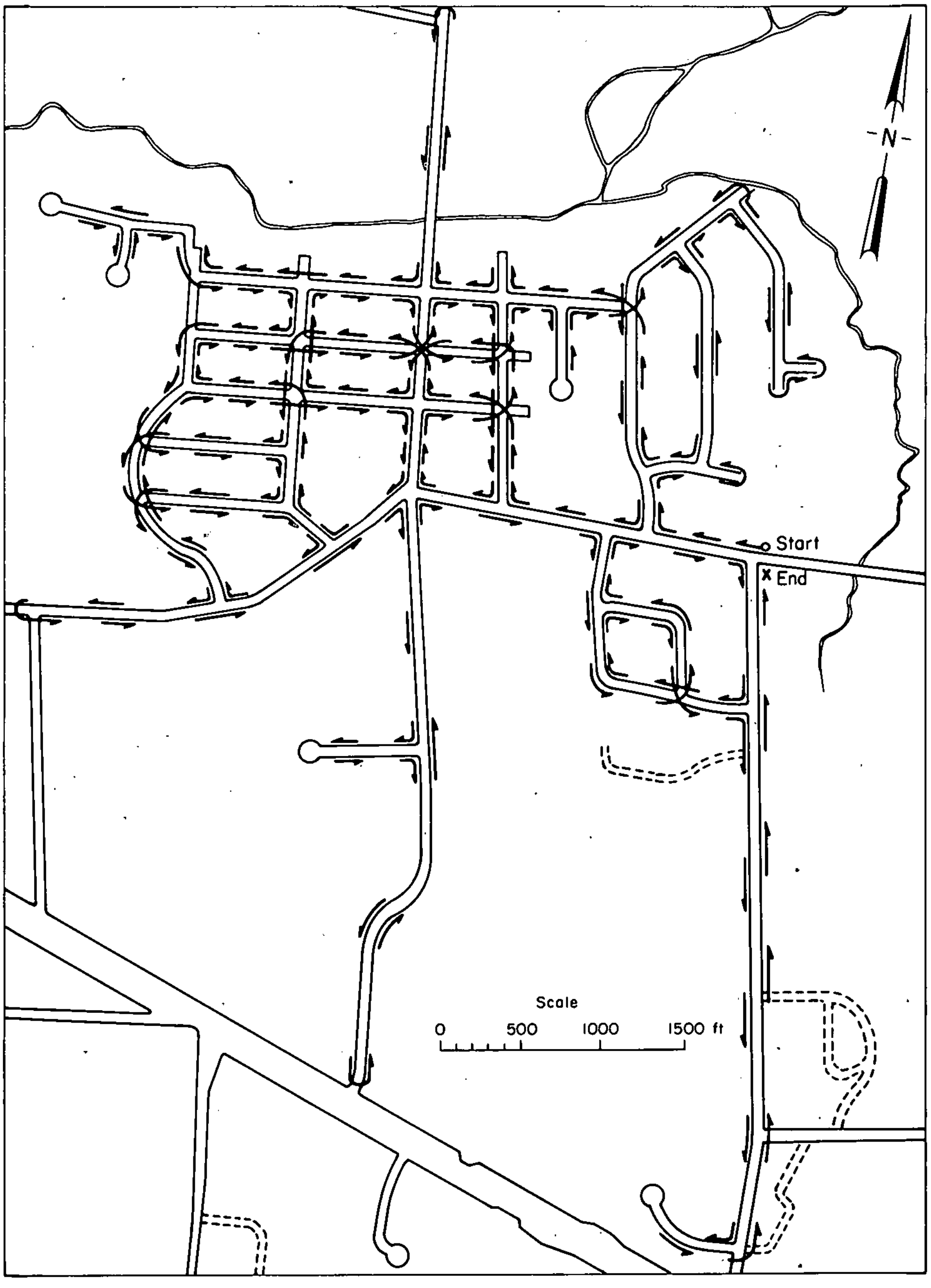


Table 3. Comparison of different routes for section 321 (time in hours).

	Storm 1 Length=14.5 hr Rate = 0.28 in./hr (0.71 cm/hr)	Storm 2 16.5 hr 0.55 in./hr (1.39 cm/hr)	Storm 3 15 hr 0.20 in./hr (0.50 cm/hr)	Storm 4 24 hr 0.25 in./hr (0.64 cm/hr)	Storm 5 16 hr 0.44 in./hr (1.12 cm/hr)
Newington Route	14.9	19.0	14.9	24.9	18.3
Authors' Route	15.6	18.8	15.4	25.0	18.0

contrast, however, the efficiency of removing snow from the intersections in our route is apparently lost, in particular with left turns. In reality this may require separate trips back to those intersections to completely clean them. This debate, however, is beyond the scope of this study, and beyond the resolution of the simulation without an additional programming effort. The point to be made here is that the simulation can now be utilized to test routings that are a function of length, number of intersections, and the amount of deadheading. Modification of the program will be necessary if the degree of efficiency of routes is to include the type of turns and cleanout procedures used at intersections.

Conclusions

The results of the validation tests on Newington are encouraging for a "first order" simulation scheme. Considering the fact that program constants or calculation procedures were not changed during the evaluation, we are especially satisfied that our original concepts seem to be adequate. It is also believed that our results would appear reasonable for storms with higher accumulation rates if additional data were available.

The simulation can be used in its present form to assess the sensitivity of a municipality to certain storm parameters. Plowing times will almost certainly have a linear response to storms of different lengths having the same accumulation rate. The effect that various snowfall rates will have seems to be a parameter that warrants further serious study. It seems intuitive that there should be a nonlinear response to accumulation rate as the program is showing. Once these parameters are examined with the simulation, a municipality can keep only equations or graphs on file for any potential equipment or route mix. Potential savings from such tactics as delaying the start of a plowing operation can be quickly calculated from the data on file.

The simulation program can be used to quickly assess the relative efficiency of various routing strategies as far as route length, number of intersections and amount of deadheading are concerned. Program modifications are necessary if the effect of the various intersection maneuvers is to be incorporated. The consequences of the operations should also be considered, however. That is, while left and right turns may be more efficient in time as far as normal route traverses are concerned, some sacrifice in time may be required for the truck to return at some point and completely clear the intersections. Another area of the program that should be improved is the slowing of the plow because of deeper snow. Although the speed of the truck appears to be more regulated by factors other than snow characteristics (i.e. curves, traffic, grade, etc.), it would be useful to have relationships which describe truck performance when the snowfall or windrow is extreme. Both of these potential modifications require further study of actual snow removal operations to obtain reasonable empirical relationships.

We feel that the general simulation model presented here would perform adequately in most communities. With the small improvements mentioned above, better plowing time predictions should be possible. If a community requires very accurate simulations, certain factors characteristic of that community may be added to the present program with little difficulty.

Acknowledgments

This work was supported by NSF Grant No. APR 75-0621A02 and DA Project No. 4A161102AT2401. We thank Mr. Robert MacDonald of the Connecticut Conference of Municipalities for spurring us into testing the laboratory model in a real situation and for initiating contact between ourselves and Newington. We owe a great deal of thanks to the Newington, Connecticut, Highway Department, particularly Mr. Keith Chapman, for providing us with the base data set and for many facts on snow removal procedures in Newington. We also thank Ms. Margaret Kulos for many helpful suggestions.

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Countermeasures Against Snow Accretion and Icing on Radomes

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Television broadcasting through an artificial satellite calls for a task of solving various problems of propagation of electromagnetic waves in snowy countries, where serious problems of attention is paied to removal of snow accreted on the surface of a radome covering a receiving aerial. Since the wavelengths of electromagnetic waves to be used in satellite broadcasting are extremely short, they are easily absorbed by liquid phase existing in wet snow. The rate of attenuation of a 24-GHz wave was measured as a function of thickness of a water film and found to be 18 dB/mm. One of the most convenient and economical devices to remove wet snow deposited on a radome surface was to rotate the radome at the rate of 100∼1400 r.p.m.. Meanwhile, brushing of the surface of a rotating radome was found effective in removal of rime deposits formed by freezing of supercooled water droplets thereon.

This paper contains some investigation results and countermeasures against snow and ice accretion on the surface of a radome covering a receiving aerial.

Effects of Snow Accretion on a Radome

Television broadcasting through an artificial satellite is being planned in various countries, using electromagnetic waves in the range of 10∼30 GHz. How to prevent antennas from snow accretion may become a serious problem in snowy districts, because the elevation of a receiving antenna aimed to a satellite resting above the equator should be set at a fairly high angle, e.g., 37° in Tokyo and 30° in Sapporo. Therefore, the upward facing surface of a parabolic antenna allows easy accumulation of snow, causing much attenuation of the intensity of the electromagnetic waves received by the antenna. One of the convenient ways to prevent the antenna from snow accretion is to cover it with a plastic dome composed of a low-dielectric loss material, so-called "radome". However, further problem may arise from how to prevent the surface of the radome from snow accretion.

Y. Asami et al. (1) investigated microwave propagation in 1958 in snowy districts in Japan, whereby showed that snow or rime deposited on antennas did not cause any significant trouble for the propagation of microwaves unless accreted snow or rime contained much free water in it. This suggests that, if wet snow accretes or deposited dry snow begins to melt on the surface of a radome, the energy of a microwave received by an antenna may be significantly reduced by the absorption of free water existing in snow. The purpose of this paper is to show the rate of attnuation of an electromagnetic wave ranged in 10∼30 GHz by absorption of the free water and to find a convenient and economical devise to remove snow or rime from the surface of a radome.

Absorption of a 24-GHz Wave by a Water Film on a Radome Surface

Michiya Suzuki, (2) Mitsuhiro Ono and Yasuo Nomura made in 1973 a simple experiment on the attenuation of an electromagnetic wave by absorption of a water film, using a 24-GHz wave (1.25 cm in wavelength), one of the waves to be used in satellite broadcasting in future. As shown in Figure 1, the 24-GHz wave was emitted perpendicularly against a plastic board (0.5 m × 0.5 m; 1 cm in thickness), where water was continuously flowed on its surface. A sensitive receiver was placed behind the board to measure the attenuation of the wave which passed the board. Since the surface of the plastic boad was hydrophobic, a sheet of gauze was stretched on the surface to maintain flowing water in a uniform thickness.

When the surface of the plastic board was dry, the attenuation of only 0.2 dB was observed. While water began to flow uniformly through the gauze, the attenuation increased as a function of the thickness of water film or the flow rate of water as shown in Figure 2, a, where a solid line indicates theoretical values of attenuation calculated by the formula given by Hippel (1961) on the assumption that numerical values of dielectric constant and loss factor of free water in the range of 24 GHz are 34 and 0.265, respectively. As seen in this

Figure 1 Block diagram to measure the attenuation of a 24-GHz wave by absorption of a water film
K: Transmitter of a 24-GHz wave
R: Sensitive receiver
SA: Absorber of an electromagnetic wave
SP: Plastic board (0.5 m × 0.5 m; thickness 1 cm)
W: Water flow on the surface of the plastic board

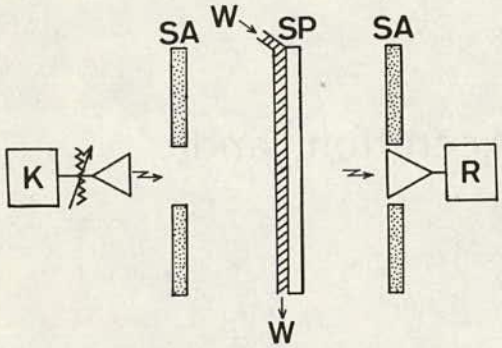
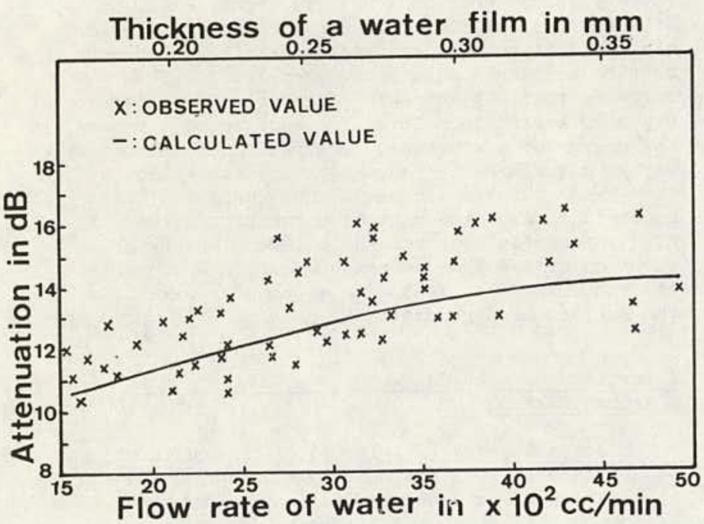


Figure 2 Attenuation factor vs. thickness of water film and flow rate of water



figure, the rate of attenuation of the 24-GHz wave by a water film found to be approximately 18 dB/mm.

It should be noted, however, that, when poured water flowed down in the form of strings, as shown in Figure 3, the attenuation depended upon the percentage of area screened by stringing water. This expermental result strongly suggests that wet snow deposited on the surface of a radome reduces significantly the intensity of an electromagnetic wave. In acuality, it has been reported (3) that wet snow deposited in thickness of about 0.33 m on a radome surface attenuated the intensity of a 11-GHz wave in value of 8.5 dB.

Shape of Snow Deposited on a Radome

In order to find a convenient and economical devise to remove snow accreted on a radome surface, two types of radomes, i.e. cone- (or umbrella-) type radome and spherical radome were tested in our investigation. The typical shape of snow deposited on a radome placed in a natural snowfall is studied first.

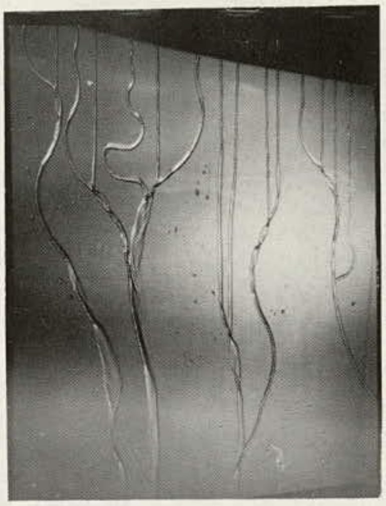
a) Deposition of snow on a cone-type radome

A cone-type radome which consists of a fiber-reinforced plastic (F.R.P.), 3.3 m in diameter and 120° in the flair angle, was placed on the rooftop of a building of Yamagata University. The angle of elevation of the radome was set at 45°. Figure 4,a, shows a typical shape of deposition of wet snow on the surface of the radome. The thickness of the snow deposited was approximately 0.2 m at the upper part of the radome. When the air temperature approached 0°C, snow accreted on the lower part of the radome was removed by gravity. Figure 4,b, shows a photograph taken about 2 hours later than the previous picture. As the air temperature rose to +2.1°C, a large part of snow was dropped off, leaving a small amount of snow at the upper surface of the radome. However, melted water came out from the remaining snow and flowed down continuously on the surface of the radome, forming many strings. Many water droplets also adhered on the surface of the radome. Though the removal of snow by gravity was accerelated as the result of the rise of air temperature and radiation of the sunlight, the moistened radome surface have caused a significant attenuation of the electromagnetic wave.

b) Deposition of snow on a spherical radome

Figure 5,a, shows a typical shape of deposition of snow on the surface of a spherical radome, 0.5 m in diameter. When the spherical radome was placed in a calmly precipitating snowfall, a cylindrical deposit was formed vertically on the hemisphere of the radome, as seen in this picture. However, when it was placed in a windy snowfall, snow accreted at both the windward and lee-side surfaces, as shown in Figure 5,b.

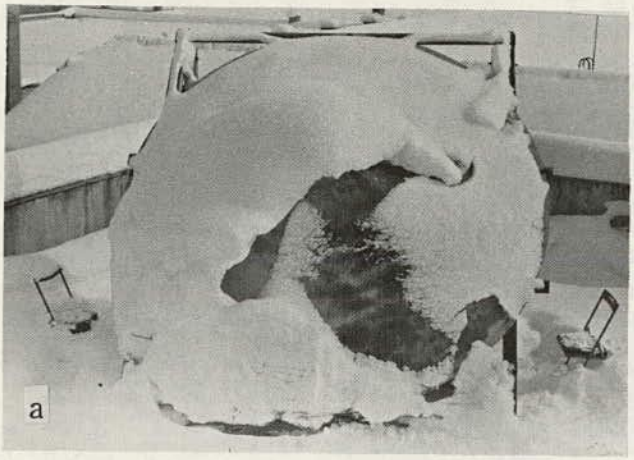
Figure 3 Stringing water flow on a radome surface



How to Remove Deposited Snow from a Radome Surface

Many studies have been made with a view to removing snow deposited on a radome surface. One of the most effective ways for de-icing and anti-icing is to heat the surface of the radome until deposited snow is completely removed by melting. Since the method of de-icing by heating consumes much energy

Figure 4 Shape of wet snow deposited on a cone-type radome (3 m in diameter; 120° in flair angle) Elevation angle : 48.2°
a) +1.5°C; 10h30m, Feb. 10, 1973
b) +2.1°C; 12h45m, Feb. 10, 1973


a

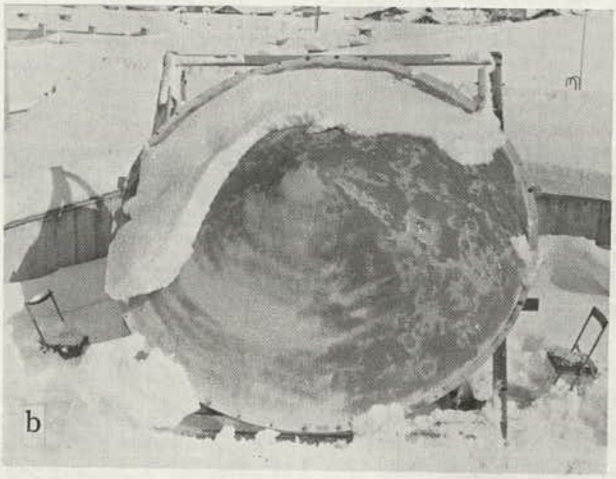

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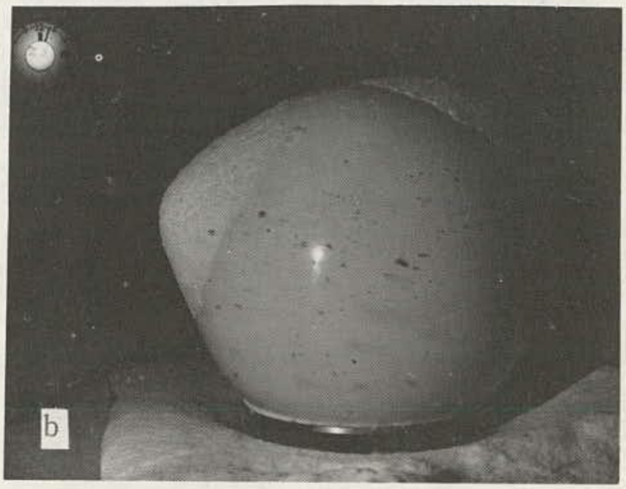
Figure 5 Shape of snow deposited on a spherical radome
a) Cylindrical deposit formed in a calm snowfall
b) Cone-shaped deposit formed at windward and lee-side of a sphere in a windy snowfall


a


b

depending on the amount of deposited snow and meteorological conditions, heating is far from satisfying the need for individual houses to keep their radomes free from snow accretion. The application of a chemical de-icer may also be too inconvenient to be used in residencial areas. Therefore, mechanical de-icing methods (4) were tested in our investigation.

a) De-icing by rotation of a radome

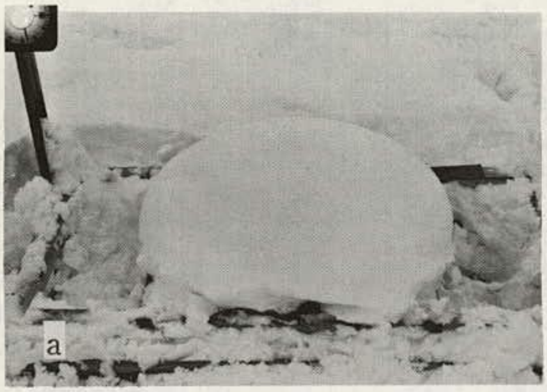
To remove snow deposited on a radome surface by action of centrifugal force, the radome was rotated around its principal axis at the rate of 100~1400 r.p.m.. Figure 6,a, shows the shape of snow deposited on a resting cone-type radome (before the application of rotation). Its elevation angle was 80°. When it began to rotate, a large part of snow was removed within 10 seconds. As seen in Figure 6, b, the rotation was continued for 60 seconds in a heavy snowfall, but no snow flakes were allowed to deposit on the surface of the radome except at the vertex of the cone where action of centrifugal force diminished.

Figure 7 shows the schematic diagram of an experimental apparatus used to rotate a spherical radome, 0.5 m in diameter and 2.4 kg in weight. Figure 8 shows the photograph of a spherical radome taken two hours after the application of rotation at the rate of 300 r.p.m. in a heavy snowfall. The air temperature was -2.5°C, but no snow was allowed to deposited on the surface of the radome except at the zenith of it. According to our experiments, de-icing by the rotation of the radome was successful for snow accretion occuring at the air temperatures above -3°C.

b) De-icing by brushing

The method of de-icing by rotation of a radome was effective for wet snow deposition, but it was not always successful for rime deposition created by freezing of supercooled water droplets. For removal of rime deposits, a brushing device was applied on the surface of a rotating radome. Figure 9 shows two types of brushes applied, while Figure 10 represents a typical brushing result for de-icing. When riming occurred at the wind velocity of 1.5 m/sec and the air temperature of -9°C, the brushing device was applied on the surface of a radome rotating at the rate of 500 r.p.m.. This

Figure 6 Removal of snow by rotation of a cone-type radome (0.8 m in diameter; the angle of elevation: 80°)
a) Before rotation
b) 60 seconds after rotation at 300 r.p.m.



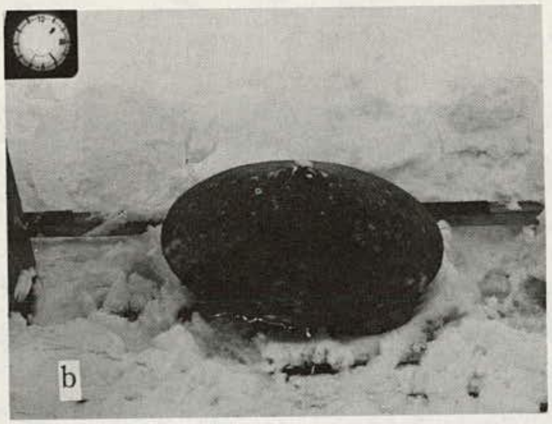


Figure 7 Schematic diagram of an experimental appratus to rotate spherical radome

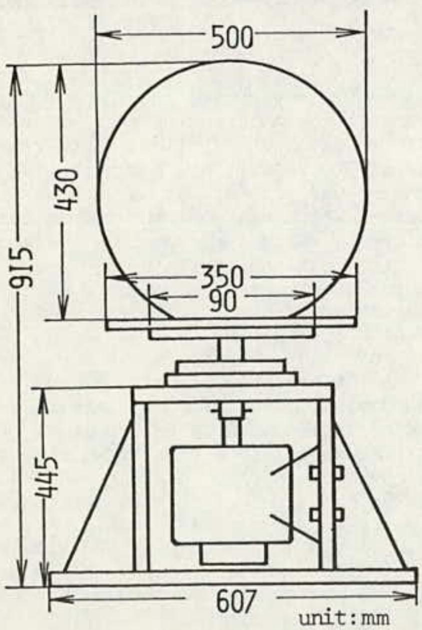


Figure 8 Result of removal from a spherical radome, the picture being taken 120 min. after application of rotation at -2.5°C

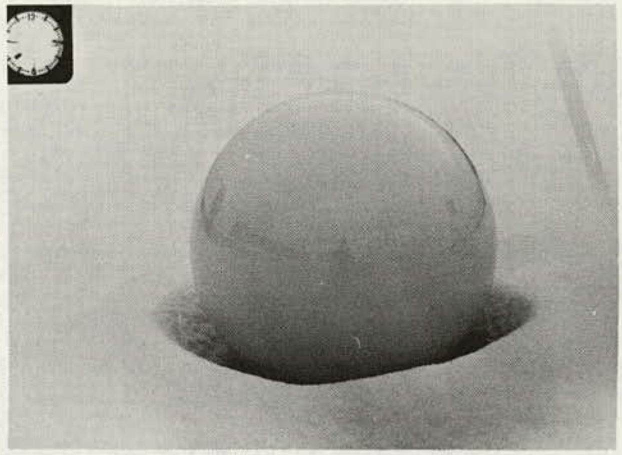
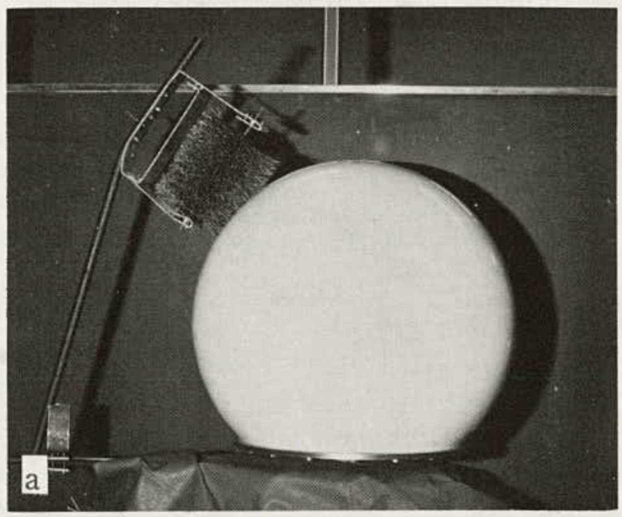


Figure 9 Two types of brushes applied on a radome surface
a) Brush is contacted on the surface
b) Brush can move on the surface like an automobil's wiper



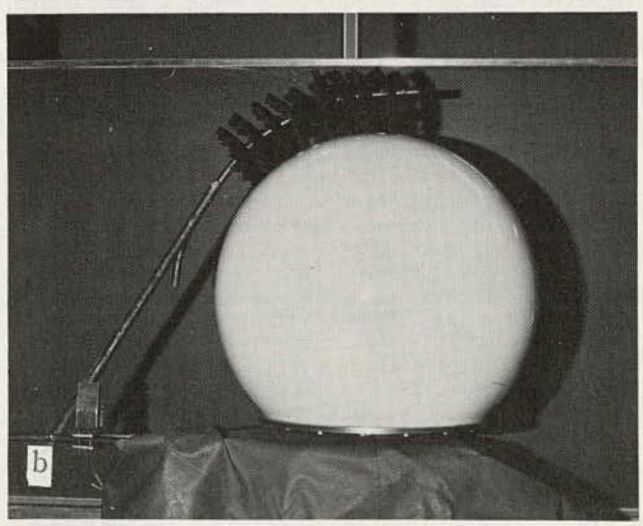
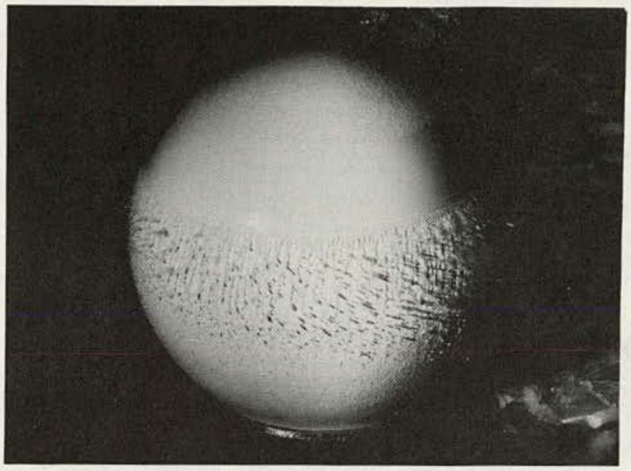


Figure 10 Typical brushing result of removal of rime from the surface of a rotating radome at -9.6°C

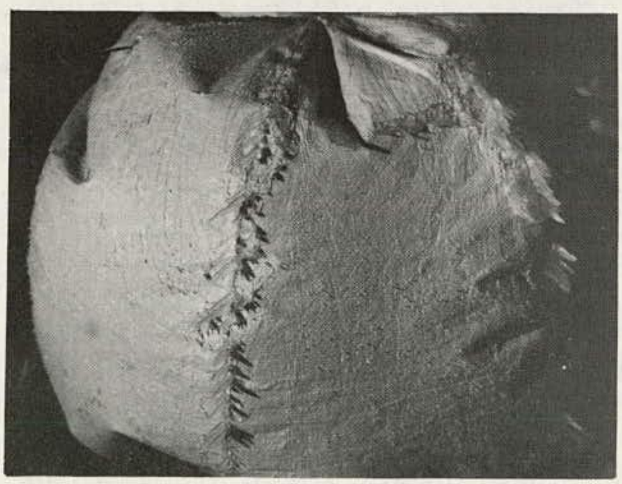


picture indicates that brushing is effective to remove rime deposits from the surface of rotating radome.

c) De-icing by inflation or fluttering of a soft plastic sheet covering a radome surface

It has been accepted that thick rime or ice deposited on the leading edge of an aircraft wing could be removed by inflation of a rubber sheet stretched on the surface of the leading edge. Following this idea, a simple test was made to remove ice deposited from surface of a radome. The surface of a spherical radome was loosely covered with a soft plastic sheet composed of a fine polyethylene net and laminate resin. After making ice deposits on the surface of the sheet by spraying water droplets at low temperature, an air gap between the sheet and the radome was periodically inflated by the aid of a blower. A large part of ice deposits were removed except ice fragments which had adhered along a seam of the sheet, as shown in Figure 11. The efficiency in removal of ice deposited on the surface of a soft plastic sheet could be increased by fluttering of the sheet by action of a natural wind and rotation of the radome.

Figure 11 De-icing by inflation of a soft plastic sheet covering a spherical radome



Concluding Remarks

It was shown by simple experiments that the intensity of a 24-GHz wave was attenuated by the absorption of a water film at the rate of 18 dB/mm. Therefore, snow or rime that accreted on the radome surface should be removed completely before the deposit begins to melt. Our investigations showed that the rotation of a radome was very successful to prevent the radome surface from snow accretion and that the application of an appropriate brush de-icer on the rotating radome surface was effective to remove rime deposits formed by freezing of supercooled water droplets at low air temperatures.
A d.c. electric motor used to rotate a radome in our experiments required the electric power of about 100 watts for a spherical radome (0.5 m in diameter; 2.4 kg in weight) at 300 r.p.m. and about 26 watts for a cone-type radome (0.8 m in diameter; 2.1 kg in weight) at 300 r.p.m..

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Protection Methods for Railway Switches in Snow Conditions

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Research and Development programs conducted on several different methods of overcoming the problem of railway switches failing in the presence of snow and ice are outlined. The most common method at present is the application of heat by the combustion of fossil fuel. By the application of forced convection heat transfer switch protection under reasonably severe environmental conditions is possible. A novel combustion heater based on the valveless pulse jet engine has been applied to railway switches. A non-thermal method employing a horizontal air curtain has been developed to prevent the deposit of snow in critical areas. Two switches have been designed and developed for field evaluation. Both switches are capable of operation in snow and ice conditions.

The fact that railway track switches fail to function properly in the presence of snow and ice is well known in the railway industry. The switch that is in general use throughout the world with only minor variations is the moving point type. The outside rails are standard in design and diverge from the point or apex to the rear or heel of the switch. Within the fixed outer or stock rails two machined rail sections are positioned that are hinged at the heel end and move in unison to provide for straight-through or turning traffic. The machined rails or point rails swing transversely on slide plates and at the apex the points of these rails must fit closely to the head and the base of the stock rail. In operation one point is closed and one is open and in transferring the open and closed points are exchanged. The switch transfer can only be accomplished providing that no foreign material is lodged in the open point between the moving rail and the fixed rail. Although freshly fallen snow can be compressed by a sizeable ratio, a standard railway switch can be rendered unserviceable by as little as .6 cm(¼-in.) snowfall.

At one time it was common practice to clean switches with brooms and shovels and in fact Figure 1 is from a newspaper publication of January 1976 showing that currently it is still in use in some locations. Solutions to this problem have been sought for over a century as was indicated by a patent search disclosing that alternate switch designs were considered more than a hundred years ago and switch heating had been used in the New York and London metropolitan transit systems in the 1890 era.

The advent of Centralized Traffic Control on the railways required that all switches and signals be operated from remotely controlled dispatcher locations. In some cases the switches and signals may be 320 km (200 miles) from the control point. Obviously if a switch is to be controlled by a dispatcher some miles distant it is essential that the switch be capable of operation in all weather conditions. It was the application of CTC to rail operation that has necessitated the development of equipment to protect switches from failure due to snow or ice.

In Canada the two major transcontinental railways had by the late 1960s invested several million dollars in various types of heaters developed in both Europe and North America that were intended to protect a switch from snow failure. The heaters had been developed to satisfy requirements in somewhat more moderate climatic areas; however, when installed in locations with somewhat more severe ambient conditions the equipment had proven to be inadequate. Through an NRC Associate Committee on Railway Problems the Low Temperature Laboratory was asked to look at the problem, to set up standards and to investigate various methods of solving the problem.

Defining the Problem

In cooperation with the CNR and the CPR, arrangements were made to evaluate three of the heaters that the railways had in use in the 1960s. A winter field test was arranged at the Divisional Railway Laboratory. It was a successful field trial inasmuch as all three heaters failed a number of times with different modes of failure, and two of the heaters experienced explosions, fortunately without significant damage. The unit that had not exploded was subsequently investigated further in the laboratory.

In order to evaluate both the problem and possible solutions under controlled conditions it was arranged to install a full scale main line switch in the large cold chamber of the Low Temperature Laboratory. This chamber is 15 meters (50 ft) long and switches of 6.6 meters (22 ft) and 11.7 meters (39 ft) nominal length have been installed at different times for tests. Most of the research and development work was carried out with the 6.6 meter

(22-ft) long switch.

Snow making had been carried out for a considerable period of time prior to the railway switch work; however, for this test program the snow making equipment was modified to allow for different conditions. An overhead air-water multiple nozzle array was installed to supplement the normal snow making nozzles that are mounted on wind chill fans. With three sets of snow making nozzles a maximum snowfall rate equivalent to 12.5 cm (5 in.) per hour could be produced.

The railway track switch was installed in the cold chamber complete with ties, crushed stone ballast and approximately 30 cm (1 ft) of subgrade material. While evaluation of the one heater remaining from the field test was carried out, development of a test standard in cooperation with the railways was pursued. Ultimately it was agreed that the laboratory test standard to be employed for either evaluation of new heaters or for research and development programs should be a snowfall rate of 2.5 cm/h (1 in. per hr), a wind velocity of 32 km/h (20 mph) and an ambient temperature of -17.7C (0°F). It was appreciated that all three conditions could be exceeded in nature at a number of locations; however, the chance of all three being exceeded simultaneously was low as indicated by climatic data.

Thermal Protection

In due course it was established from the cold chamber test program that to protect a switch under the previously noted conditions a thermal system should distribute the heat by forced convection to the critical areas of a switch and with a good duct system a thermal capacity of 62,500 kilocalories (250,000 BTU) per hr was required for a 6.6 meter (22-ft) long switch. Three manufacturers eventually developed heaters that produced this quantity of heat and used forced convection distribution ducts to direct the heat to the critical areas. The conventional forced convection combustion heaters that were developed had a number of serious design deficiencies, e.g. dirty combustion, inadequate air inlet systems, excess electrical power consumption.

The laboratory undertook to develop an advanced design forced convection combustion heater that would eliminate or alleviate these specific problem areas. To ensure clean combustion a cyclone burner combustion chamber with a conical re-entrant outlet was chosen. By careful design of the air inlet, the combustion chamber by-pass, the cross duct and the distribution ducts and by application of a higher efficiency fan the electrical power consumption was reduced to approximately 50% of a commercial model. The air inlet was designed with a low velocity re-entrant system to eliminate almost all snow ingestion. This had been a serious problem with all previous heaters. Prototypes of the cyclone combustion heater have been field tested(1) and arrangements completed to place this heater in production.

The forced convection combustion heater for railway switches can be applied at any location with sufficient single phase electrical power; however, the power demand of one to two kilowatts has ruled out the use of this heater where it has not been economically feasible to bring in power lines to switch locations. The CPR outlined a requirement for a forced convection combustion heater that would have an electrical demand of under 100 watts. While consideration was given to engine-driven or engine generator units for the conventional heater, another means of producing forced convection combustion was pursued.

One of the developments resulting from World War II was the pulse jet engine used to power the German V 1 missile. This simple device produced thrust with only an air flapper valve as the single moving part. Post war developments led to the so-called valveless pulse jet engine which in fact employed an aerodynamic valve based on a tuned length re-entrant tube. It was considered possible that a forced convection combustion heater might be developed using a valveless pulse jet as the combustion chamber with the thrust from the engine to produce the forced convection heat transfer means. As reported earlier (2) the pulse jet combustion heater was successfully developed to meet the railway requirements for a unit capable of producing 62,500 kilocalories (250,000 BTU) per hr and distributing this through a duct system to the switch. Figure 2 shows a unit in a field evaluation location approximately 96 km (60 miles) from Ottawa. This heater is extremely simple in concept although there are several critical design aspects that required major development. Figure 3 shows a cross section of a typical switch heater installation. One of the major disadvantages of the pulse jet heater is the noise level produced by this combustion process. It will produce a sound pressure exceeding 120 db "A" scale. Originally this was not considered a disadvantage in view of the intended use in remote locations where power line costs were prohibitive. Subsequently, however, a request was received to install units in areas where the noise would be a problem. The pulse jet design was modified and the units were installed in sound insulated metal bungalows complete with a silencer air inlet while a Maxim type exhaust muffler was installed in the cross duct. This treatment reduced the source noise level to 80 dB "A" scale.

While the pulse jet was under development there were parallel developments by commercial interests of propane engine driven forced convection heaters, and in addition heater installations incorporating an engine-generator to provide electrical power to a standard forced convection switch heater. The combination of a combustion heater, an engine-generator together with a control system housed in a metal bungalow results in a fairly expensive solution to the snow and ice problem with railway switches.

The thermal method of protecting switches is an energy intensive means since the snow is melted and some is vaporized for disposal. The efficiency of this energy application even with a good distribution duct system is quite low since a large portion of the heat is dissipated to the atmosphere except under the more severe snowfall conditions. With the rising cost of hydrocarbon fossil fuels the heating of track switches for a winter season is becoming prohibitively expensive. There are recorded cases where the cost of heating a switch for a winter season has exceeded $1,000.00.

The thermal protection method has both advantages and disadvantages. The major advantage with this method is that a switch that is completely covered in snow can be restored to service by the application of heat. The disadvantages resulting from the switch heater include the following. Overheating can result in ignition of the creosote impregnated wooden ties. With a forced convection duct system supplying air, all of the ties in a switch can be burned out resulting in an unsupported switch assembly. This has occurred on several railways with various heaters, and currently protective devices to shut down the heater in the event of overheat are required. Although the heat is directed primarily at the rails and the slide plates, the operation of a switch heater for extensive periods does result in thawing of the ballast. Traffic movement over soft ballast can force the rails and ties below the normal level requiring the application of shims to restore rail level. The maximum allowable shim application of 2.5 cm (1 in.) can be exceeded depending on heater use and the grade of ballast. The melt water resulting from a switch

Figure 1. Manual switch cleaning January 1976, courtesy Toronto Globe & Mail.

Figure 2. Pulse jet switch heater at Perth, Ontario.

Figure 3. Cross section of pulse jet switch heater installation.

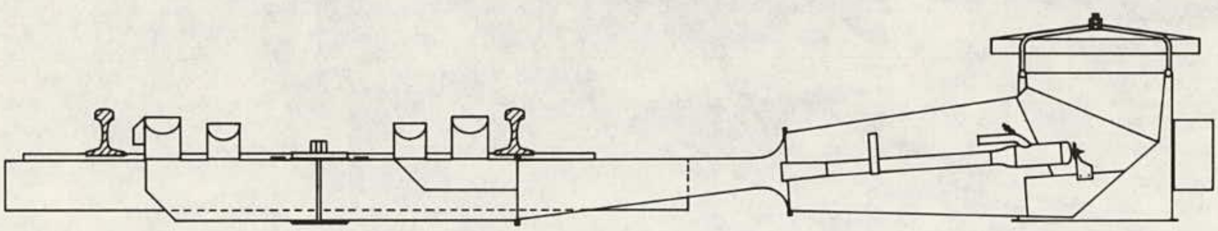

Figure 4. Horizontal air curtain switch protector.

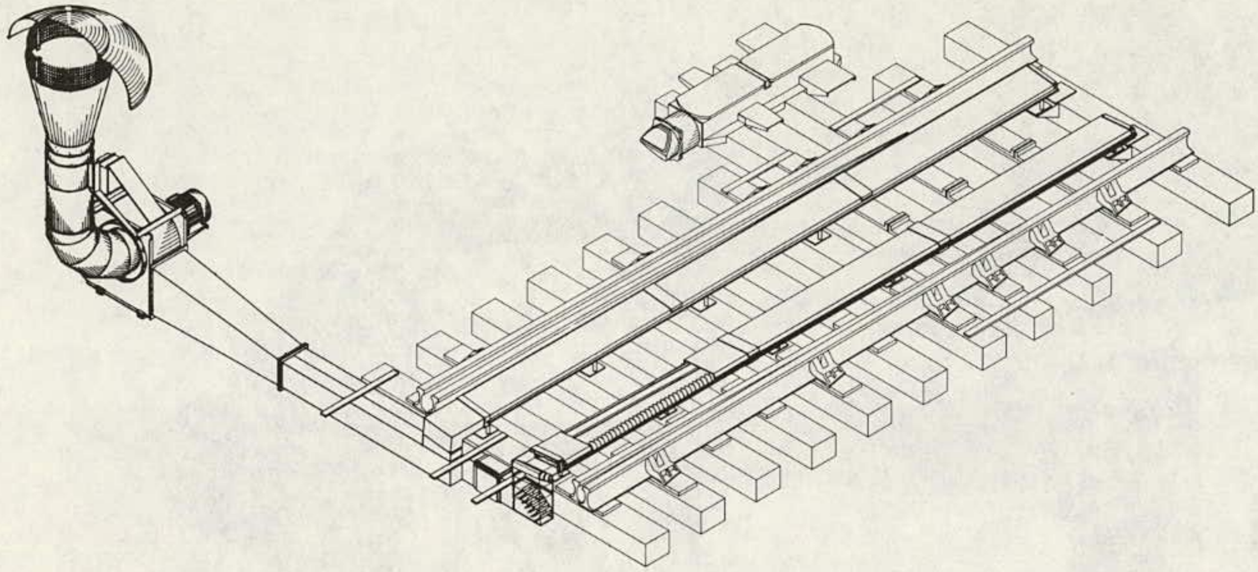

Figure 5. Horizontal traverse switch.

heater operation during snowfall runs down into the ballast and in areas where the ballast is frozen it subsequently turns to ice. It is not uncommon for a switch heater to cause the formation of an ice dam in the ballast around a switch. If the snowfall and low temperature are of sufficient duration the ice dam may grow to such an extent that melt water accumulates in the crib spaces. On heater shutdown this turns to ice and in some cases it renders the switch unserviceable by freezing in the throw rods from the switch machine.

The high cost of fuel is forcing the railways to look to the automatic operation of switch heaters using local condition snow sensors. The units used to date are heated moisture sensors and while they do detect snow some of them may also detect any other foreign conducting material.

While work was being conducted on thermal protection methods, some thought was given to other means of solving this problem since it was considered that heating, in view of the principal disadvantages, i.e. the high operating cost and the consumption of fossil fuel, was unacceptable except as an interim answer.

Non-Thermal Protection

In another field the Low Temperature Laboratory was investigating snow removal from surfaces by non-contact methods. One method under investigation was removal of deposited snow from a surface by the use of high speed air jets. While conducting these tests it was observed that an air jet propelled the airborne snow a considerable horizontal distance before fallout of the particles. This raised the question of whether a railway switch might be protected by an air jet that would prevent snow from depositing in the critical areas. Some preliminary calculations indicated that the energy required appeared to be within reasonable and acceptable limits. The initial mathematical model of the concept was rather crude but served to show the order of magnitude on energy considerations. To investigate further an experiment was set up immediately with an available blower to which a longitudinal duct with a slit nozzle was fitted. This assembly was placed adjacent to an experimental track and subsequently tested under natural snowfall conditions. The initial test verified that a horizontal air curtain could maintain an area free from snow deposit and accumulation.

The horizontal air curtain switch protector is premised on the idea of adding a horizontal velocity component to the existing vertical velocity component of falling snow particles such that the resulting velocity vector will cause the snow particles to be deposited on an area outside of the protected area (3,4,5). The terminal velocity (the vertical velocity component) of falling snow particles has been measured by previous observers. The area of a switch that must be protected against snow deposit includes that between the open point and the adjoining stock rail, the slide plates within the switch, and the top of rail in order that snow does not fall from here into the critical zones.

The duct and nozzle design that ultimately resulted was that of two outward directed longitudinal nozzles to clear snow from within the switch area to deposition zones outside the stock rails. In order to get the jet close to the point and stock rails a double duct system evolved with two longitudinal nozzles. The configuration of the MK III Horizontal Air Curtain Switch Protector is shown in Figure 4. It consists of a low velocity re-entrant design air inlet so that the upward velocity at the entry is less than the terminal velocity of snow particles. This supplies air to a centrifugal fan discharging air to the distribution system at the specified flow and pressure. The duct system is composed of a cross duct, elbows and two longitudinal ducts with slit nozzles.

The MK III Horizontal Air Curtain has subsequently been superseded by a production model, the MK IV, that incorporates various modifications found necessary for field installations. This method of protecting a switch consumes much less energy than the thermal method, e.g. 5 kw electrical energy compared with 62,500 kilocalories (250,000 BTU) per hr of fuel. Several of the problems resulting from operation of switch heaters are eliminated. It has the disadvantage that it is a non-recovery device, i.e. it must be in operation at the beginning of a snowfall since it cannot remove already deposited snow. With the use of snow detectors this method offers a more economical means of protecting existing switches from snow blockage.

There is one other protective method that must be mentioned in discussing this problem and that is housing the switch. The problem with this solution is how long to make the house so that snow does not block a significant length from the end openings. This approach to this problem has been applied by Quebec North Shore and Labrador Railway to one switch. The building is 75 meters (250 ft) in length and unfortunately the problem has not been solved completely by this method. Ore trains moving through the switch and shelter drag along dry snow into the switch. Some improvement resulted by narrowing the building cross section at the switch area so that the higher local velocity would keep the snow moving. The enclosure has resulted in a new secondary problem. Under certain conditions with snow on the roof, moisture condenses and drips to form ice deposits along the track including the switch.

The ultimate answer to the snow problem with railway switches is to redesign the switch so it will not fail from ice or snow. Numerous inventors have outlined various schemes that supposedly overcame this problem and in the Mechanical Engineering Division at NRC we have designed and developed two switches both of which do not fail from ice and snow. One of these switches employs vertical hinged point rails moving in opposition. The other switch is a horizontal hinged assembly in which both the point and stock rail are one swinging beam hinged at the heel end. The switch has been tested in the field for two winters and has not failed due to ice or snow. Figure 5 shows a locomotive crossing the operating switch in winter. Whether these switches are adopted by the railway industry is a question. We do believe, however, that a new switch design will be the long range answer to the snow and ice problem with the existing switch.

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Development of a Snowplough/Salt Spreading Vehicle for Ice and Snow Clearance of Motorways in England

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Reason for Development

In England Central Government has a direct responsibility for about 1336 miles (2150 km) of motorway and 5059 miles (8400 km) of all-purpose trunk roads which are shown in Figure 1. Remaining roads are the responsibility of Local Government.

Central Government delegates maintenance on an agency basis to local highway authorities; that is, the Agent Authority provides the staff, workforce, plant and material with the costs charged against Central Government funds. Generally, this arrangement applies to winter maintenance operations on trunk roads. There is, however, a departure for motorways since not all local authorities have large specialised salt-spreading vehicles with the capacity to cope with motorways.

Such specialised vehicles are therefore provided and maintained by the Department of Transport and operated by drivers from the Agent Authority.

From the mid-1960's, the Department started taking delivery of 6x6 vehicles with a gross vehicle weight (GVW) of 20 tons (20.32 tonnes) which were based on a highly specialised chassis built against a tight engineering specification. This was followed in the late 1960's by a larger, improved version of the same vehicle having a GVW of 22 tons (22.35 tonnes) built by the same chassis manufacturer. The builder brought in all parts of the vehicle from separate suppliers and acted as an assembler only.

This led to in-service problems because there was very little dealer back-up in the field, which resulted in the Department having to purchase and set up a spares organisation of its own.

In 1973 it was decided that the Department would confine itself to supply vehicles for motorway winter maintenance purposes only. This prompted engineering thinking toward a different design approach because the operational parameters of a snowplough/salt spreading vehicle for use only on motorways dictates different design requirements. In this case, maximum gradients are tied by motorway specification to only 1 in 20 (5%) for slip roads (entry and exit) and 1 in 25 (4%) on the main carriageways. Road construction is such that heavy drifting of snow is almost eliminated and the road surface is kept to a high standard in terms of friction coefficients and adhesion factors.

The fleet consists of some 227 6x6 vehicles with two vehicles covering each 15 miles (25 km) of motorway with some additionally held in emergency depots. Early vehicles are in need of replacement due to age and ever-increasing corrosion problems exacerbated by the mode of spreading salt. The bodies have twin spinners, one on each side of the vehicle, situated between the back of the cab and the front of the body, and this results in heavy salt contamination of the vehicle. The body has a conveyor belt that is driven mechanically by drive from the transfer box power take-off (PTO) through drive shafts, a reduction gear box and flexible couplings, etc., which means that to engage the conveyor belt drive the vehicle must be stationary. The spinners and plough lifting ram are hydraulically powered from a small pump directly driven off the engine timing chest.

The conveyor belt carries salt to two cross augers running in troughs at the front of the body where it is fed into chutes which direct the salt onto the spinners. This design makes it difficult to achieve low spread rates - this will be clarified later in the paper.

In 1974 vehicle development trials started with the object of selecting a suitable chassis/cab and body to meet the Department's future requirements. The intention was to find as near a manufacturer's standard chassis/cab as possible with a 6x4 configuration by subjecting several different makes to exacting performance and operational trials. In the spreader body market all salt spreading body manufacturers are specialists in the field and we decided to try six makes of body and fit these to five makes of chassis. The trials were competitive and each unit was judged on its own merits, that is, each chassis/cab and each body separately.

Design Requirements

Broad specifications were issued for chassis/cabs and bodies which allowed manufacturers wide scope. The six bodies tested were all different in the method of operation - the only common factors being that of payload capacity and salt being spread from the rear. The main specification items for the chassis/cab and body were:

Chassis/cab

- 24 ton gross vehicle weight
- 6x4 configuration
- Power/weight ratio 8 BHP/ton
- Tractive effort 25,000 lb
- Chassis frame stiffness at front end to take standard sub-frame for snow plough mounting
- Diesel engine with automatic fan and PTO facility from crankshaft
- Conventional manual control gearbox
- Standard on/off highway tyres (cross-ply construction)
- Differential lock-up facility between and across axles
- Automatic chassis lubrication system with minimum number of points
- Cold starting aid
- Leading dimensions (overall height, length, etc.)
- Low centre of gravity
- Tilt cab to give quick access to engine compartment
- Minimum maintenance and good accessibility to those parts requiring maintenance
- Paint specification to give lasting protection against salt-induced corrosion
- Insulated earth return electrical wiring
- Additional sets of obligatory lamps above cab
- Heavy duty alternator (50 amp)
- Heavy duty batteries.

Body

- Payload capacity of 12 tons (12.192 tonnes) with spreading device at rear of body
- Hopper shaped body to give good salt flow, with a low centre of gravity
- Hydraulic operation of conveyor system, spinners and plough lift
- All controls operable from cab whilst vehicle is moving
- Salt spread to be constant in each setting regardless of vehicle speed (road-related spread)
- Capable of spreading salt to a width of 60 ft symmetrically and asymmetrically
- Spread rate from 1.16 oz/yard^2 (40 g/m^2) down to 0.29 oz/yard^2 (10 g/m^2)
- Minimum maintenance with good accessibility to those parts requiring maintenance
- Salt spreading sensor unit to give driver indication in the cab of spread or no spread
- Body and sub-frame construction to be free from pockets where salt poultices could form
- Good accessibility for washdown by high pressure water hose
- Steel mesh sieving screens over body angled at 35° to the horizontal
- Rapid off-load facility for unused salt.

Procedure and Selection of Equipment

The five makes of chassis/cab were chosen after advertising in the national press and by direct approach to manufacturers who were requested to quote a price against our specification. Originally nine manufacturers expressed an interest but only seven quoted.

The body advertisement attracted quotations from seven manufacturers and six were chosen. The imbalance of five makes of chassis/cab to six makes of body was corrected by purchasing two chassis/cabs of the same make.

Chassis/Cabs

It was arranged that proprietary vehicle equipment, which also required assessing, should be allocated to different manufacturers. Five makes of automatic chassis lubrication equipment were chosen to be assessed together with three makes of automatic engine cooling fans.

There was a considerable degree of variation between the chassis/cabs both in cost terms and design.

Only two vehicle manufacturers could offer differential locks across axles with one offering a limited slip differential as a solution. There was a wide variation in transmission ratios which were aimed at giving maximum tractive effort but which gave operating problems at 30-35 mph (48-56 km/h) in the wrong engine speed band. Top speed of the slowest vehicle was 48 mph (77 km/h) and the fastest was 70 mph (113 km/h). Rear bogie suspensions were offered in two and four-spring configurations.

Power/weight ratios varied from 7.5 BHP/ton (5.85 kW/tonne) to 12.3 BHP/Ton (9.03 kW/tonne).

Cab tilt operation varied from quick and simple to slow and cumbersome.

The power take-off from the engine crankshaft was a new departure for all manufacturers and this facility varied from easy to install to very difficult - one had a rectangular hole in the radiator to allow the drive shaft to pass through. It is a criticism of all engine manufacturers that not enough basic engine design work has been applied to give good PTO facilities from the engine. With a tilt cab the obvious place for power take-off is at the rear of the engine where the capability of extracting some 30 HP presents no great problems and the driven pump unit would be well guarded and readily accessible for maintenance, etc.

All makes were fitted with cold starting aids.

Chassis/cab weight varied from 14,538 lb (6608 kg) to 18,764 lb (8529 kg).

Wheel-bases varied from 186 in. (4.737 m) to 197 in. (5.022 m).

Bodies

Of the six bodies, one had an auger conveyor system, two had chain-driven single conveyor belts, two had single rubber conveyor belts and one had twin rubber conveyor belts.

Body design varied from low profile to high profile with the attendant low and high centres of gravity. It was noted that the auger body had its body design inhibited by the auger length which resulted in a high C of G. Some bodies had high-pressure hydraulic control valves in the cab. Others were remotely controlled through cables. The tilt cab presents problems for body controls as they either have to be disconnected behind the cab when tilting or routed around the cab hinge point.

There was a wide variation in the method of obtaining the road speed/belt speed constant ratio. One manufacturer's solution was to take drive off a rear road wheel by means of a small friction wheel which was held in contact with the inner tyre wall by a spring controlled arm; the wheel in turn powered a small hydraulic pump which gave a metering signal to the main pump.

The remaining five manufacturers all used the vehicle transmission propellor shaft as a drive source for either direct-acting hydraulic pumps or for metering devices to control the main hydraulic pump. Direct drive pumps had to deliver 15-20 HP and this presented problems because of the imposed side-loading on the propellor shaft and variable centre distances of the drive pullies. A metering device drive only absorbs fractional HP (about 1/3).

Two bodies had gas/hydraulic accumulators fitted to give pressure consistency at low engine speed, e.g. gear-changing periods.

Off-loading facilities varied from simple and rapid to difficult and slow.

Body weights ranged from 5152 lb (2342 kg) to 6800 lb (3091 kg).

Overall heights varied from 10.34 ft (3.15 m) to 11.75 ft (3.58 m).

Hydraulic pressures ranged from 1750 psi (123 kg/cm^2) to 3000 psi (211 kg/cm^2).

Performance Trials

A project sheet was compiled and issued to clearly define the work required. Testing facilities existed at Government Experimental and Developmental Establishments and these were used on a hired basis. Each complete vehicle was checked dimensionally and weighed and then taken on to a test track to carry out performance running to determine top speeds, fuel consumption, retardation and reliability mileage, etc. A large area in the centre of the test track (skid pan) was used to check draw bar pulls, to determine tractive effort and rolling resistance, and to also check turning circles.

Vehicle overturn angles (tilt angle) were checked on a special hydraulically operated tilt rig. The information derived from this test, i.e. the tilt platform and body roll angles, was used to calculate the true vertical centre of gravity for each vehicle.

To thoroughly investigate chassis and body robustness, the vehicles were driven over a suspension course which consisted of irregularly spaced 1-in. concrete sets. This was chosen to simulate driving over frozen rutted snow and was a very effective test of the vehicle's suspension system, body mounting brackets, all bolted-on assemblies and welded joints.

Tests to stop and restart the vehicle on a 1 in 4 (25%) gradient were carried out on a purpose-built test slope.

Salt spreading calibration trials were carried out on a disused aerodrome site. This was a painstaking exercise to determine the bodies' actual spread rates and their conformity to British Standard 1622, which is a standard drawn up by the British Standards Institution to guide manufacturers through set testing procedures.

All results from performance trials were recorded and tabulated. One of the widest variations was in the tilt angle test where the worst vehicle was 22.5° and the best, 27° which gave C of G heights of 6 ft 3.65 in. (1920 mm) and 5 ft 9.37 in. (1762 mm), respectively. Obviously the stability of the worst machine was unacceptable and modifications were carried out before continuing further trial work.

Operational Trials

The vehicles were tested over two winters (75/76 and 76/77) under actual operating conditions on the motorways. Selected sites were chosen in the North of England where weather conditions are generally more severe, and for the first winter six motorway compounds were used with the vehicles (one vehicle/compound) being moved around every three weeks to get as much operator comment and feedback as possible. Due to staff resources the number of compounds used was cut to three for the second winter with two vehicles per compound and a six-week turn-round period.

Defects were experienced on all equipment and all needed development work as the trials progressed. Obviously some needed more modification work than others but in every case the product was improved during the trial period.

Salt usage rates were carefully monitored and consistency of spread rates continually checked. This work was made more difficult because of the variation in salt conditions between motorway compounds - ranging from very wet to just moist.

All vehicles were fitted with 10-ft (3.03-m) angled blade snow ploughs built to the Department's own standard, and although ploughing work was not excessive, there was sufficient work done in ploughing snow to a depth of 3 ft (0.9 m) to establish beyond doubt the viability of a 6x4 vehicle being used in this role.

The Agent Authority drivers took some time to get used to rear spread bodies because they were accustomed to seeing the salt being spread from the front spread machines. With the new vehicles they had to rely on the salt sensor unit which gives a spread/no spread signal in the cab. They also had to reverse the vehicle with more care as the overhanging rear spinner has a propensity to damage.

On completion of the operational trials each product was assessed by taking the following information into consideration:

Agent Authority drivers' comments

Agent Authority technical staff comments

Defects—incidence and rectification by manufacturers

Manufacturers' performance - supply of spare parts, etc.

Performance trial results

Department of Transport engineering and technical assessment.

From this exercise a chassis/cab and body, together with the most successful chassis automatic lubrication system, automatic fan unit and salt sensor, were chosen as being the best combination of equipment to meet the Department's future requirements.

The successful chassis/cab and body had not been tested as a combination so it was decided to purchase some pre-production prototypes before a final decision was made for a bulk production order.

Pre-Production Prototype Vehicles

In the interests of testing the new chassis/cab and body as a unit and to ensure that teething troubles could be eliminated before bulk production commenced, it was decided to purchase four units and make a fifth unit from the original trial prototype equipment.

The five vehicles have been thoroughly tested over the past winter. Teething troubles came up and were dealt with to such an extent that it has resulted in a snow plough/salt spreading vehicle having the capability of operating reliably at low ambient temperatures (down to -20°C) and being able to spread salt at very economical rates.

In the snow plough role the experience gained over the past winter has been invaluable. English winters are not normally renowned for severity and heavy snowfalls, but on this occasion the raw material for testing purposes was supplied in abundance and the prototypes dealt with the problem without trouble.

Conclusions

The complete testing programme over the past three winters has resulted in a development of equipment not only to suit the Department but also to improve the products being offered to local government, because each manufacturer who participated in the exercise gained valuable experience and was able to make improvements as the trials progressed.

The development aspect was a joint effort between the Department and Industry - advice was given freely to all concerned on how to overcome problems as they arose.

The greatest benefit arising out of the trials is the capability to spread salt at 0.29 oz/yard^2 (10 g/m^2) for the precautionary salting operation. This figure is unattainable with the existing 6x6 vehicles because of the cross auger system not being able to deal with such small quantities of salt coming through the discharge gate.

Main areas of cost benefit are:

Savings of about 30% on salt usage

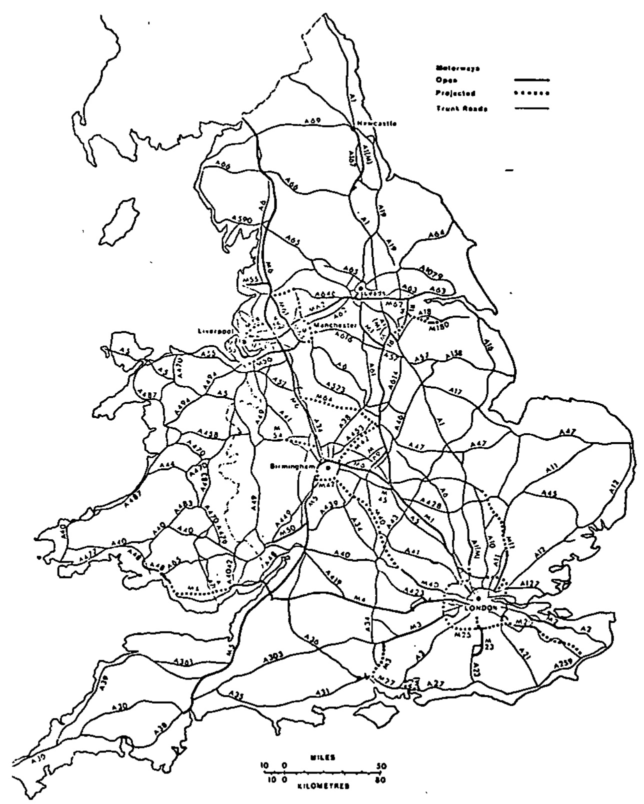
Prime cost of chassis/cab 6x4 standard against 6x6 special - saving 40%

Servicing and maintenance costs reduced - assessed at about 20%

Operational efficiency increased - saving in staff time and vehicle down time.

From the engineering perspective an appreciable advance in the development of winter maintenance vehicles has been achieved, but to get the best return of capital out of the equipment it still comes down to the operator being properly trained to use the vehicle as it was intended by the engineer. We try to eliminate chance and take operations and decisions away from the driver but until we get the equivalent of an automatic pilot we have to accept the vagaries of human nature. In closing it is opportune to say that we are constantly criticised by the public for spreading salt on the highways, which does result in increased corrosion of vehicles, but being a simple engineer, I see it as a straight choice. The conscientious motorist can get to grips with corrosion by preventative maintenance but he cannot get to grips with a sudden lack of adhesion between tyre and road surfaces.

Figure 1. Plans for the trunk road system.



Snow Collection by Possible High Speed Guideway Sections

T. R. Ringer and R. D. Price, National Research Council of Canada

A program to observe the formation of snow accumulations on possible high speed transportation tracks was initiated in 1969. The track sections tested include π shaped, box, inverted Tee and channel cross section beams. At extremely low wind velocities the snowfall accumulation is equal on all beams. At high cross flow velocities the beams with vertical members rising from horizontal surfaces cause severely distorted accumulations. The vertical member(s) acts as a 100% density snow fence resulting in a parallel ridge formation. With dry snow and high wind velocity the plane surface beams accumulated little or no snow.

The accumulation of snow during the winter is one of the major causes of disruptions to traffic systems whether these are road, rail or aircraft. During the past winter the north-east portion of the U. S. suffered one of the most severe storms experienced this century and these traffic systems all encountered breakdowns that lasted from one to as many as five days according to newspaper accounts. Passengers flying by air from Miami and Fort Lauderdale were delayed in the south for one or more days because of flight cancellations to New York, Boston and other northern cities. Whether passenger delays in southern Florida due to a northern snowstorm can be classified as an inconvenience is questionable. No doubt many of those in the Boston and New York area during this storm (that has become known as the Blizzard of '78) can attest to the severity of the traffic disruptions. The photo coverage of this and an earlier storm in the New York area showed freeways with abandoned cars and trucks, and streets with mounds of buried cars. Train delays due to extremely severe snow drifts were reported in the midwest during a January storm. During early February in western Canada another blizzard caused cattle deaths due to 4.5 meters (15 ft) deep snow drifts. The same storm caused derailment of 26 cars from a train as a result of hitting a high snow drift. In the same area a train and snow plow dispatched to clear a line got stuck in the snow. Other locations in the northern hemisphere suffered from severe snowfalls in January and February of 1978. Valdez Alaska was reported to have had an 80 cm (32 in.) snowfall during one day. Parts of northern Scotland had roads buried under snowdrifts that were up to 6 meters (20 ft) deep. While the winter of '78 will be remembered in New England for some time, other areas have different years to commemorate as the most severe winter within memory.

In considering new transportation modes it is essential that the designers consider the environment of the areas for which they are intended. For the northern U. S. and Canada the requirements of a transportation system are somewhat different from that suitable for Miami or Los Angeles. In the northern parts of the country lower temperatures are experienced as well as snowstorms. The low temperature is not too difficult for traffic equipment designers to provide for in either vehicles, tracks or buildings, since this is an area in which major advances have been made in engineering during the past twenty or thirty years. Advances in dealing with the snow problem have not been as outstanding except possibly by the provision of more and larger equipment for snow removal from vehicle rights-of-way. In some instances, snow plow equipment on the railways for example, there has not been any significant improvement in fifty or sixty years in North America.

The winter season during which snowfall is experienced varies in duration across Canada, and in some areas includes both spring and autumn. For example Calgary, Alberta has a snowfall season that can extend from September to June, although the mean annual snowfall is only 150 cm (59 in.), while Saint John, New Brunswick experiences snow only over six months but has an annual average snowfall of 200 cm (80 in.) per year (1). Across Canada the mean annual snowfall varies from a minimum of 30 cm (12 in.) along the Pacific coast to over 300 cm (120 in.) along the continental divide. The prairie provinces have from 100 to 150 cm (40 to 60 in.) per year while from Ontario to the Atlantic the mean varies from a low of 80 cm (32 in.) in southwestern Ontario to 300 cm (120 in.) in several areas (1,2). Figure 1 gives the Mean Annual Snowfall for Canada. The number of days on which snow falls, and might thereby cause traffic disruption by direct snowfall, varies from a low of 10 days per year on the Pacific coast to a high of 100 days per year in an area to the east of Hudson's and James Bay. Figure 2 gives the Mean Annual Number of Days with measurable snowfall.

The minimum wind speed to transport snow is given by various authors (3) as 4 to 7 m/sec for dry snow and up 8.3 to 11 m/sec for a snow in the wet English climate. The winter season mean wind speed for a considerable area of Canada is 4.2 m/sec (10 mph), i.e. just exceeding the lower limit for snow transportation, thus considerable drifting can occur. The implication from this is that although trace snowfalls may be restricted to a limited number of days for a given area, drifting may occur all winter while a snow cover exists. Obviously for most areas it would be advantageous to employ a transportation method that is not influenced by drifting snow.

Snowfall accumulations on the ground may exceed 200 cm (80 in.) in limited locations but for much of Canada 125 to 150 cm (50 to 60 in.) is the maximum recorded depth. For drifting snow with a strong wind (16 m/sec) more than 98% of the snow transported is within one meter of the snow surface (see Table 2). It is an obvious advantage to elevate a track structure to eliminate problems resulting from the drifting of an accumulated snow cover.

During the 1960s guided air cushion vehicles were under development in the U. K., France and the U.S.A. Since then development has been undertaken on magnetic levitated and guided vehicles in the previously mentioned countries and in Japan, Germany and other countries including Canada. A variety of guideways or tracks have been considered by the various designers; however in the late 1960s the three more popular designs were the inverted Tee of Bertin & Cie. of France, the deep box beam of British Tracked Hovercraft and the channel track of two U. S. developers. All of the track sections proposed for either air cushion vehicles or magnetic levitated vehicles have employed horizontal and/or vertical surfaces for support, guidance and propulsion. Although some consideration had been given to snow and ice problems by the agencies developing these systems, the relative merits of the track designs from this aspect had not been evaluated due primarily to lack of information on the susceptibility of the various sections to snow accumulation.

In 1969 a decision was made to investigate the formation of snow on representative samples of the various track designs that were proposed at that time. Consideration was given to simulated tests using scale models in a laboratory tunnel with a snow substitute. Reports on the Simulation of Drifting Snow (4) and Scale Model Studies on Snow Drifting (5) indicated the need for further development work on simulation, thus it was decided to observe the accumulation of natural snow on full scale track sections.

Test Site

The choice of a convenient test site was limited by the availability of readily accessible locations with good exposure to winds and preferably some distance from buildings or wooded areas. The requirement to photograph the accumulations after each snowfall and to clean the beams after each storm with a minimum labor input further restricted the choice. Of the available NRC locations in the Ottawa area that were considered, the site of the Helicopter Icing Research facility in the northwest section of Ottawa International Airport was chosen as the most suitable. This site has office space, a workshop, power and steam generating capacity, together with a reasonable amount of space to the north of the helicopter icing spray rig. The installation of the test tracks at this location allowed the same staff as used for icing work to observe, photograph and maintain the high speed vehicle tracks.

The test beams are located along a height of land at an elevation approximately 108 meters (360 ft) above sea level. To the east of this ridge the land drops approximately 150 cm (5 ft) over a distance of about 100 meters (several hundred feet). The only structure adjacent to the test beams is a weather radar unit to the southeast. On the west side the land falls away rapidly with a change of 6 to 9 meters (20 to 30 ft) in elevation within 30 meters (100 ft) of the track sections. The nearest buildings to the west are all well below the elevation of the test site. To the south and southwest there is an extensive wooded area; however, this is on land approximately 9 to 12 meters (30 to 40 ft) lower in elevation and over 100 meters (several hundred feet) from the test site. Figure 5 shows the location of Uplands Airport at Ottawa while Figure 6 shows the location of the test site on the airport. Figure 7 is an aerial photograph of the test site showing the location of the track sections and the surrounding area. During the winter the predominant direction of the winds is west and northwest. The direction frequency of winter winds for Ottawa is given in Figure 8.

Test Track Sections

Four different cross-section track sections comprising nine test beams were installed on the test site. During the 1969-70 season four test beams were installed at temporary locations, and while an additional five beams were received in 1970, it was not until 1971 that all beams were installed on their final test locations. The test sections were mounted on concrete columns at a height sufficient to allow for ground drifting without effect but at a convenient height for photography and maintenance. In practice the tracks would be mounted somewhat higher to allow for vehicle underpasses.

The cross-sectional dimensions of the various test beams are given in Figures 9 to 12 inclusive. The box beam was actually two short sections mounted end-to-end to form a 10.5 meter (35 ft) long test section. All other test pieces are 12 meters (40 ft) long. The π-shaped beams were precast sections chosen to provide simple horizontal surfaces of approximately the same width as the box beam. One inverted Tee is a slightly modified version of the Bertin track. Three of the inverted Tees were precast inverted roof beams. The dimensions are slightly different from those of the Bertin track. The channel track consists of two precast inverted Tees mounted in parallel to form a channel with horizontal external fins.

Snowfall Accumulations

During the winters 1969-70 and 1970-71 the test beams were on temporary sites with only timber supports above the surrounding ground level. In one storm during 1969-70 it was observed that snow can accumulate to depths varying from 22.5 to 47.5 cm (9 to 19 in.) on the inverted Tee beam while only 5 cm (2 in.) had deposited on the π-shaped beams. It was noted during the 1970-71 season that snow did not accumulate on the horizontal surface

Figure 1. Mean annual snowfall.

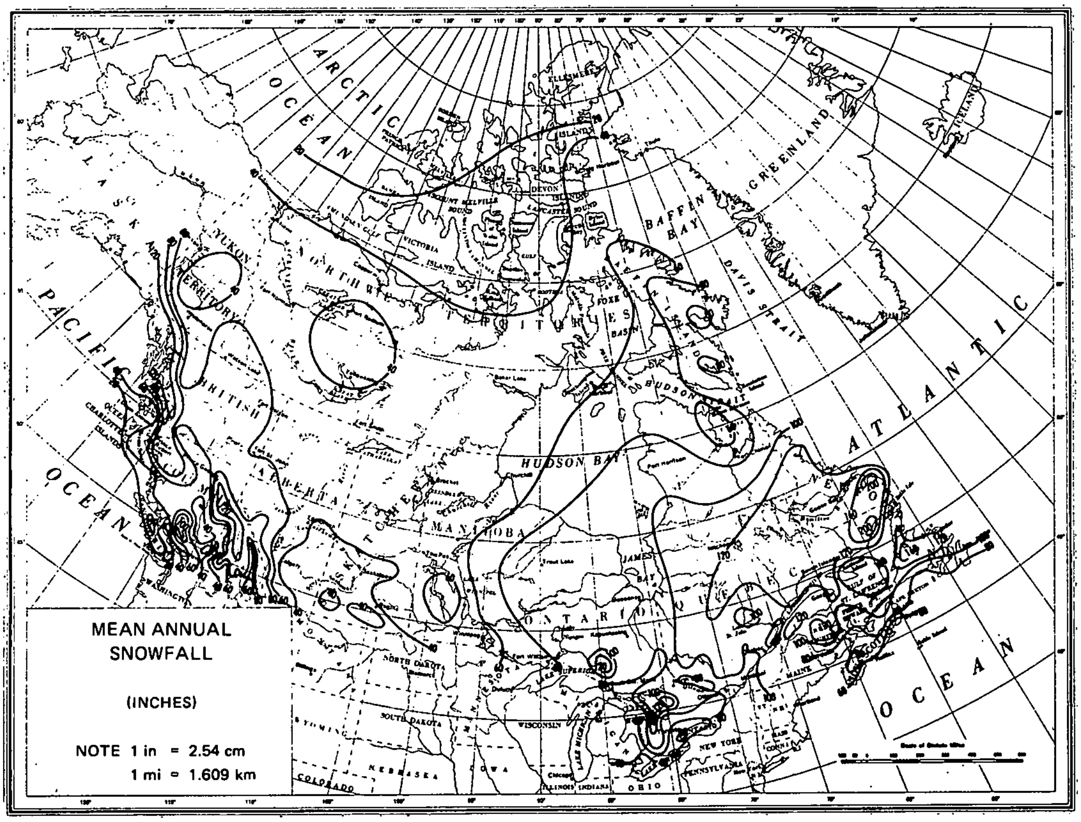


Figure 2. Mean annual number of days with measurable snowfall.

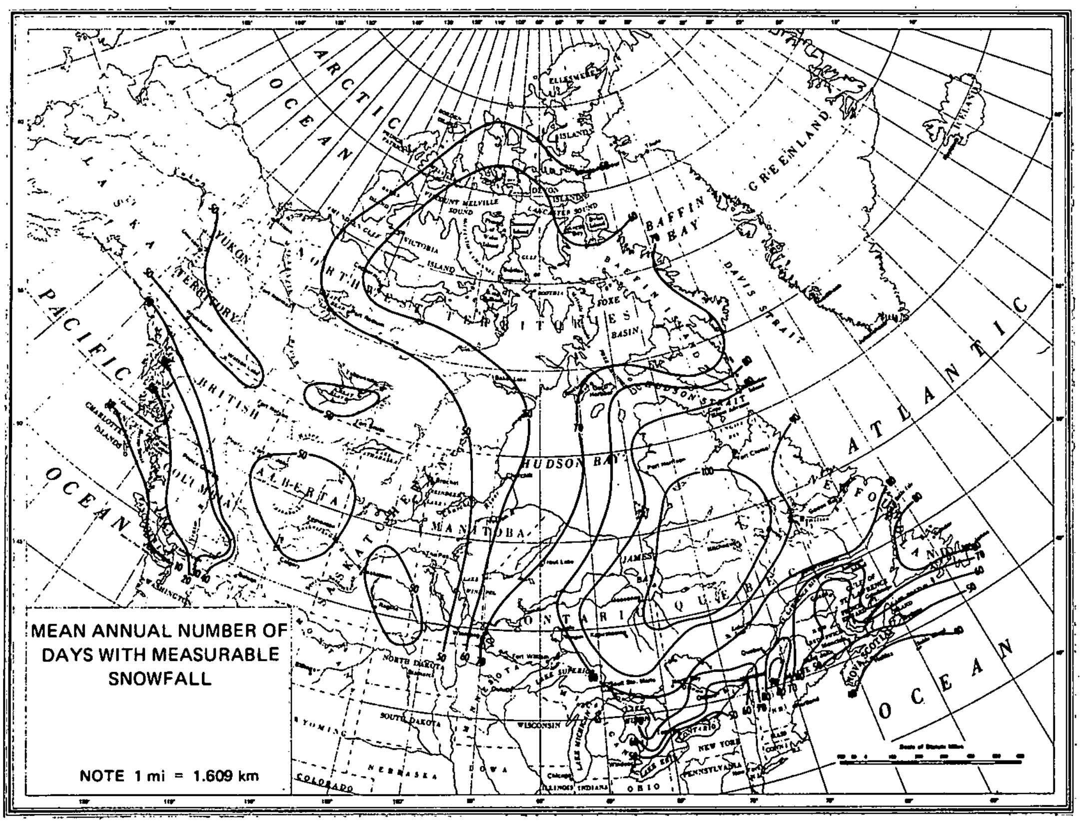


Figure 3. Mean winter season wind speed.

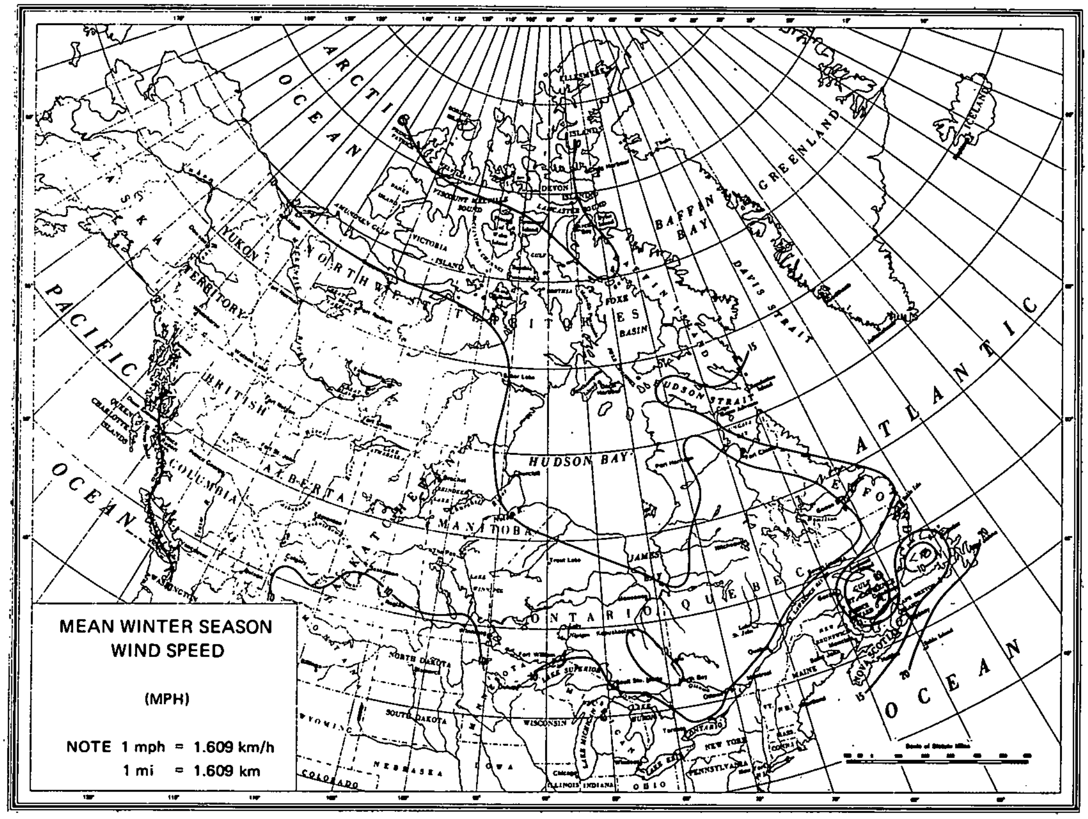


Figure 4. Maximum recorded depth of snow on the ground 1941-50.

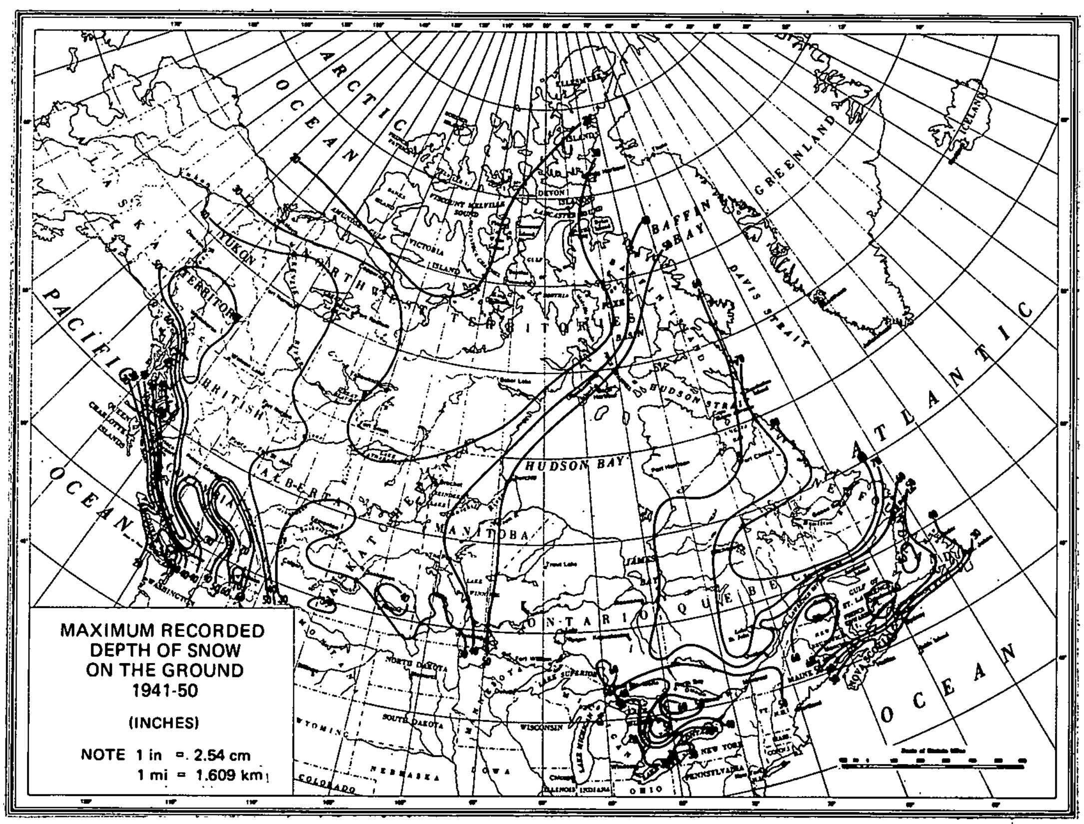


Table 1. Mean monthly and annual snowfall at selected major cities.

City	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	Apr.	May	June	Annual
Vancouver, B. C.			2.5	10.1	25.4	15.2	5.1				58.3
Victoria, B. C.			2.5	5.1	12.7	5.1	2.5				27.9
Calgary, Alta.	7.6	12.7	15.2	15.2	17.8	20.3	25.4	25.4	7.6	2.5	149.7
Edmonton, Alta.	2.5	10.1	20.3	22.8	22.8	20.3	20.3	15.2	2.5		136.8
Regina, Sask.	2.5	7.6	17.8	15.2	17.8	17.8	17.8	10.1	2.5		109.1
Winnipeg, Man.		7.6	22.8	20.3	25.4	20.3	20.3	10.1	2.5		129.3
London, Ont.		2.5	25.4	40.6	43.2	38.1	27.9	7.6			185.3
Ottawa, Ont.		2.5	17.8	45.7	43.2	43.2	35.6	7.6			195.6
Toronto, Ont.			12.7	25.4	35.6	33.0	25.4	7.6			139.7
Montreal, Que.		2.5	20.3	53.3	58.4	58.4	48.3	10.1			251.3
Quebec, Que.		2.5	33.0	58.4	73.7	66.0	53.3	27.9			314.8[a]
Saint John, N. B.			12.7	40.6	50.8	48.3	35.6	15.2			203.2[a]
Halifax, N. S.			5.1	33.0	45.7	48.3	35.6	12.7			180.4
St. John's, Nfld.		2.5	12.7	63.5	73.7	68.6	48.3	15.2	5.1		289.6[a]

Note: 1 cm = 0.3937 inch.

[a]Period 1921-1950, all other data based on standard 30-year period from 1931-1960.

Source: Department of Transport, CIR-3977, TEC-503, 24 Jan./64.

Table 2. Drifting snow density vs height.

Height Above Ground (cm)	Strong Wind (16m/sec) Snow Density %
100-200	1.3
50-100	2.0
30-50	1.6
20-30	1.8
10-20	5.9
0-10	87.4

Note: 1 cm = 0.3937 inch. 1 m/sec = 3.28 ft/sec.

Source: National Research Council of Canada, TT-1038.

Table 3. Meteorological data - winter season 1969/70

Date	Duration (hours)	Snow Thickness (cm)	Average Snowfall Rate (cm/h)	Wind Direction	Average Wind Velocity(km/h)	Temperature (°C)
22/12/69	4	4.6	1.14	S	16	-3
29/12/69	44	26.4	.61	NW	64	-8
9/1/70	6	3.0	.51	SW	16	-16
13/1/70	21	.2	.10	NE	8	-15
27/1/70	15	13.7	.91	E	24	-7
3/2/70	16	15.7	.99	NW	40	-9
10/2/70	30	48.3	1.60	W	32	-7
2/3/70	27	24.6	.90	E	32	0

Note: 1 cm = 0.3937 inch. 1 cm/h = 0.3937 inch/hr. 1 km/h = 0.6214 mph. °C = 5/9 (°F-32).

Table 4. Meteorological data - winter season 1970/71

Date	Duration (hours)	Snow Thickness (cm)	Average Snowfall Rate (cm/h)	Wind Direction	Average Wind Velocity (km/h)	Temperature (°C)
16/11/70	24	12.7	.51	NNE	24	.6
4/12/70	10	13.0	1.30	ENE	29	-12
7/12/70	14	7.1	.51	NW	32	-14
10/12/70	20	25.9	1.27	ENE	32	-13
14/12/70	8	10.2	1.27	ENE	19	-14
18/12/70	6	11.7	1.96	ENE	42	-8
21/12/70	16	14.0	.86	W	39	-11
23/12/70	18	11.7	.69	ENE	34	-22
29/12/70	36	15.7	.43	NNW	26	-16
11/1/71	18	16.3	.89	NNW	16	-12
12/1/71	8	6.6	.81	NNW	27	-19
22/1/71	18	10.4	.56	W	31	-6
26/1/71	8	10.9	1.37	SW	37	-6
21/1/71	12	8.9	.74	W	68	-19
28/1/71		Results of Blowing Snow		W	37	-24
1/2/71	17	13.0	.76	ENE	39	-11
8/2/71	13	17.8	1.37	ENE	21	-10
9/2/71	10	21.6	2.16	W	42	-3
15/2/71	38	58.7	1.98	W	40	-9
22/2/71	27	28.7	1.07	ENE	35	-4
26/2/71	24	31.2	1.40	ENE	26	-2
5/3/71	16	31.2	1.93	WNW	48	-4
9/3/71	12	20.8	1.93	WNW	35	-9

Note: 1 cm = 0.3937 inch. 1 cm/h = 0.3937 inch/hr. 1 km/h = 0.6214 mph. °C = 5/9 (°F-32).

Table 5. Meteorological Data - winter season 1971/72

Date	Duration (hours)	Snow Thickness (cm)	Average Snowfall Rate (cm/h)	Wind Direction	Average Wind Velocity (km/h)	Temperature (°C)
7/11/71	14	2.0	.15	WSW	26	-4
10/11/71	23	8.1	.36	NNW	19	-5
12/11/71	17	2.8	.15	NNE	11	-4
21/11/71	16	7.6	.48	NNW	24	-2
27/11/71	26	4.1	.15	E	27	-7
30/11/71	34	10.4	.30	NNE	27	-8
6/12/71	22	9.7	.43	E	26	-11
15/12/71	8	2.8	.36	ESE	40	-7
20/12/71	23	5.8	.25	ENE	19	-13
27/12/71	10	10.2	1.02	ENE	19	-19
30/12/71	14	14.2	1.02	ENE	42	-18
2/1/72	13	6.6	.51	W	34	-9
4/1/72	23	4.1	.18	NE	24	-10
6/1/72	33	2.8	.08	E	16	-23
13/1/72	6	2.8	.46	NW	58	-10
17/1/72	13	11.7	.89	SSW	27	-20
20/1/72	12	9.9	.81	W	24	-13
28/1/72	7	3.0	.43	SW	18	-11
3/2/72	32	42.4	1.32	ENE	39	-14
13/2/72	18	14.2	.79	ENE	32	-8
19/2/72	36	16.3	.46	ENE	37	-11
21/2/72	20	8.1	.41	E	26	-22
26/2/72	11	2.5	.23	ENE	26	-12
29/2/72	12	4.1	.33	N	23	-7
1/3/72	43	28.2	.66	ENE	35	-11
4/3/72	10	2.5	.25	E	24	-19
5/3/72	5	2.8	.56	WNW	31	-12
7/3/72	20	4.1	.20	ENE	34	-17
18/3/72	33	3.0	.10	NNW	35	-9
22/3/72	34	16.2	.38	ENE	37	-5

Note: 1 cm = 0.3937 inch. 1 cm/h = 0.3937 inch/hr. 1 km/h = 0.6214 mph. °C = 5/9(°F-32).

Figure 5. Ottawa area.

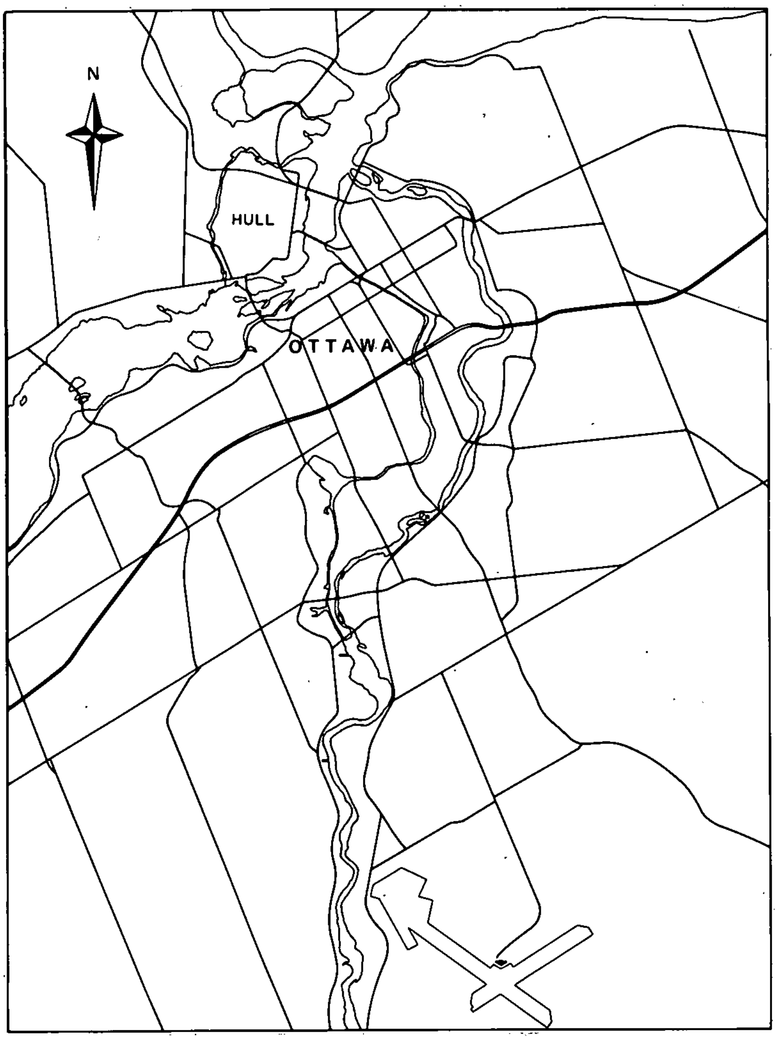


Figure 6. Ottawa International Airport (Uplands)

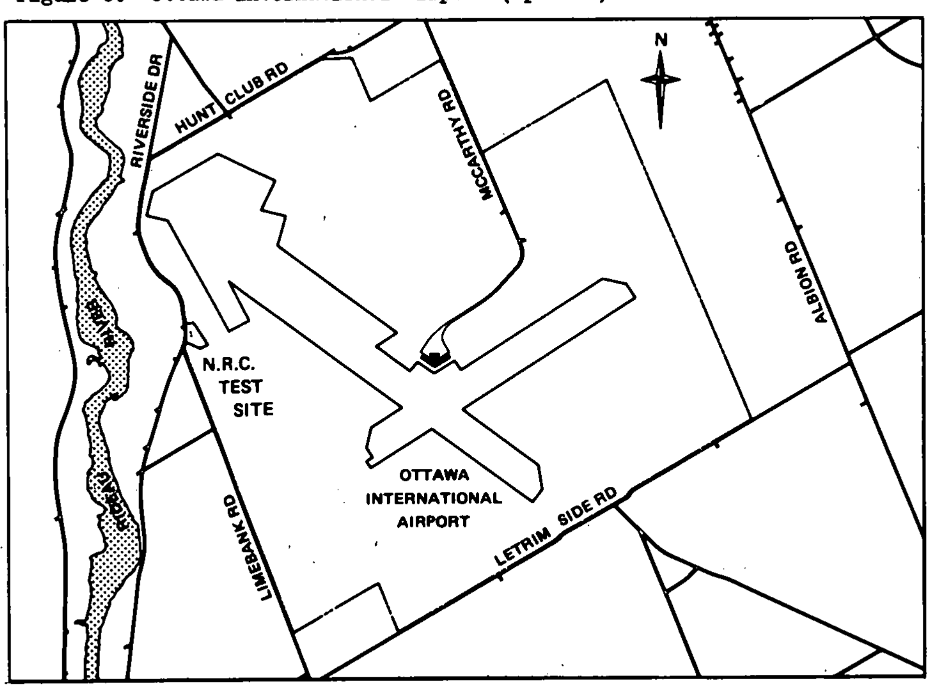


Figure 7. Test site.

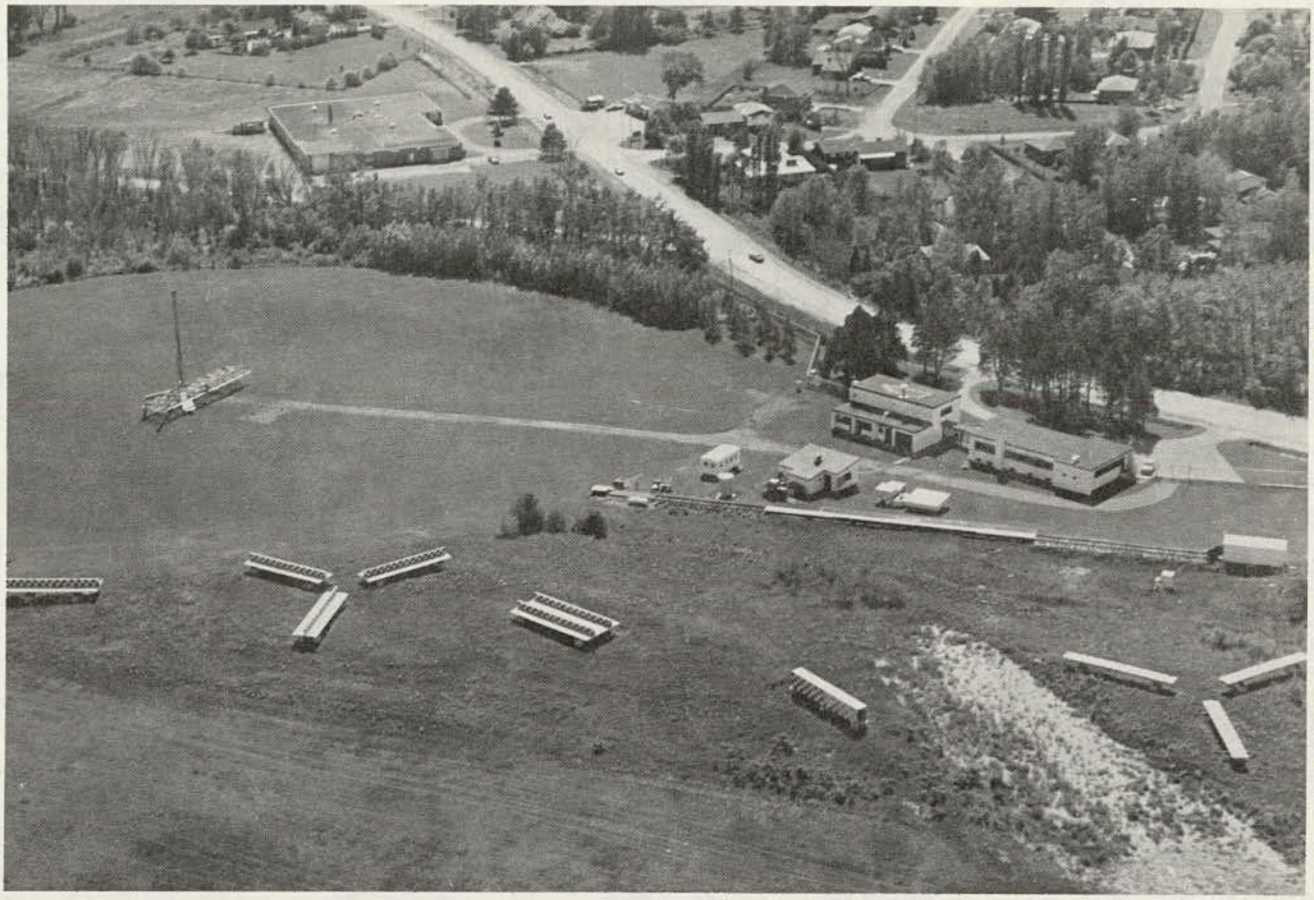


Figure 8. Direction frequencies of winter winds for Ottawa.

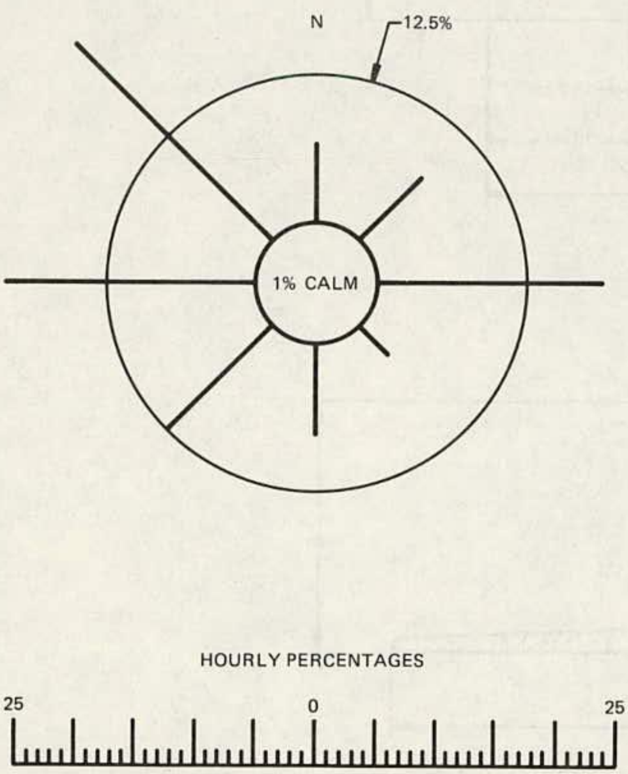


Figure 9. Box beam section.

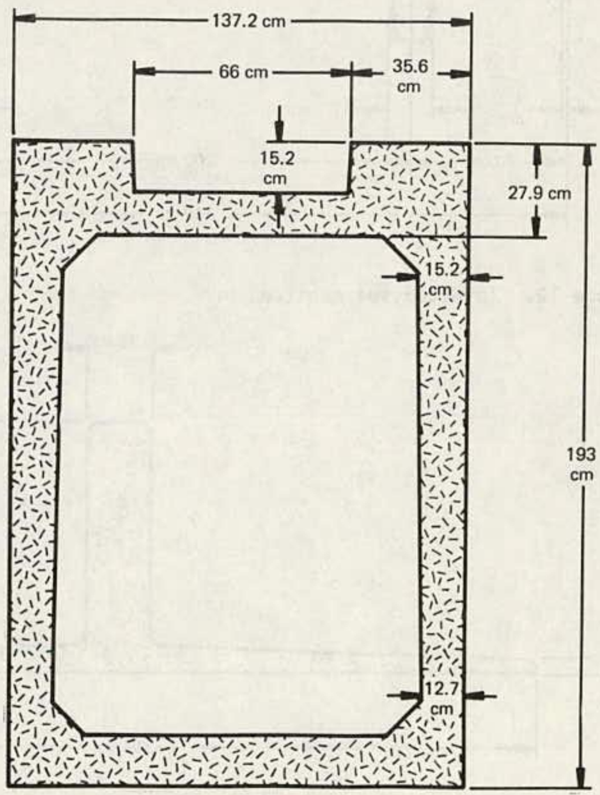


Figure 10. π section.

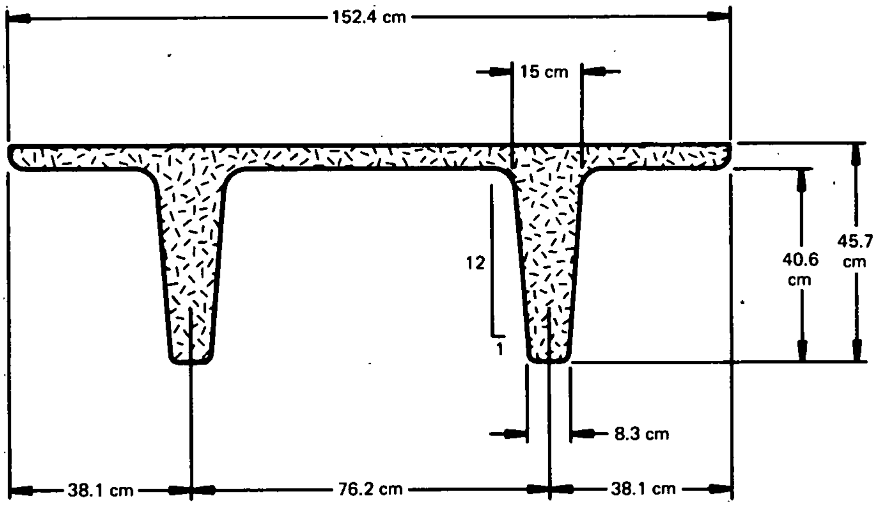


Figure 11. Bertin beam (modified) section.

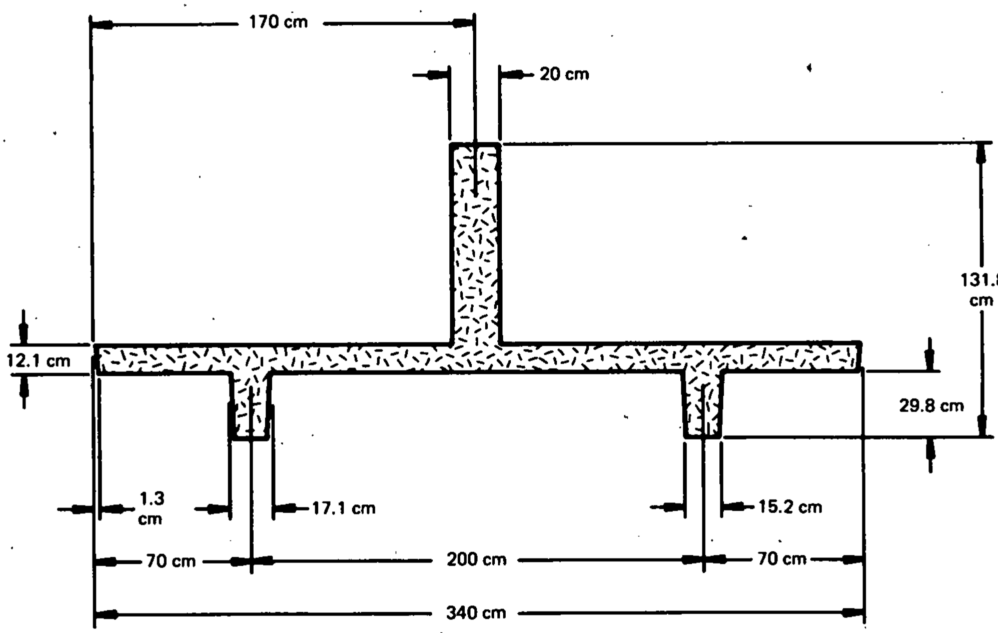
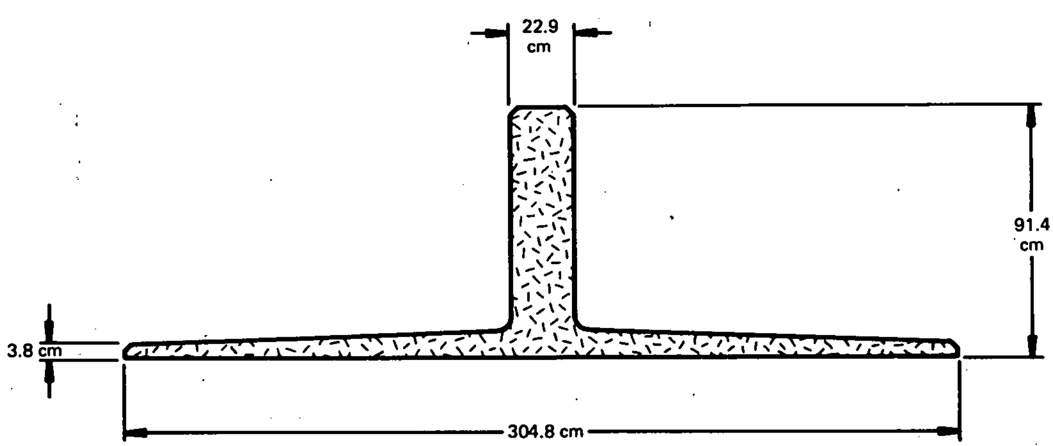


Figure 12. Inverted tee section.



of the π-shaped beam at wind velocities over 16 km/h (10 mph).

During the years subsequent to 1971 it has been observed that the depths of snowfall accumulations are always much less on the box beam and the π-shaped beam except when the wind velocity is very low. Snowfalls during a calm period or at low velocities have deposited equivalent depths on all beams; however, these storms have been the exceptions in the Ottawa area.

With a wet sticky snow both the horizontal and vertical surfaces of the test beams accumulated a cover. Wind driven wet snow also accumulated on the horizontal surface of the π and box beams.

The channel section generally accumulated an average depth somewhat less than the inverted Tee beams with the same orientation to the wind. The maximum depths of accumulations were similar, although the extent of coverage was somewhat less for the channel during wind conditions.

Conclusions and Recommendations

With a snowfall at low wind velocity all track sections accumulated snow at the same rate and obviously from a materials handling aspect the track with the narrowest width has a major advantage for snow clearance.

With snowfall at high wind velocities in cross flow to the track the plane horizontal surface design accumulated much less snow and has the minimum distortion. With dry snow and velocities of 24 km/h (15 mph) or greater there is little or no snow accumulation.

Track sections with vertical members extending above a horizontal surface cause distorted accumulations in snowfalls with winds of more than 11 km/h (7 to 8 mph). In cross flow a vertical member acts as a 100% density snow fence causing a snow deposit with a ridge parallel to the vertical member.

The track sections tested were not sufficiently long to examine the effects of wind driven snow in the longitudinal direction.

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Combatting Ice on Airtrans and Other Guideways

Robert J. Patton and Roland R. Raven, Vought Corporation, Dallas, Texas

The AIRTRANS transportation system at the Dallas/Fort Worth Airport, manufactured by the Vought Corporation, is fully automated and transports people and cargo throughout the airport complex. The AIRTRANS system uses 13 miles of guideway with 68 vehicles to interconnect 4 terminals, 2 remote parking lots, a hotel and the maintenance areas. The AIRTRANS system operates 24 hours a day, 7 days a week and has accumulated a total of 14 million vehicle miles since the opening of the airport in 1974. The system was designed specifically for the climatic environment of the Dallas/Fort Worth, Texas area. The original plan for operation during the infrequent periods of severe weather was that the constant vehicle movements throughout the system would keep the guideway and wayside system clear of ice and snow. This procedure proved completely inadequate and has resulted in system shutdown during periods of severe ice and snow. Buses and trucks are used during these periods to provide movement of people and cargo. This paper describes the approach the Vought Corporation undertook to combat the AIRTRANS environmental problems. The proposed improvements were considered too costly for the few days of severe weather and resulted in backup bus service at onset of icing weather. It is essential that for site specific applications, a Systems Engineering approach be utilized in order to match performance requirements with cost effective methods. Finally, a full scale demonstration is required to validate the selected approach.

Introduction to AIRTRANS

The AIRTRANS transportation system of the Dallas/Fort Worth Airport (Figure 1) was designed to transport people and cargo throughout the airport complex safely and automatically. The 4 terminals, 2 remote parking lots, hotel, and maintenance areas are interconnected by AIRTRANS, using 13 miles of guideway (Figure 2) with 51 people vehicles and 17 cargo vehicles. The vehicles (Figure 3) travel over the guideway on a series of dedicated routes, 5 for passengers, 4 for employees and 3 for cargo. The routes overlay each other forming a complex network. Over 24,000 switch operations and 9,000 station stops per day occur throughout the system. The vehicles stay on their individual routes taking the proper direction at switches, unless rerouted by the central control operator.

The AIRTRANS system employs sophisticated computers and other electronic equipment to provide operational efficiency and flexibility; however, the operational safety of the AIRTRANS system depends on the high reliability railroad relays and hard wiring in the vehicles and wayside electronic units. A traditional fail-safe approach to automatic signalling, proven by decades of service in the railroad industry, has been adapted for AIRTRANS. Failures of individual relays, modules, computers, power supplies, pneumatic systems, etc., may stop the operation of a single train or the entire system, but, in all predictable circumstances, every vehicle is fully protected from collision with other vehicles. If central control or any other element of the supervisory system fails, vehicle operation will continue safely and automatically, though at a sub-optimum performance level.

The AIRTRANS system was designed specifically for operation at the Dallas/Fort Worth Airport and the climate of this area. Specification requirements included 0° ambient temperature, operation in winds up to 65 mph and blowing snow; but not combined. Originally, it was assumed that frequent vehicle operation would keep the guideway system clear of ice and snow. This plan proved completely inadequate, and it was realized that additional steps would be required even for the Dallas/Fort Worth area. The onset of a "blue norther" with freezing rain has shut the entire system down within four (4) minutes or less.

AIRTRANS Vehicle Configuration

The AIRTRANS passenger vehicles (Figure 3) are designed to transport 40 passengers in an environment of comfort and quality comparable to aircraft travel. Upholstered seats, vertical handholds, a carpeted floor, heating and air conditioning, light level sufficient for reading, tinted windows, and ABS

FIGURE 1
D/FW AIRPORT
AT DALLAS/FORT WORTH, TEXAS

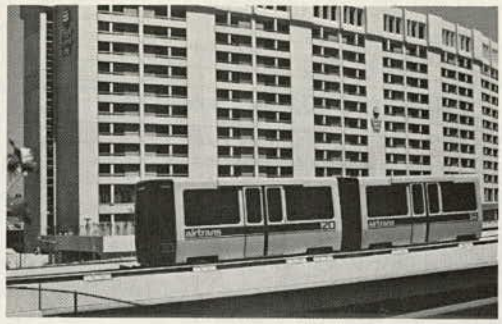


FIGURE 3
AIRTRANS VEHICLE
PASSING AIRPORT
MARINA HOTEL

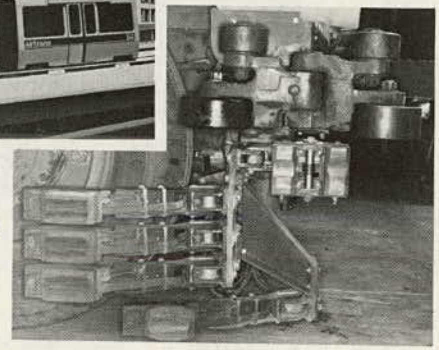


FIGURE 4
VEHICLE SIGNAL AND
POWER COLLECTION
SYSTEM

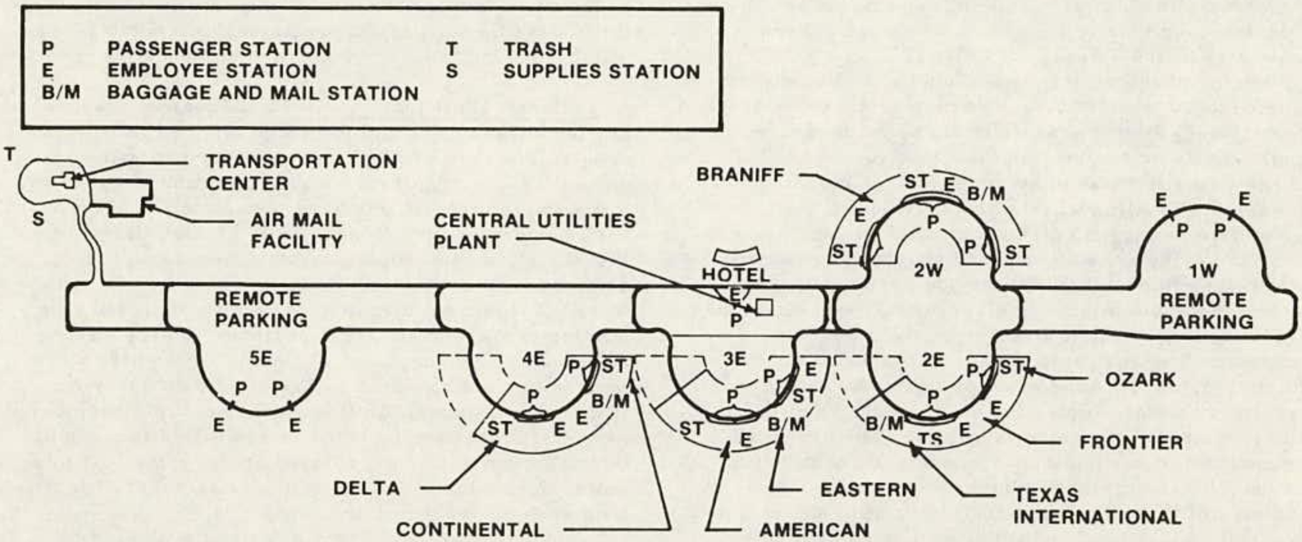


FIGURE 2
GUIDEWAY AND TERMINAL LAYOUT
AT D/FW AIRPORT

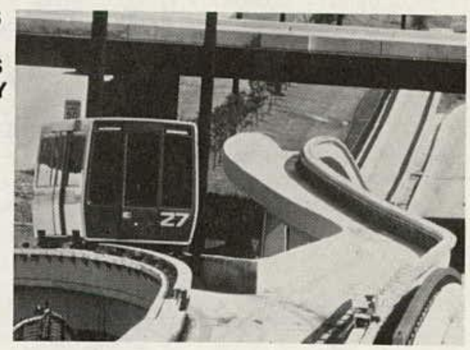


FIGURE 6
VIEW OF
AIRTRANS
GUIDEWAY

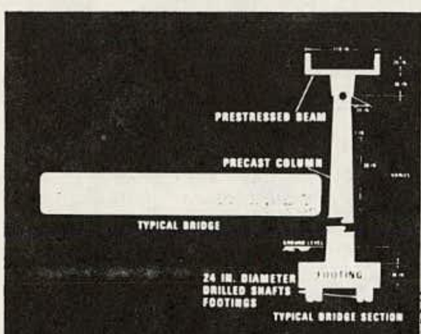


FIGURE 5
CROSS SECTION
OF AIRTRANS
ELEVATED
GUIDEWAY

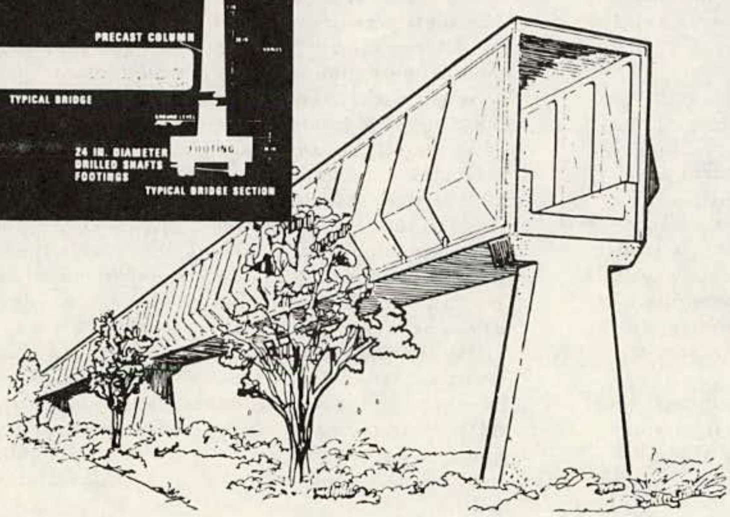


FIGURE 7
PLASTIC COVERED
GUIDEWAY CONCEPT

plastic interior panels are tastefully utilized within the vehicle.

The vehicles operate both as single and two-car consists. Each vehicle is 21 feet long, 10 feet high and 7 feet wide. The steel frame acrylic skinned fiberglass bodies are suspended on a chassis by air bag suspension units. Bi-parting doors are provided on one side and emergency egress doors are located at each end of the vehicle. Shock absorbing bumpers which can absorb 3 mph impacts are located at each end of the vehicle. Mechanical and electrical coupling is provided for multiple car operation.

Vehicle propulsion is provided by a 60 horsepower electric motor coupled through a differential and planetary gear reduction to the wheels. The motor is controlled by a controller which converts 480V, 3 phase, 60 hertz power into a variable voltage DC through SCR's (silicon controlled rectifiers). Drum brakes in the wheels are used for service and emergency braking. Service braking is pneumatic for application while emergency braking is spring applied with pneumatic hold off. Fail-safe operation is achieved since loss of pneumatic pressure causes application of the emergency brakes.

Steering of the vehicle is accomplished by polyurethane covered wheels in each corner of the vehicle which roll on the vertical walls of the guideway. These wheels are connected through a mechanical linkage to the Ackerman steering linkage mounted on both axles. Smaller wheels are provided in the same mechanism to engage entrapment rails in switch areas where the guideway walls spread apart. The entrapment rails and switch rails provide positive containment of the vehicle through diverge and merge switches. The 480V, AC power is brought onboard the vehicle by 3 collector brushes located at each corner of the vehicle (Figure 4). The brushes are a carbon/graphite material which slide on copper capped steel rails mounted on the guideway walls. The brushes are mounted on spring loaded arms made of injection molded FRP (fiberglass reinforced plastic). The geometry of the rails, particularly in switch areas, is arranged so that two brushes of each phase are always in contact with rails so that arcing never occurs.

In addition to carrying passengers, the AIRTRANS system is designed to carry cargo. Cargo vehicles which can carry 3 large containers operate in the same guideway, intermixed with the passenger vehicles. Special cargo stations which can automatically off-load and on-load any combination of the containers are provided throughout the system. The cargo vehicles are equipped with the same subsystems as the passenger vehicle except those functions particularly related to that vehicle's purpose.

AIRTRANS Guideway Configuration

A pre-stressed concrete box beam is combined with two parapets to form the channel-shaped structure (Figure 5) required to support the AIRTRANS vehicle system. The beam upper surface (or traction surface) is sloped toward the beam centerline to form a trough utilized to conduct water away from the vehicle wheels. The trough conducts the water to a low grade point where it is then introduced into a pipe submerged in the structure and then down a column into a storm sewer.

The parapet is utilized to position and support the wayside signal and power rails. Steering inputs are provided by the vehicle guidewheels acting along the parapets inner surfaces.

The parapet upper surface serves to support the switchblade and entrapment rails in the guideway merge areas. The switch actuating mechanism is housed in the box beam.

Most of the guideway features described thusfar are encompassed in Figure 6 which shows a segment of the AIRTRANS guideway. Note the channel shaped guideway, the power and signal rails and the entrapment rails.

The upper rail on the parapet inner wall is the signal rail, the next lower three are 480V power rails and the lowest is the ground rail. There are approximately 10 miles of at-grade guideway and 3 miles of elevated guideway.

Vought's Approach to Combatting AIRTRANS Ice and Snow Problems

The initial problems encountered by AIRTRANS in snow and ice conditions were: 1) loss of signal, power and ground continuity to wayside; 2) traction of the main support wheels. Comprehensive programs for both of these specific problems were established which involved laboratory and guideway testing.

Collector/Rail Interface. To adequately assess any potential solution to the collector/rail interface problem, a snow and ice test chamber with wind capability was required. Since comprehensive testing of the collector/rail interface dynamics had already been performed on a Vought-built 12 foot diameter test wheel, an environmental chamber was built around the wheel. Wind velocities of up to 40 mph were incorporated by using a blower and closed loop ducting arrangement. Test chamber cooling was accomplished through use of liquid CO_2 and ice was formed by cooling water to 33°F and then spraying it into the chamber. Initial operation of the chamber established that ice buildups of 1/8 to 1/4 inch could be easily and uniformly formed on the rails. At this point, development testing of the collector/rail interface problem was initiated.

Various brush configurations were evaluated to try to secure a scraping action removal of the ice. These included: cast iron, copper impregnated carbon, wood and other materials machined with grooves and flutes. All of these approaches were unsuccessful, and it was learned that a layer of ice (or frost) as thin as .01 inch was sufficient to cause loss of signal or power continuity. It had always been felt that the power rails would arc through the ice to the brush; however, this proved not to be true. The tests were performed by pulling the collector arms back from the rail while the ice was formed, and then dropping the arms to obtain contact. Although constant contact is not required for vehicle operation, the time of individual discontinuity permissible is quite short. As previously mentioned, the power collectors are arranged so that two brushes are always in contact with the rail. This also was incorporated in the cold chamber tests. Other approaches tried included a high contact pressure wheel to crush the ice and increasing the normal force on the scraping brush from 9 to a high of 40 pounds. Seventy-seven separate attempts were made to scrape or crush the ice from the rail before it was concluded that the ice bond was too strong to break mechanically. Several chemical treatments were tried unsuccessfully prior to experimenting with ethylene glycol. This solution successfully prevented the ice bond from forming and would not wash away immediately during rainfall. This material by itself, however, was not sufficient for satisfactory rail/collector continuity and it was determined through additional testing that:

1. The brush contact force would have to be increased by 50%.
2. A scraper (grooved) brush configuration of copper carbon material.
3. Heaters placed behind the brushes to keep ice from clogging the scraper grooves.

This configuration used in conjunction with the ethylene glycol on the rails produced repeatable satisfactory results and was considered acceptable for incorporation into the AIRTRANS system.

A spray rig to distribute the ethylene glycol was built onto an AIRTRANS utility vehicle and consists of an insulated, heated 200 gallon storage reservoir, a gasoline engine driven fluid pump, an insulated fluid distribution system, a front mounted manifold with attached shutoff valves and spray nozzles and an operator's cab containing the necessary controls. In operation, high pressure jet sprays are directed at operator selected portions of the channel-shaped guideway. Vehicle speed and fluid dispersal rates are matched to the conditions of the guideway. Pre-snow ice conditions or light snow conditions are conducted at normal vehicle speed (17 mph).

The spray rig has the additional capability of wiping the signal rail with the ethylene-glycol mixture when frost conditions are anticipated.

The sidewall mounted power, signal and ground rails and the wheel track running surfaces can be sprayed to provide an anti-adhesion coating prior to the formation of ice on the surfaces.

Preliminary studies of collector/rail heating were also conducted. These showed electric rail heating to have an initial cost of $768,000 plus an annual operating plus demand cost of $144,000 for eight days of operation. For the Dallas/Fort Worth area, this was not considered a cost effective solution.

Traction Surface. The traction problem on AIRTRANS appeared prior to the first ice and snow storm. This was caused by use of a "polishing" aggregate in the concrete, as specified by contract, and by grinding the concrete surface to assure the required vertical alignment. The grinding left a "terrazzo" like finish on approximately 25% of the guideway. To rectify the traction problem created by the "terrazzo" finish, longitudinal grooves were cut into the surface. While this helped the lateral traction of the tire, it reduced the longitudinal traction capability by some factor. The aggregate used in the concrete, crushed limestone, is the same as that used in Interstate Highway construction. Unfortunately, with repeated tracking of the vehicle over exactly the same surface area, even unground areas polished out at a rate of 4 to 6 times that encountered on Interstate Highways. The traction problems were observed initially on upgrades shortly after the start of a rain. In Texas, a layer of dust produces an excellent lubricant when moistened. A sustained rain will wash the surface with a resultant restoration of traction capability.

Based on the collector/rail tests, it was concluded that ethylene glycol would also prevent the bond from forming between the ice and concrete, and that the tire action would squeeze the resulting slush out of the tire track. While some lubricating effect of the glycol was expected, a reduction of traction capability of approximately 50% occurred, making upgrades and acceleration areas impassable.

Several approaches to the wet weather traction problem were considered. A temporary solution was implemented in critical guideway areas by bonding abrasive (course sandpaper) to the guideway track. This immediately corrected the wet traction problem and lasted longer than anticipated (over 9 months).

Considering the snow and ice traction problem along with the wet traction problem and the need for a long term solution, several other approaches were evaluated. These approaches included:

1. Mechanically attaching an expanded metal grid (1 3/4 x 3 1/2 inch diamond shaped) to the guideway surface. While this proved effective in icing conditions, chunks of rubber were shed from the tire in high torque conditions. Normal operation did not damage the grid or tires.
2. Sand spread on the traction surface was found to be a clean-up problem, would accelerate brush wear and contaminate the traction motors and other mechanical equipment.
3. Urea, a nitrogenous compound ($CO(NH_2)_2$) used on airport runways as a deicer was tried and found to be corrosive to copper (used on the collector/rail faces) and potentially the reinforcing steel in the concrete.
4. Explosive driven nails and nails in pre-drilled holes with anchors in the traction surface were evaluated. The explosive nails were driven with a 22 caliber charge and protruded 1/4 inch above the surface. Since the concrete was completely hard (two years old), cratering of the concrete occurred as much as 1.5 inches in diameter by 3/8 inch deep. Pre-drilling the holes and using anchors was considered excessively expensive. Spacing was such that only 2 nails were engaging the footprint at a time and rubber chunking was feared in a high torque condition along with minimum traction improvement.
5. Studded tires were evaluated on one vehicle operating on a particular route. Within two weeks, longitudinal grooves were detectable in the guideway in select areas of that route. Studded tire tests were stopped prior to encountering an icing condition in the guideway. Extensive guideway damage seemed apparent had the entire 68 vehicles been converted to studded tires. Estimates from highway data indicated with all cars equipped with studs we could expect 0.15 inch concrete wear per month.
6. Walnut hull impregnated tire retreads were evaluated to improve traction. While this seemed to be an improvement over the standard tires for wet traction, the magnitude was insufficient to be worthwhile for ice conditions.
7. Cross grooving of the traction area was evaluated in a 25 foot section of guideway. No spalling was observed during cutting; however, after only 50 vehicle passes, sufficient spalling had occurred to make this approach unacceptable. This may have been caused in part by the longitudinal grooving mentioned before which resulted in a waffle pattern on the surface.
8. A change to the control system to reduce to jerk rate (rate of change of acceleration) and the acceleration rate were considered since it had been observed that a vehicle under manual control could accelerate up a grade that a vehicle under automatic control could not. Development in the control system was initiated and is still being pursued.
9. A limited slip differential was installed in one vehicle for evaluation. While it operated satisfactorily as a differential, the increase in traction before breakout occurred did not warrant modification.

A slight clicking noise occurred in turns (80% of the D/FW AIRTRANS guideway is in turns). The clicking was a negative factor to consider.

10. A hot air blower unit was mounted on the front of a vehicle to evaluate melting the ice particularly from the rails. Although this was not evaluated on the traction surface, for the rails it proved unsatisfactory because the quantity of heat required was enormous when the vehicle was moving at any speed at all, and the water refroze as soon as the vehicle passed by, resulting in a condition potentially worse than what it had been before the vehicle went by.

11. Prior to turnover of the system to D/FW Airport, Vought concluded that a traction course of epoxy mixed with a fracturing (as opposed to polishing) aggregate such as calcined bauxite, aluminum oxide, carborundum or sandblasting sand (slag) should be spread over all areas of the guideway that exceeded 3% grade, and normal acceleration areas that are subject to rain (approximately 4 miles). After D/FW Airport took over operation, they applied an epoxy aggregate course in known traction problem areas.

Coincident with the collector/rail and traction surface programs, a chemical evaluation of the possible detrimental effects of various deicing and cleaning compounds on the guideway and rails was performed. Included in the study was urea, sand, "DuBois DeIce", commercial antifreezes (ethylene glycol, propylene glycol, Quaker Maid, Preston, Zerex and Rain-Bo) and commercial detergents (Vel, Triston X-100, Turco). All of the materials tested on copper-iron rails and reinforcing bars show corrosion, the commercial antifreeze mixture showed the smallest attack. Urea and urea combined with all the above materials show increased corrosion of iron. The "DeBois DeIce" compound severely attacks copper, but does not significantly affect iron. The Vel or Triston X-100 are good cleaning agents for the rails. The Turco detergent both corrode the copper rail. Sand will not interact with any of the materials tested to aggravate corrosion.

D/FW Procedures for Operation of AIRTRANS in Severe Weather

Severe weather conditions are anticipated through the monitoring of all available weather information by the D/FW Airport Operations Department. The sources of information include the U.S. Weather Bureau and airline reports. When indications dictate, one of the following conditions is declared by the Operations Department:

1. Weather Alert. When all available information indicates that a potentially hazardous weather condition will be in the area of the airport within 24 hours.
2. Weather Emergency. When all available information indicates that a potentially hazardous weather condition will be in the area of the airport within the next 6 hours.

When a Weather Alert is declared, preparations are made to respond to a Weather Emergency. These include notification of personnel and standby equipment and readying the AIRTRANS spray rig. The spray vehicle is parked in the Trash, Dump and Wash siding. The reservoir is filled with a mixture of ethylene glycol and water. The reservoir thermocontroller is set at 180°F. Six 55-gallon drums of the mixture are placed in a supply container onboard the vehicle and drum heaters attached. The drum heaters are also set at 180°F.

Two hours prior to forecast of severe weather onset spraying of the guideway and rails is initiated. The areas to be sprayed depends on the type of weather anticipated. Removal of the AIRTRANS system from revenue service is a judgment by the Central Control Supervisor based on the forecast. When removal from revenue service is initiated, the passengers are off-loaded at stations and the vehicles stored in the terminal building. A backup bus system is then activated which transports the passengers over the motor vehicle roadway.

The spray rig continues to operate until the entire guideway system is coated with glycol or until weather conditions deteriorate so that operation must be halted.

For snow or ice accumulations which exceed the capability of the spray rig, manual removal techniques are used after the accumulation ceases. These methods include the use of self-propelled portable snow blowers and shovels. Experience has shown that the application of ethylene glycol prior to ice/snow accumulations greatly eases the subsequent removal operations.

These techniques have enabled the AIRTRANS system to maintain normal operations during frost conditions and have permitted rapid return to service following snow or ice accumulations which required cessation of operation. Actual levels of service achieved during the past 2 years are compared below. It should be noted that the service availability values are based on a system operational time of 24 hours a day, 365 days a year.

Table 1. Levels of service achieved during past 2 years.

Calendar Year	Service Avail. Total	Service Avail. Exclusive of Ice/Snow	Total Hours Lost Due to Ice/Snow
1978 (thru 3/4/78)	76.0%	98.7%	344
1977	95.1%	97.4%	214
1976	97.5%	98.0%	33

Alternate Approaches to Ice and Snow Control on AGT Guideways

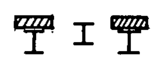
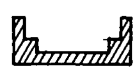
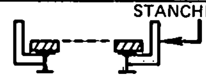
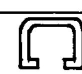
The foregoing discussions dealt with the ice and snow measures that were developed specifically for AIRTRANS: an existing system at a particular airport in a moderate climate. If the candidate solutions for that situation seem numerous, then, the list of alternatives is, indeed, even greater when one is free to consider a wide choice of feasible approaches. Such latitude might be the case during conceptual design or when considering a new installation. The diversity of ice and snow measures for AGT systems is illustrated by the tabulations on Table II. This table attempts to name the different approaches that are feasible or that are backed up by some precedent. From this wide choice of alternatives, the correct solutions for a given AGT installation are dictated by many factors, most of which are constraints resulting from considerations of:

TABLE II SNOW AND ICE CONTROL METHODS

I. GUIDEWAY MEASURES
- A. Traction and Snow Handling
  1. Covered Guideway
  2. Subway
  3. Wind Swept Guideway
  4. Tractive Surface Treatments
  5. Elevated Guideway
  6. Snow Plows
  7. Snow Blowers
  8. Sanding
  9. Salting and Other Solid Chemicals
  10. Spraying Glycol Solution
  11. Spraying Methanol
  12. Heating with Pipes and Pumped Fluids
  13. Heating with Buried Electrical Wires
  14. Heating with Low Voltage on Buried Mesh
  15. Heating with Conductive Asphalt
  16. Heating with Earth Heat and Heat Pipes
  17. Heating with Flowing Ground Water
  18. Heating with Radiation
  19. Continuous Blowing with High Velocity Air
  20. Coating with Hydrophobic Films
  21. Elevated Gratings for Running Surface
  22. Steel Rails (With Steel Wheels)
  23. Linear Induction Motor
  24. Aerial Tramway
- B. Collector and Control
  1. Rail Heating
  2. Covered or Enclosed Rails
  3. Inverted Rails with Side Covers
  4. Glycol Spray
  5. Rugged Steel Rail (With Aggressive Scraping)
  6. Flexible Catenary Overhead (With Scraper)
  7. Inductive Control (Contactless)

II. VEHICLE MEASURES
- A. Traction
  1. Tire Chains
  2. Steel Wheel (On Steel Rail)
  3. Studded Tires
  4. Snow Tires
  5. Positive Cog Drive
  6. Linear Induction Motor
  7. Slip/Slide Systems
  8. Reduced Speed
  9. All Wheel Drive
- B. Collectors
  1. Brush Heating
  2. Scraper Brushes
  3. High Contact Pressure
  4. Servo-Aimed Laser to Loosen Ice From Rails
- C. Systems and Components
  1. Heating
  2. Shielding
  3. Periodic Cleaning with Hot Water Spray
  4. Vortex Separators on Air Intakes
  5. Hydrophobic Paints
  6. Ice Scrapers on Piston Rods
  7. Air Inflated Boots
  8. Ice Excluding Designs
  9. Ice Tolerant Designs

TABLE III
PRINCIPAL FEATURES OF PROMINENT AGT SYSTEMS

SYSTEM	SUSPENSION			PROPULSION			GUIDEWAY TYPE
	RUBBER TIRE	AIR CUSHION	STEEL WHEEL	COLLECTOR RAILS	CONVENTIONAL ELECT. MOTOR	LINEAR MOTOR	
Westinghouse	X			X	X		
Unimobil	X			X	X		 STEEL BOX GIRDER
Rohr "P"	X			X	X		
Ford ACT	X			X	X		
AIRTRANS	X			X	X		
Morgantown	X			X	X		STANCHION 
Wedway			X			X	
Cabinenlift	X			X		X	
Otis		X		X		X	

- economics or cost
- implementation
- function or effectiveness
- aesthetics.

Of the alternatives shown on Table II, some might provide a complete solution and others are best utilized in combination.

A survey of the candidate DPM* automated guideway systems quickly reveals the majority are rather conventional, electrically powered vehicles running on a dedicated guideway or surface. Table III attempts to identify the principal features of these systems. The features they have most in common are open guideways, rubber tires and rail/collector systems. Some of these systems display a degree of natural tolerance to ice and snow. However, it is toward those conventional vehicle systems that the bulk of ice and snow operational developments is directed.

Clearly, the most effective means for all-weather operation is provided by "protected" guideway systems which includes subway, covered guideways (Figure 7) and those monorails wherein the tractive components run inside the suspension beam. These are completely effective because they do not expose any of the functional aspects of the system to weather. Each of these approaches, however, are characterized by some undesirable constraint: subways are prohibitively costly for most installations; covering the entire above-ground guideway may meet with objections for their cost and aesthetic intrusions (especially in downtown scenarios). Overhead monorails enjoy wide use but in some instances impose certain requirements on vehicle characteristics and pose aesthetic concerns for certain applications. These objections are probably more intense in the DPM application because of the fact that the systems will be installed into available space of an already developed business district. The environmental and safety concerns weigh heavily.

Next in terms of inherent all-weather effectiveness are steel wheel/steel rail concepts. There is vast experience with steel wheel/steel rail in heavier equipment and they are inherently ice and snow tolerant where traction is concerned because of the ability of the small area, high stress situation to break down and melt the ice. Rail systems, however, have experienced only limited consideration for AGT vehicles because conventional rail usage concepts bring on aesthetic and operational objections when they are applied to AGT type scenarios.

The conventional vehicles that comprise the majority of automated vehicle systems rely primarily on rubber tires and more or less conventional suspensions. Seven of the nine DPM-approved systems fit this category. If the guideways of such vehicles are chosen not to be covered, then the vehicles and guideways will be subject to weather and their ice and snow operational problems can be categorized:

- traction
- accumulation removal
- power and signal rails functioning
- on-board systems functioning.

The problems are not unlike those we have all experienced with automobiles in severe winter weather, except that power rail icing presents some new and unique problems. Indeed, we go to highway departments for some of our most feasible solutions to ice and snow operation.

*Downtown People Mover (DOT Demonstration Program)

Guideways Deicing - Snow Removal

Removal of snow accumulations from guideways is achieved by either mechanical removal (plowing or snowblowing) or, in the case of heated guideways, by simply providing drainage for the melted snow. The unique problems associated with plowing or blowing have to do with adaptation of equipment to peculiar guideway shapes and disposal of the snow that has been removed. Disposal is often a problem because AGT guideways are frequently routed above streets, parking lots, etc., so that it is not permissible to merely "dump it over the side". Hence, the requirement to collect and dispose of it. A snow-melting transport vehicle concept similar to that in use at JFK Airport is attractive because of its ability to transport large quantities in the melted form; e.g., fewer service disruptions by snow removal vehicles.

Once the running surface is snow plowed, the remaining ice layer or compacted snow layer still requires removal to provide traction. Salts and other chemicals are known to be a cost effective means of clearing these thin surface layers on highways. However, due to recently well-publicized latent problems associated with chemical use, plus the labor intensive nature of their application, chemicals, in general, find disfavor in automated guideway systems. Chemicals create additional problems in the vast electrical and signaling systems associated with automated guideway transit.

Traction improving devices have been used extensively in other modes of transportation. These include chains, stud tires, sand, etc. These are even less attractive for automated vehicles because of their cost of implementation, damage to the guideway and, in the case of sand, requirement for subsequent removal. All these approaches impose a heavy burden on maintenance manpower.

One category of special running surfaces includes those approaches that "shed" ice and snow or make it possible to be easily scraped away (see Table II). Experience with bridges and elevated approaches using open metal mesh or grate type running surfaces indicate a degree of effectiveness of these surfaces in permitting ice and snow to fall or be passed through these meshes and leaving the surfaces in reasonably good condition. Decreased normal traction, greater tire wear, noise and less than complete effectiveness are the undesirable characteristics of such surfaces.

A new surface treatment development that shows promise is a hydrophobic coating. Such a coating, which might be a silicone or other durable release agent, is applied to the running surface prior to precipitation and acts to prevent bonding of ice to the running surface. Traffic or scraping can then keep it broken up. The EPA has sponsored attempts to develop a practical coating. A somewhat similar approach or action might be afforded by a flexible running surface that flexes sufficiently to break up the ice. This approach will be evaluated under a future AIRTRANS program.

Clearance of ice and snow by heating of the running surfaces is an alternative that continues to gain increased use on highways, sidewalks and on automated guideways. Heat is usually supplied to the running surfaces by embedding heated fluid tubes or electrical resistance elements under the running surfaces. The energy might be supplied from a number of different sources (see Table II). Thermal anti/deicing is attractive for automated guideways because:

- it is effective
- heating systems are easily automated and do not impact the labor force requirements
- since AGT vehicles are guided, they track and therefore, only a narrow strip of pavement requires heating instead of the full width; this reduces energy use per lane
- a variety of energy sources can be used, including low temperature natural sources
- melting also alleviates the need for removal of bulk accumulations.

Guideway heating, however, is expensive, both in capital costs and operating costs. Electrically heated systems are less expensive to install than fluid systems, but are more expensive to operate, since, depending upon local conditions, electrical heat costs two to three times more than fossil fuel heat. The selection of electrical versus fossil fuel energy then is a tradeoff subject that depends upon annual energy usage and projected future cost escalations of energy.

The use of earth thermal storage and geological heat for roadway heating have both been demonstrated in highway applications and have been proven to be feasible. Using the thermal storage of earth (depths to 50-75 feet) is costly in that a large amount of heat transfer surface (pipes) must be put into the ground. Both heat pipes and active fluid loops have been proven practical for transporting the heat up to the surface. The essentially zero operating cost of such an installation can, over a period of years, offset its higher capital costs.

Geological sources (natural warm or hot water) are utilized by pumping the warm water through a heat exchanger to the circulating fluid. The operating costs are only the pumping power and maintenance. An installation of this type operates successfully in Oregon.

Solar energy for heating is very expensive and, based on at least one study, could not compete with earth or geological heat because of the heat storage requirement. Perhaps solar energy in combination with earth storage would prove a practical combination for certain sites.

Hydrokinetic removal of snow and ice (Table II) is the use of large quantities of low temperature water, at sites where it might be available, to melt ice and snow by simply flowing the water over the guideway surface. The water is drained off at certain intervals and more applied. Hydrokinetics has been used on highways in Greenland, the Scandinavian countries, and in Japan.

One demonstrated method of reduction of guideway heating costs is to restrict heating to only critical guideway sections: steep grades, station approaches, switches and merges. This is possible because it has been shown that vehicles can be operated on level non-critical sections of guideway under reduced traction conditions by employing a combination of:

- removal of appreciable snow accumulations
- 4-wheel drive
- anti-slip/slide controls
- degraded cruise speed.

This approach emphasizes that combinations of actions are likely to be the optimum approach to operation of rubber tired vehicles in exposed guideways.

Power and Signal Rail Anti-Icing

Keeping the collector system free of ice is a must. The application of electrical heat to the rail is practical for short spans, but there is little experience with long spans. The first AGT system to employ long spans of heated rails will be the Morgantown Phase II system. Hard steel rails with cast iron scrapers can be made to work with adequate pressure applied to the scrapers. Rail covers can be used; however, they interfer with switching and rail maintenance.

Application of chemicals such as glycol is effective for a short time but should not be considered a complete solution. By-products of these chemical agents are current leakage, and guideway cleaning tasks.

Recommendations

The winters of 1977 and 1978 will probably go down in history as the most severe weather periods on record. Not only does this apply to the classical winter areas but to the so-called sunshine belt of Florida through Texas to California. Cities in all regions of the country planning conventional or AGT systems must utilize a Systems Engineering approach to determine hardware requirements for their site-specific application to address their severe weather operational requirements. This scheme will match system performance requirements with the most cost effective methods available at the time.

Conclusions

Nature has demonstrated a disdain for all our systems the past two years and will continue to challenge our best efforts in this area. Although there is a long shopping list of options available for combatting ice and snow, better means are needed. Also, most of the options discussed in this paper have been investigated to a very shallow depth and in most cases their potential benefits to AGT applications have been extrapolated from data related to airports, highways, automobiles, railroads, aircraft and the construction industry.

The investments required to research these potential methods are substantial and should be funded by the Federal Government. A program planned and executed on a timely basis which includes basic engineering analytical techniques, laboratory experiments, followed by full scale hardware testing in the weather regions which produce the baseline weather, will insure that the American people have dependable mass transportation when all other forms of people movers are stuck in the snow.

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All-Weather Protection for AGT Guideways and Stations

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This paper presents a synopsis of the state-of-the-art review of winter weather protection for existing AGT (automated guideway transit) systems conducted as part of the U.S. Department of Transportation UMTA sponsored AGT Guideway and Station Technology Project. The objective of this paper is to identify the problems, experiences, and techniques associated with winter weather operation of AGT systems. The information presented was compiled through a literature search and from information provided by system and equipment operators and manufacturers. Bottom-supported, rubber-tired AGT vehicle systems are the focus of the paper as they are the only type of AGT system with significant winter operational experience. These systems include Bendix at Toronto Zoo, Boeing at Morgantown, Ford at Fairlane, Vought at Airtrans, and the Westinghouse test tracks at South Park and West Mifflin. Three AGT guideway-related areas are identified as being most susceptible to the adverse effects of winter weather--power and signal collection, maintenance of traction, and switching. The problems experienced and countermeasures currently employed in each of these areas are presented. The countermeasures include mechanical, thermal, chemical, abrasive, manual, and other approaches. The paper also identifies techniques which warrant further investigation to improve AGT all-weather operation.

All transportation systems, including rail, bus, automobile, and aircraft, suffer deterioration in service, performance, and safety during adverse weather conditions. For automated guideway transit (AGT) systems, operating without the judgment provided by a driver or on-board attendant, the problems inherent in operation during severe weather are especially important. Achievement of the high productivity potential of fully automated operation will depend in large measure upon a satisfactory resolution of the issues associated with safe and reliable all-weather operation.

AGT systems, such as those shown in Figure 1, have been carrying passengers in completely unattended vehicles since 1965, when Westinghouse, under a $5 million contract from the U.S. Department of Housing and Urban Development, installed a 3.2 km (2 mi) loop demonstration system at South Park, a suburb of Pittsburgh. It carried nearly 41,000 passengers during the 1965 Allegheny County Fair. Since then numerous AGT systems have been installed in airports, universities, and other activity centers.[1] A total of 23 domestic installations comprising over 64 km (40 mi) of guideway and almost 700 vehicles have carried in excess of 200 million passengers over the past 13 years. They range in size from systems with approximately 360 m (1200 ft) of guideway and a few vehicles to those with guideways of over 21 km (13 mi) and more than 50 vehicles. Despite this accumulated experience, information on AGT all-weather operations is fairly limited. The great majority of AGT applications have been located in regions with mild climates, have been in amusement parks which do not operate during the winter, or have the option of not operating under severe weather conditions.

To further the development of AGT systems, the U.S. Department of Transportation Urban Mass Transportation Administration has established the Automated Guideway Transit Technology Program. The objective of this AGT program is to address among others the technological, operational, environmental, and cost aspects of AGT systems and to identify solutions to problems which have been identified. The program includes three generic types of AGT systems. These are shuttle-loop transit (SLT), group rapid transit (GRT), and personal rapid transit (PRT).

The AGT program includes a number of projects. One of these--the AGT Guideway and Station Technology Project--has as its primary objective the establishment of guideway, weather protection, and station concepts which will result in lower cost AGT installations. The work related to the weather protection area currently under way in this project is the basis for this paper.

In the weather protection area, the work involves a review of existing weather protection problems and techniques used in both AGT and other related transportation systems, the development and analysis of weather protection concepts, and the testing of weather protection concepts. To date the review portion of this work has been completed. The focus of this review was on bottom-supported, rubber-tired, operating AGT systems and the difficulties associated with winter weather operation.

The review of existing AGT winter weather-related operating experiences included the Ford Fairlane system and Cherry Hill test track, the Boeing Morgantown system, the Westinghouse South Park and West Mifflin test tracks, the Vought Airtrans system, and the Bendix Metropolitan Toronto Zoo system. Though the latter is not an automated system, its design and operating characteristics are similar to those of an AGT system, and it provides operating experience in a severe winter environment.

The most severe winter operational requirements are faced by the Morgantown system at the University of West Virginia. This system is required to provide normal service during the winter months in a region with significant ice and snow accumulation. The terrain is rugged, with guideway grades of up to 10 percent.

Figure 1. Typical operating AGT systems. (Top) Westinghouse at Busch Gardens in Williamsburg, Virginia. (Bottom) Ford at Fairlane Shopping Center in Dearborn, Michigan.

A more severe winter environment is faced by the rubber-tired people mover system at the Toronto Zoo. However, this system, being under manual control, has a degree of flexibility in coping with weather conditions not available to unmanned fully automated systems.

Ford AGT systems have also accumulated appreciable experience with ice and snow operation, both at the Ford test track in Cherry Hill, Michigan, and at the two-vehicle shuttle system at the Fairlane Shopping center in Dearborn, Michigan.

Although Westinghouse has installed a number of AGT systems, none of their commercial installations has required operations under conditions of ice and snow. Westinghouse does have, however, a considerable body of data accumulated from test programs involving operations in ice and snow. This includes tests conducted on the South Park demonstration system and more recently at their test facility in West Mifflin, Pennsylvania.

Finally, the Vought Airtrans system at the Dallas-Fort Worth Airport has had limited experience operating in ice and snow. While the Dallas-Fort Worth climate is relatively mild, there is sufficient ice and snow to require countermeasures for coping with winter weather.

Through this review, three guideway-related areas were identified which offer potential for winter-weather problems: (1) icing of signal and power rails; (2) loss of traction due to ice, snow, sleet, or freezing rain; and (3) freezing and jamming of guideway switches. Table 1 summarizes the winter weather provisions found in these three areas at the AGT systems examined. A discussion of the problems associated with and the countermeasures employed in each of these areas follows.

Power Rails

Icing of signal and power rails was found to be the most critical AGT guideway-related winter weather operational problem. Icing of rails may occur even without precipitation; with precipitation, the problem may be compounded. Signal and power flow to the vehicle can be interrupted by even a thin frost formation on the rails. Such an interruption typically results in automatic stopping of vehicles and possibly a system shutdown.

The rail icing problem can be combatted in a variety of ways including rail orientation, application of anti-icing or deicing chemicals, electric heating, and manual ice removal.

Figure 2 illustrates some of the power/signal rail arrangements employed by current AGT systems. Only the Toronto Zoo system, which incorporates stainless steel-clad aluminum rails with the contact surface facing downward, has experienced no rail icing problems. Among non-AGT transportation systems, only the Southeastern Pennsylvania Transit Authority's Market-Frankford line, with an underriding power rail configuration, reports similar ice free experience. Westinghouse's South Park test track did experience winter icing difficulties with a downward facing configuration, but that system's center guidebeam arrangement subjected the power/signal rails to water splashed by the vehicle guide wheels.

The most common rail icing countermeasure employed to date is chemical spraying of the rails. At both Airtrans and Morgantown the rails are sprayed with a heated ethylene glycol solution as an anti-icing measure. At Fairlane, the rails are sprayed with methyl alcohol (methanol) as a deicing measure. Chemical spraying as an anti-icing measure requires anticipation of frost, sleet, or freezing rain conditions sufficiently in advance to allow time for system application. A deicing strategy, however, allows ice or frost to form and possible system operation interruption before clearing of the rails is initiated.

At Airtrans, a converted automated cargo vehicle which incorporates spray nozzles, chemical storage drums, pumping equipment, and a spray operator booth, shown in Figure 3, is used to spray the power rails. Another similarly configured vehicle is used to apply the ethylene glycol to the power rail by a sponge wiper arrangement. Morgantown has several portable spray rigs for use with standard automated vehicles which spray the ethylene glycol on the rails and a towed service vehicle which incorporates spray nozzles and a bristled brush for clearing and cleaning the rails.

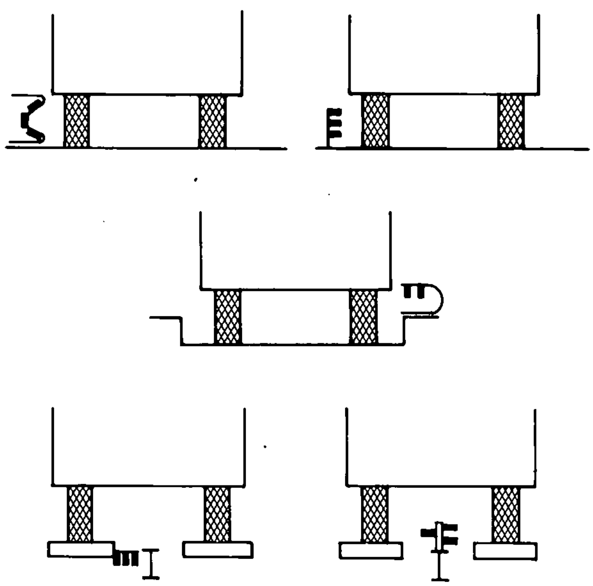
One of the disadvantages of ethylene glycol in this application is the residue it leaves on the rails. This residue must be cleaned off periodically, as it can result in electrical leakage between phases and can trap contaminants which may accelerate power collector wear.

At Fairlane, an internal combustion engine utility vehicle is employed for spraying the rails. This vehicle contains a storage tank and a compressor which supplies methanol through a reeled hose. A maintenance person walks behind this vehicle while using the spray nozzle to manually spray the rails. Fairlane also tried spraying with ethylene glycol and UCAR, a proprietary urea and ethylene glycol deicing agent. At Fairlane, both of these chemicals

Table 1. Summary of AGT systems winter weather provisions.

	Traction Surface				Power Rails			Switching
System	Primary	Backup	Snow Tolerance	Prediction	Primary	Backup	Collectors	Primary
Airtrans	Ethylene glycol spray	Snow blower	2.5 cm.	Monitor forecasts	Ethylene glycol spray/ wipe	-	-	-
Fairlane	Embedded electric	Snow blower	2.5 cm	Monitor forecasts	Methanol spray	Manual scrape	-	-
Morgantown	Embedded pipe	Snow blower	None	Weather service	Heated ethylene glycol spray	Manual scrape	Heated	On board heated
South Park	Selective embedded electric	-	4.6 cm	Detector	Electric heat	-	-	-
Toronto Zoo	Sand/urea pellets	Snow blower	2.5 cm.	Monitor forecasts	-	Broom underneath	-	Switch pit heated

Figure 2. Typical AGT power rail arrangements and their relationship to guideways and vehicles. (Top left to bottom right) Morgantown, Airtrans and Fairlane, Toronto Zoo, South Park, and West Mifflin.



were considered unsatisfactory due to the residue problem.

Whenever the towed vehicle is in use at Morgantown and the self-propelled utility vehicle is in use at Fairlane for spraying the rails, all power to the rails is shut off.

At Morgantown, the power rail system initially had several fires caused by the salt used for snow removal on station platforms and on an adjacent highway. The saline runoff from the platforms and the splashing of highway slush onto the power rails created conductive paths between rails and in combination with the ABS plastic carrier and glycol resulted in fires. As a result of these problems, use of salt on station platforms has been prohibited and a splash guard has been erected between the at-grade guideway and the highway.

A similar review of the use of chemicals for anti-icing or deicing of power rails on electrified rail transit systems was made. This review concluded that rail transit usage of chemical methods of rail icing control has met with very limited success. For example, the Long Island Railroad has been testing anti-icing agents for power rail application since 1973. To date, the products tested have not been successful in reducing power rail ice adhesion for more than a few days without leaving an unacceptable residue on the rail.

Electrical heating of AGT power rails has only been employed at test track installations. These include Ford's Cherry Hill test track and Westinghouse's South Park and West Mifflin test tracks. The Ford AGT system installation at Bradley Airport in Hartford, Connecticut included electric power rail heating, but the system has not been operated. Electric heating of the power rails is scheduled for installation at Morgantown as part of the current Phase II system expansion and retrofitting. Typically, electric power rail heating is provided by an electrical resistance heating wire, rated at 49.2 W/m (15 W/ft), which is installed in each power rail. Since most of the AGT systems employ an average of four rails, the total amount of energy used is 196.8 W/m (60 W/ft) of guideway. Activation of the installed rail heating systems is accomplished manually in response to weather forecasts or after rail icing occurs.

Manual ice removal from AGT power and signal rails is a backup method used once ice has adhered to the rail and service has been disrupted. Manual frost and ice removal methods are not only laborious and crude, but extend system downtime. Two of the AGT systems employ in-house manufactured ice scrapers. Fairlane uses a modified metal bracket at the end of a common fiberglass bicycle safety flag and Morgantown employs a plexiglass scraper blade at either end of a polyvinyl chloride pipe. While vehicle-mounted scrapers have been tested, results to date have not been satisfactory. The only success with a vehicle-mounted scraper was achieved in a test chamber experiment conducted by Vought. It was successful, however, only when the ice was first sprayed with ethylene glycol and the scraper heated to keep its flukes clear.

Figure 3. Airtrans spray vehicle and close-up of spray nozzles.

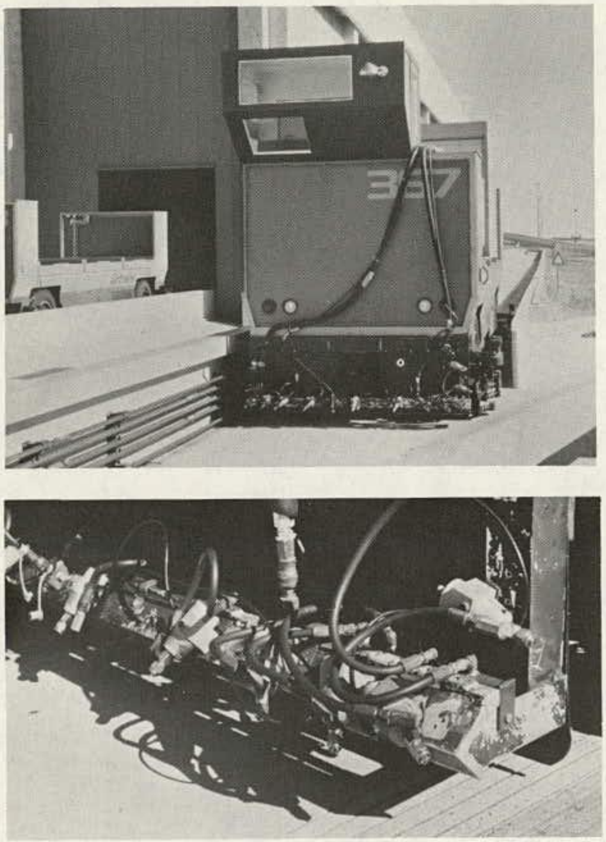
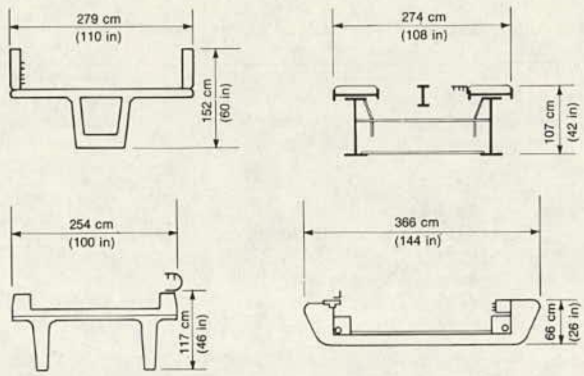


Figure 4. Typical AGT guideway configurations showing arrangements of traction and guidance surfaces. (Top left to bottom right) Airtrans, South Park, Toronto Zoo, and Fairlane.



Traction

Maintaining traction between AGT vehicle tires and the guideway is a second operational problem and the most critical one from a safety standpoint. All presently operating AGT systems require traction for emergency braking. This includes AGT systems with linear induction motor (LIM) powered vehicles. Mechanically guided rubber-tired vehicles also require traction for propulsion, service braking, and station stopping. Laterally unconstrained rubber-tired vehicles, such as at Morgantown, require traction for steering control as well. Typical AGT guideway shapes and their associated traction surfaces are shown in Figure 4.

Though traction is a function of pavement aggregate characteristics, surface texture, tire material properties, tread pattern, and vehicle speed, the most significant factor affecting available traction is the presence of rain, snow, or ice on the pavement surface. The friction factor on snow and ice is considerably less than on bare pavement surfaces. Unlike wet and dry pavement traction, traction on ice and snow is not heavily dependent upon speed. Traction on ice--which exhibits the lowest friction factor--does not exhibit any speed dependency. Similarly, the available friction on ice is not particularly sensitive to wheel slip.

Two significant factors affecting friction on ice are temperature and tire pressure. Wet ice at or near a temperature of 0°C (32°F) has the lowest friction factor; as temperature decreases, the friction factor increases, typically doubling at -18°C (0°F). The direct relationship between friction factor and stopping distance is critical to the safety of the system and headway control. Properly inflated, higher pressure tires tend to have a lower friction factor than properly inflated, lower pressure tires. Thus, buses, trucks, and AGT vehicles have lower skid numbers than automobiles. This is significant in that the wealth of literature relating to automobile stopping tests and experience must be used with caution when applied to AGT systems.

The braking traction available in snow depends primarily upon the condition of the snow--dry, wet, loose, or compacted. The skid number on ice is roughly half that on snow. The use of traction aids, such as abrasives, snow tires, studs, or chains enhances traction on snow in that order. Studs and chains enhance traction on ice. Abrasives are more effective on wet ice than dry ice.

Current AGT systems employ a variety of methods to maintain traction in snow and ice conditions. These include embedded pavement heating, abrasives, chemicals, snow blowers, and an assortment of manual measures.

Embedded pavement heating is provided by both electric resistance wire and piped systems. The entire 0.9 km (0.6 mi) Fairlane system includes electric resistance wires spaced 20 cm (8 in) apart, 2.5 cm (1 in) below the concrete running surface. The heating system is divided into 31 zones which can be activated simultaneously or alternately (every other zone). The entire 8.8 km (5.5 mi) Morgantown system includes 2.5 cm (1 in) diameter pipes, spaced 30 cm (12 in) apart, 5.1 cm (2 in) below the concrete running surface. The heating system is divided into three zones through which a propylene glycol solution, heated by ten gas-fired boilers, is circulated. Both systems are designed for a heat output at the surface of 646 W/m^2 (60 W/ft^2).

The alternating section scheme installed at Fairlane to allow lower average heat output and energy consumption as weather conditions permit, has not been successful as it creates a washboard effect from alternating sections of accumulating and melting snow/ice. The systemwide activation approach as installed at Morgantown, though capable of heat modulation, is not sufficiently segregated to heat only those sections experiencing icing. Consequently, during cold conditions when earth heat is sufficient to keep grade level sections of the guideway free of ice, the entire heating system must be operated to clear ice on elevated sections.

Pavement heating has proven to be an effective, though costly, method of ensuring guideway traction. In addition to large initial capital costs, guideway heating incurs ongoing operating and maintenance costs. Embedded pipe system energy costs are dramatically overshadowed by the high power demand charges imposed upon embedded electric systems.

During the 1977-78 winter, the Ford Fairlane heating system operating policy was changed to avoid over-reacting to weather problems and to reduce energy consumption and costs. This new policy did not require anticipation of bad weather and also terminated use of pavement heating. The system successfully operated with up to 2.5 cm (1 in) of packed snow on the guideway. (The allowable depth of packed snow is constrained by the vertical tolerance of the power collector assembly.) Loose and packed snow was mechanically removed from the guideway by a small front-end loader and walk-behind snow blowers with the system shut down. Less system downtime was reported from undrained refrozen melt water and the cost of guideway heating was eliminated. At the relatively short and level Fairlane system, this unheated guideway approach to winter weather operations is now preferred.

In addition to adequate drainage of melted snow/ice and capital and operating costs, several other considerations in the employment of guideway heating are relevant. To ensure timely heating system activation sufficiently in advance of precipitation, accurate weather forecasting is essential. The relatively long lead time required to bring pavement temperature up to melting temperatures, one to four hours, also makes false activations a significant energy/cost factor. Further, splashing of melted snow from vehicle tires may result not only in power rail icing, but in ice accumulation on the underside of the vehicle. This underbody icing may interfere with the operation of mechanical components and even lead to steering malfunctions on unconstrained systems.

At South Park, Westinghouse experimented with a load sharing concept which interlocked the vehicle power supply to the electric pavement heating power supply. This approach, while reducing the effective heat density, offers a potential to reduce electric power demand charges.

Only the Toronto Zoo system successfully employs abrasives, in the form of sand, to provide traction on ice or snow. The Toronto Zoo guideway does not incorporate embedded heating. Sand was also tried at Airtrans and Fairlane, but rejected due to ingestion into vehicle intakes, fouling of bearings and joints, accelerated power collection system wear, and clean up problems.

Chemicals are employed at Airtrans and the Toronto Zoo system to remove snow and ice on the traction surface. Airtrans employs a heated ethylene glycol solution, sprayed from the previously described modified cargo vehicle. Toronto employs aero-prill urea pellets spread from a self-propelled tractor. Ford developed a vehicle for spraying UCAR, a proprietary solution of urea and ethylene glycol, on the guideway traction surface, but has not used it on an operating system. The tendency of ethylene glycol to create a slippery surface on clear pavement is counteracted at Airtrans by a pavement overlay of carborundum grit embedded in an epoxy coating.

All winter-operating AGT systems use snow blowers to clear accumulations of snow on the guideway. Fairlane and Toronto Zoo both originally used large, vehicle-mounted units, but now all systems prefer and use small garden variety snow blowers. With the larger units, difficulties were experienced with proper visibility of casting areas below the guideway and with discharge chute clogging problems. Plows are not employed by any AGT system primarily, it appears, because of disposal problems and guideway structural interferences. During the 1977-78 winter, Fairlane used a front-end loader to clear the guideway of snow accumulations and snow pack, dumping it over the guidewall onto parking spaces below the guideway.

At one time or another, all of the surveyed systems have had to resort to manual snow shoveling and/or ice chipping. Vought experimented with a hot air blower. Though it melted the snow and ice, the speed of about 0.05 km/h (0.03 mi/h) proved too slow for guideway use. Further, refreezing of melted snow after passage of the hot-air blower resulted in a more serious ice condition. Studded tires were also tried at Airtrans. These tires wore the guideway pavement at an excessive rate.

Switching

Switching--negotiating merge/diverge sections of the guideway--has not been a serious problem for existing AGT systems during winter weather operation. This is due primarily to the design of the switch systems in use, which are either inherently winter tolerant or provided with appropriate heaters.

Only the Morgantown system has experienced any difficulties in switching. These difficulties, which occurred during the first year of operation in tight radius guideway turnout areas, were primarily due to freezing of vehicle-mounted switching components. Correction of these malfunctions has been affected by the installation of heating elements and the application of non-water soluble lubricants on the vehicle switching/steering mechanisms.

Though traction is essential in switch areas to enable vehicles to stop before entering a blocked switch area, only the Morgantown system is unconstrained and steered by lateral tire traction forces. Consequently, adequate traction is a necessity at Morgantown not only for braking, but also for steering. This traction is assured by a bare pavement policy which is achieved by utilizing the embedded pipe heating system.

The Airtrans system employs an active guideway mounted switch rail and a passive vehicle switch wheel. The electromechanical switch mechanism, adapted from a conventional railroad application, is installed under the guideway, protected from weather. The Fairlane system employs a passive guideway rail and an active vehicle-mounted switch wheel system, depicted in Figure 5. The Morgantown switching system also employs a passive guideway and active vehicle arrangement, but is not captured by the guideway. The Toronto Zoo system employs an active guideway switch arrangement, shown in Figure 6, as does the Westinghouse test tracks. Neither Airtrans nor Fairlane incorporate any heating devices as part of their switch. Toronto utilizes a 15 kW space heater in the switch pit below the guideway and Westinghouse uses a combination of heaters and shields to protect against winter weather.

Conclusions and Recommendations

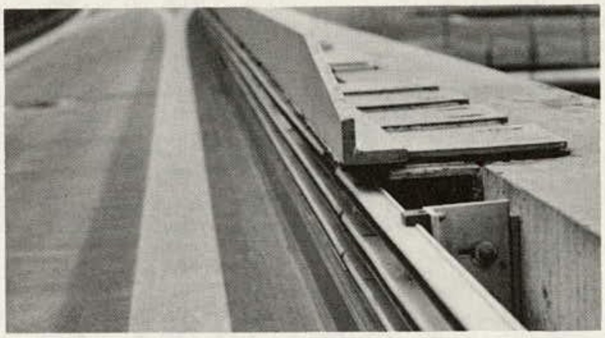
The review of existing AGT winter weather operational experience and provisions identified three problem areas--power and signal rail icing, maintenance of traction, and switching. While switching was identified as a potential winter weather related problem area, operating experience indicates that it is not currently an area of concern. The conclusions reached and the recommended topics for further investigations to improve AGT all-weather operation in the two remaining problem areas follow.

Power rail icing is the most serious operational problem experienced to date. Icing of power and/or signal rails occurs more frequently, and often before, loss of traction due to winter weather. Without rail icing countermeasures, loss of traction often is not experienced as rail icing interrupts service before traction degradation impacts the system.

Electric heating of rails appears to offer a workable solution. Engineering development of power load sharing and application techniques offer short-term potential for reducing heating-associated energy consumption costs. Inductive coupling methods of power collection may provide a long-term alternative to contact power collection and its associated weather-related problems. Susceptibility to icing appears to be minimized or eliminated by using a downward facing power rail mounting orientation. This approach, however, would require changes which may not be compatible with certain of the existing AGT vehicle/guideway/switching configurations.

While wiping or spraying of power rails with chemical solutions has been demonstrated as feasible,

Figure 5. On-board vehicle switch as employed by Ford at Fairlane. (Top) Passive switch rail mounted on the guidewall. (Bottom) Vehicle mounted switch arm/wheel engaged with switch rail.



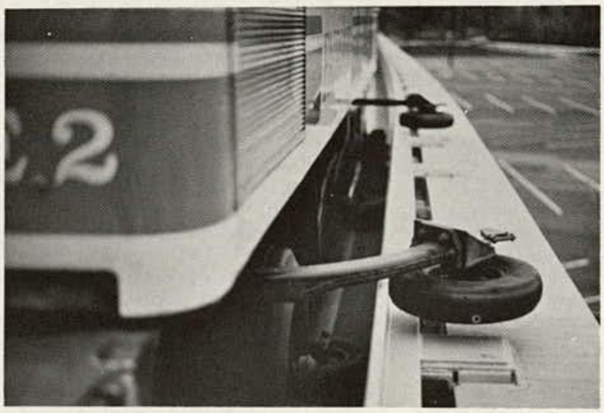
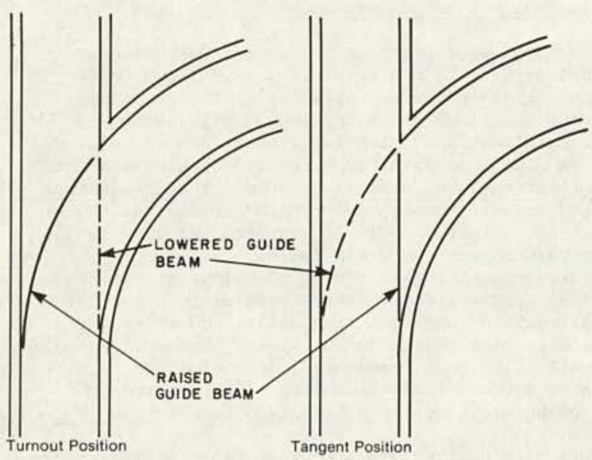


Figure 6. Active guideway/passive vehicle switch as employed by Bendix at Toronto Zoo.



a longer lasting, non-residue producing anti-icing agent is desirable. The effectiveness of chemicals in a deicing role is very limited. The goal of ice control on AGT power rails remains the maintenance of uninterrupted system operation.

Mechanical methods of power rail ice control appear ineffective in allowing uninterrupted system operation. As an ice removal method, scraping is time-consuming, relatively ineffective, and useful only as a last resort.

Traction becomes increasingly important as the power rail problem is controlled, but is not as readily resolved. The capital and operating costs of embedded pavement heating systems prompts a search for more cost-effective and lower energy consuming approaches. Provisions for maintaining traction are affected by the operating policy options established for each AGT system. Operating policies which allow an orderly shutdown of the system as an acceptable option in inclement weather, as at all the current amusement park, shopping center, and outdoor airport AGT system installations, will not necessarily be the case in future urban installations. Such urban systems may tolerate degraded service, such as increased headway or reduced speeds, but a high priority is expected to be placed on maintaining uninterrupted service in winter weather.

Techniques for reducing the lead time necessary for heating system activation and energy consumption/cost reductions are important. Reducing the area of the guideway to be heated, guideway designs to minimize snow accumulation, insulation of heat loss from the guideway, automated mechanical snow removal techniques, and modified operating strategies all offer areas of higher efficiencies. Simple snow/ice sensor activation of embedded systems, to reduce dependency upon weather forecasts and the human element, is handicapped by relatively long lead times required to bring the guideway traction surface up to melting temperature. Keeping the heating system activated at a lower output level to reduce this time lag appears prohibitive in terms of energy consumption/costs.

The adaptability of the guideway design to mechanical snow removal techniques warrants investigation not solely to replace heating methods but to augment them. Reducing the volume of snow to be melted would not only reduce the thermal energy required but possibly permit reducing the lead time of system activation before precipitation. Such a scheme would not only reduce heating system on-time, but would minimize energy wasted due to inaccurate forecasts. Disposal of snow mechanically removed from the traction surface creates problems of still another type.

Finally, there is a need for AGT vehicle stopping distance data on snow and ice. The bulk of transportation system data currently available in this area is for automobiles. Such data would strongly influence decisions on operating strategies, the need for systemwide pavement heating, and the effectiveness of mechanical snow removal.

Controlling Snow and Ice on the Morgantown People Mover System

Philip H. Morgan, U. S. Department of Transportation

This paper describes how the Morgantown People Mover has become the first automated guideway system in an urban area which is fully operational throughout winter. Unique operational methods and mechanical features of the vehicle have been developed to assure adequate tire traction, consistent steering and switching performance, and reliable power collection during their severe winter weather. Operating costs and the trends in winter operational reliability show the continuing improvement as system operating experience is accumulated.

The Morgantown system was the first fully automated people mover to be operational in an urban and university environment. The Urban Mass Transportation Administration of the Department of Transportation built the system to demonstrate and evaluate the benefits of automated guideway transit technology. The prime contractor for the system was the Boeing Aerospace Company. UMTA selected Morgantown as the site because it furthered the interests of both the West Virginia University (WVU) and UMTA. The West Virginia University wanted a people mover system to solve its inter-campus transportation problems while UMTA wanted a site sufficiently urban that a meaningful evaluation of the system for potential application to other cities could be made.

The system uses driverless, electrically-powered vehicles controlled by computers and provides direct, non-stop service from origin to destination for West Virginia University students and residents of Morgantown. The present system consists of 5.4 miles of single lane guideway with grades up to 10%, three stations, a maintenance facility and central control complex, and a fleet of 45 rubber-tired 21-passenger vehicles (Figure 1).

Initial test operation of the system took place in October, 1972. Revenue passenger-carrying operations began in October, 1975. Since then, more than 4.5 million passengers have been carried without an operations-related serious injury or fatality to either passengers or operating and maintenance personnel. The system is now owned and operated by the West Virginia University.

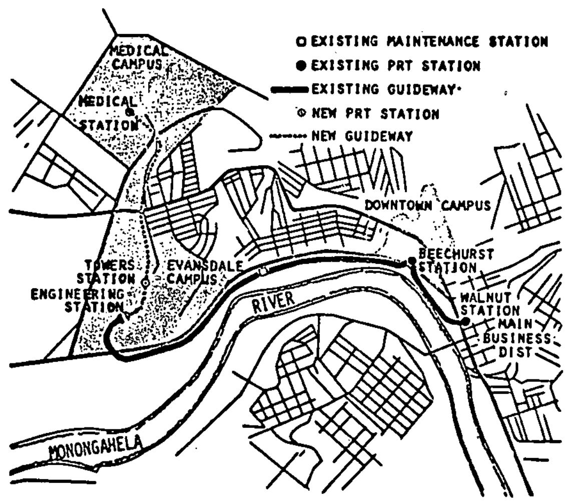


FIGURE 1. MPRT ROUTE LAYOUT CONNECTING THREE WVU CAMPUSES AND MAIN BUSINESS DISTRICT

There is a great deal to be learned from how the Morgantown system has been made operational in winter because the Morgantown environment is quite variable and subjects the People Mover to extremes of temperature, snowfall, sleet, and wind, more severe than those of any other operating Automated Guideway Transit (AGT) Systems. Typical snowfall in Morgantown is 25-75mm (1 to 3 inches) on ten days during each December and January. Trace amounts occur, perhaps, twice as often. On Figure 2, the low and high temperatures are shown for December and January of the three winters during which the Morgantown System has been operated. It has not been unusual to have a week at a time in which temperatures stay below freezing or in which low temperatures may hover between 0°C and -10°C. During the rest of the winter the temperature drops below freezing almost every night causing melted snow to refreeze and frequent formation of frost.

The subject of controlling snow and ice on the Morgantown system can be divided into four areas:

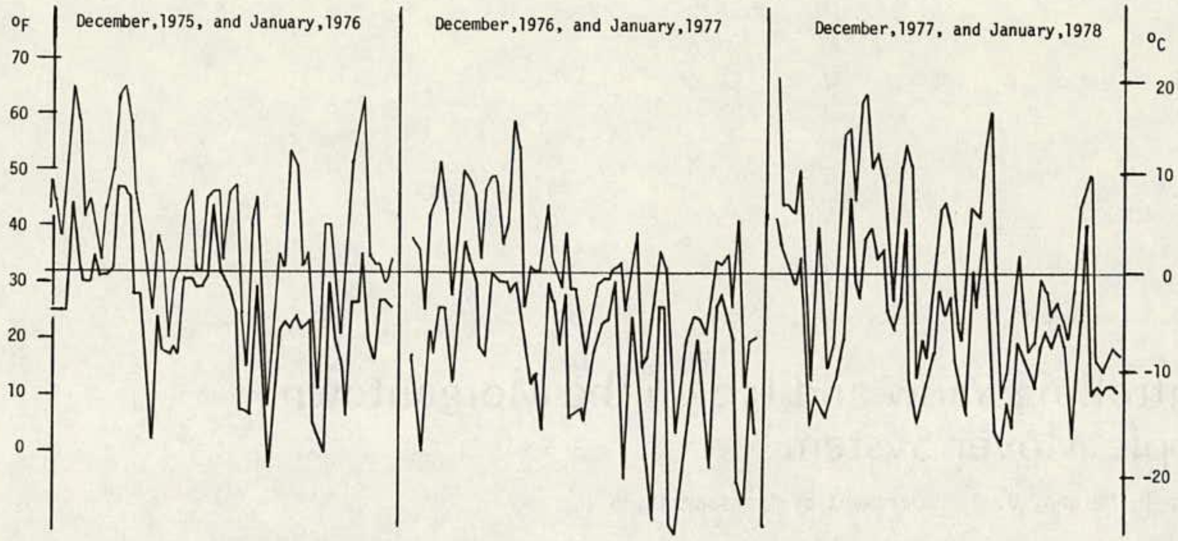


Figure 2. DAILY LOW AND HIGH TEMPERATURES IN MORGANTOWN, WEST VIRGINIA

1. how snow and ice impact the reliability of system operations,
2. what measures have been taken to reduce or eliminate these impacts,
3. how effective these efforts have been in permitting winter operations,
4. how these measures affect system operation and maintenance costs.

Snow and ice interfere with power collection, vehicle traction, and in extreme cases, even vehicle steering. Low temperatures amplify all the problems of snow and ice by reducing the effectiveness of snow removal methods and encouraging refreezing of melted snow back into ice. Low temperatures can also cause formation of frost on power rails which will interfere with power collection as much as snow or ice. Low temperatures have been found to reduce clearances between moving parts, increase friction, and, in some instances, render components inoperative. In the Morgantown vehicles control valves, check valves, sliding joints, and pivotal bushings have been particularly susceptible to these effects.

The three systems critical to operation of the Morgantown system are those for traction, power collection, and steering.

I. Traction

In the Morgantown system, maintaining vehicle tire traction has always been of primary importance in permitting winter operation. From a safety standpoint, tire traction determines the emergency stopping distances of the vehicle which, in turn, were the design basis for the block lengths of the collision avoidance system. For this reason, operating procedures prohibit system operation if there is any snow or ice on the guideway.

To insure complete absence of snow and ice, the entire running surface of the guideway is heated. A 50% solution of propylene glycol and water is heated to 82°C (180°F) by natural gas fired boilers in three locations along the guideway and circulated by pumps through steel/nickel/copper alloy pipes embedded beneath the top of the concrete running surfaces (Figures 3 and 4). The design of the guideway heating system is based on delivering 646 watts per square metre (60 watts per square foot) of guideway surface, but a capability to deliver nearer 750 watts per square metre (70 watts per square foot) was installed to assure adequate operational margin. Figure 5 shows schematically a section of the guideway heating system and the locations of the three boiler plants.

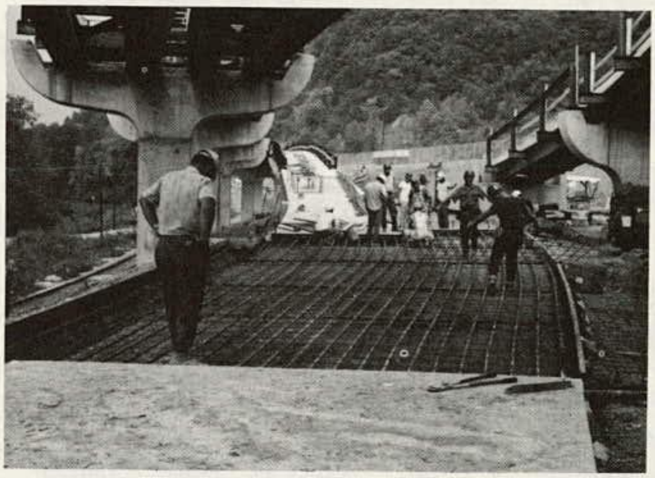


FIGURE 3 : GUIDEWAY HEATING PIPES IMBEDDED IN THE SURFACE OF AT-GRADE GUIDEWAY

The present system was selected over an alternative using embedded electrical heating wires on the basis of overall costs. Trade studies showed that the electrical heating approach would lead to a large increase in peak demand charges levied by the local power company to recover the cost of adding generating equipment. The higher electrical rates would be applied to all electricity used by the entire transit system and were expected to accumulate in 7-8 years to more than the initial savings in installation and capital costs of the electrical system over the costs of circulating glycol system's boilers and distribution pipes.

The heating system is completely automatic in operation and can be turned on and off from the central control room for the system. The operational philosophy for the guideway heating system is to turn it on sufffíciently before snow begins to fall that the guideway surface is warm

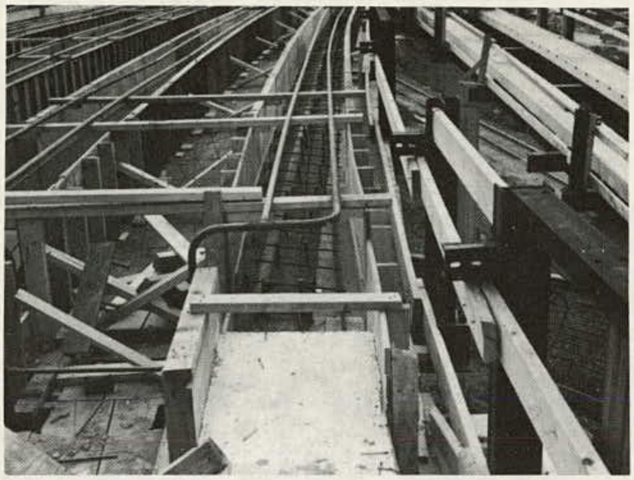


FIGURE 4 : GUIDEWAY HEATING PIPES IMBEDDED ONLY IN RUNNING PADS OF ELEVATED GUIDEWAY

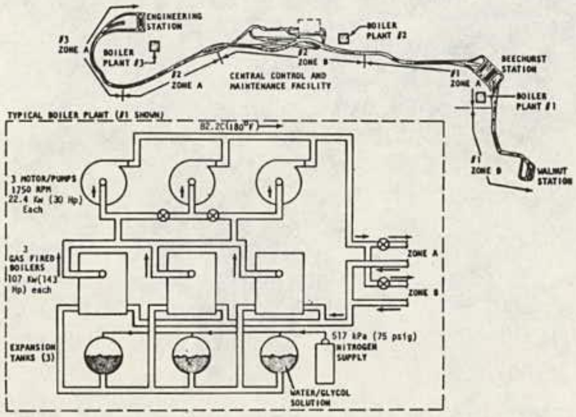


FIGURE 5: TYPICAL GUIDEWAY HEATING SYSTEM BOILER PLANT

enough to melt snow on contact and without any accumulation. As shown in Figure 6, the entire guideway, heating solution, and distribution piping requires about 2 hours to be heated from an ambient temperature of -7°C (20°F) to the melting point of snow above 0°C (32°F.) If the guideway has not been warmed sufficiently to melt snow as fast as it falls, the heating system becomes far less effective in melting the snow. The melted snow doesn't run off freely but, rather, is retained as slush and insulates the unmelted snow from the warm guideway surface. Then part of the heat output from the guideway is wasted in raising the temperature of the captive water.

Accurate forecasting of snow, freezing rain, etc., is necessary for timely use of the guideway heating system and to preclude operating the heating system unnecesarily. WVU obtains weather forecasts from a private weather service specializing in their location and relies heavily on their forecasts of snow or sudden drops in temperatures in planning the operation of the heating system and other strategies to combat effects of adverse weather. The guideway heating system has been extremely effective; the People Mover system has never failed to operate because of snow falling faster than the guideway heating system could melt it.

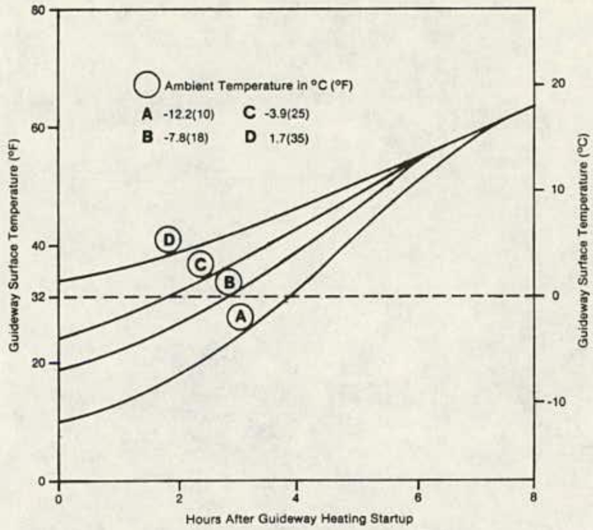


FIGURE 6: GUIDEWAY SURFACE WARM-UP TIME

II. Power Collection

The Morgantown vehicle is electrically powered by 575 volt, 3 phase, 60 hertz a.c. Interruption of power on any phase for more than 1/2 second will cause the vehicle to be stopped by service brakes. In turn, all trailing vehicles would also be stopped. The principal causes of power loss have been snow or ice on the power rail and brushes binding in the collector.

As shown in Figures 7 and 8, the power rails are arranged in a V-shaped Acrylonitrile-Butadiene-Styrene (ABS) plastic carrier and the collector holds brushes in a matching array. Rubber wheels at

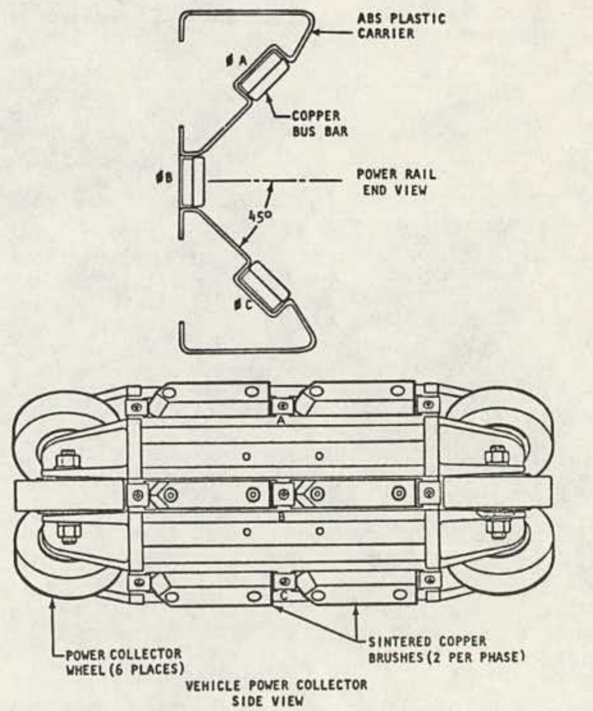


FIGURE 7: PRESENT POWER RAIL AND COLLECTOR

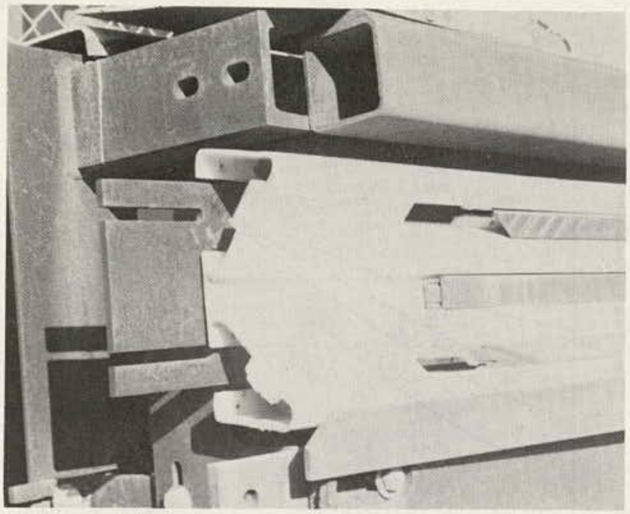


FIGURE 8: PRESENT POWER RAIL

each end of the collector body align the collector with the ABS carrier and support the collector against the force applied by the pneumatic positioning arm. Two brushes per phase are provided to minimize arcing at power rail joints. To prevent brushes from binding in the collector, the collectors have been modified by the addition of stainless steel liners to the brush cavity and 15 watt/brush heater wires to prevent icing (Figure 9).

To prevent ice from forming on the power rail,

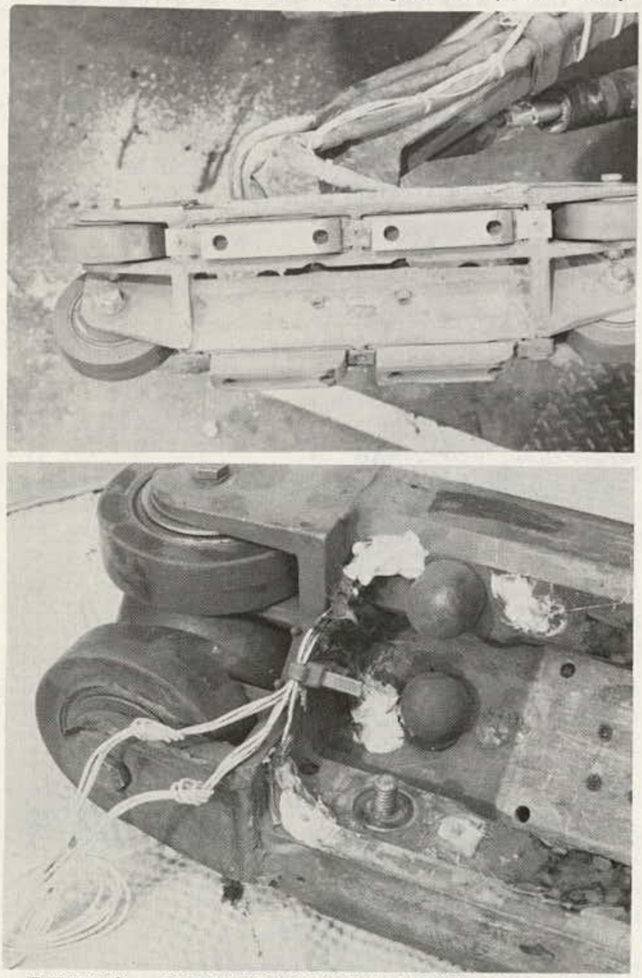


FIGURE 9: PRESENT POWER COLLECTOR/HEATING WIRES

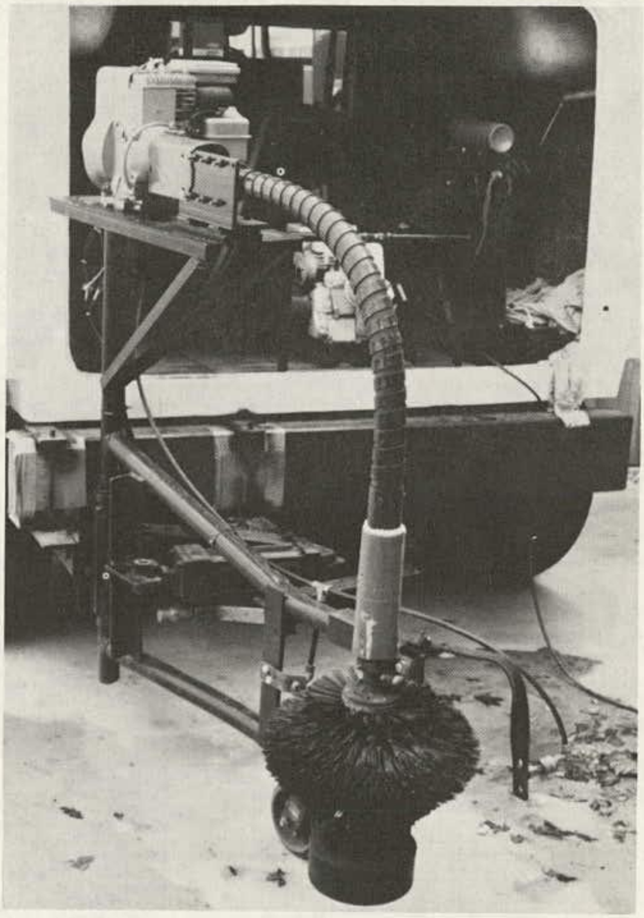


FIGURE 10: DE-ICING VEHICLE WITH ROTATING BRUSH

procedures and equipment for applying hot 25% ethylene glycol and water solution have been developed by WVU. During snowfall or freezing rain, two or three regular vehicles are equipped for spraying glycol solution and operated along the entire guideway at 20 to 30 minute intervals. Their equipment includes two 208 litre (55 gallon) drums of 60°C (140°F) glycol solution, a 689.5kPa (100 psig) pump, and spray nozzles outside the vehicle aimed to cover the power rail envelope. This has been found sufficient to prevent snow or ice accumulation on the rails. If vehicle stoppages should prevent use of automated spray vehicles or if unexpected snowfall should occur, snow or ice may accumulate on the power rails. Accumulations of snow can be removed from the power rail by towing a special deicing vehicle along the unpowered guideway with a jeep. This deicing vehicle is unpowered and has had its on-board computer, environmental control equipment, and propulsion system removed and has been equipped with five 208 litre (55 gallon) drums of heated glycol solution, a portable electrical generator, fluid pump, spray nozzles, and a motor-driven rotating brush to mechanically dislodge snow and ice (Figure 10).

The application of glycol to the power rails leads to a gummy residue and gradual accumulation of abrasive particles from the brushes as they wear.

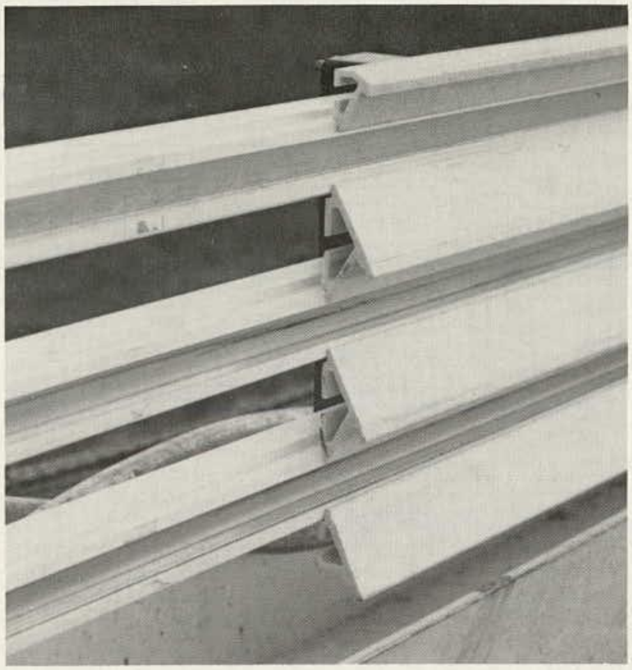


FIGURE 11: PHASE II POWER RAIL

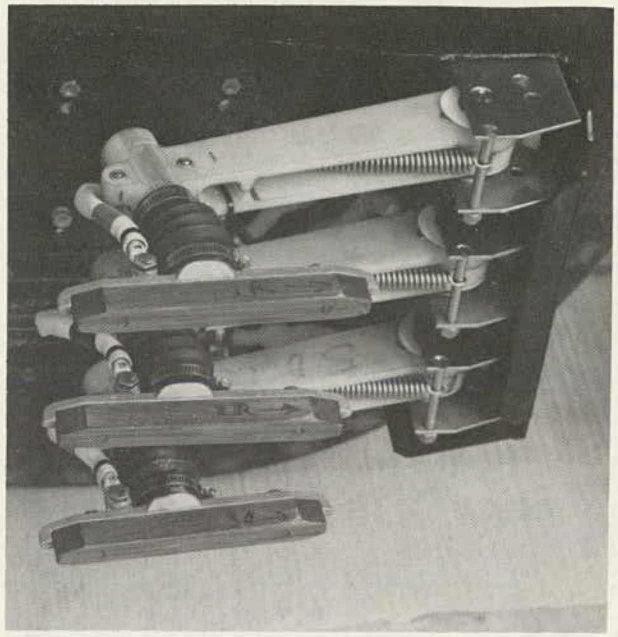


FIGURE 12: PHASE II POWER COLLECTOR ASSEMBLY

If not removed, the glycol residue soon leads to accelerated brush wear rates, electrical leakage problems, and reduced power collector performance. For these reasons, rails are routinely washed at the first opportunity after snowing and icing conditions subside. The cleaning is done with the special deicing vehicle equipped with drums of plain water and the rotating bristle brush.

In September 1976, UMTA approved a Capital Grant to the West Virginia Board of Regents for the Phase II expansion of the Morgantown system and the incorporation of some technical improvements. One of the most significant improvements being made is the replacement of the present power rail with a new one which can be heated. The new power rail assembly (Figure 11) features rails arranged in a vertical array to increase the leakage path between phases, stainless steel contact surfaces, aluminum conductor, a non-flammable Poly Vinyl Chloride (PVC) insulating carrier, and integral heating wires. It is expected that the 45.7 watt per metre (15 watt per foot) heating on each rail will be sufficient to remove frost and to prevent snow accumulation without having to apply the glycol solution. Also, the Phase II power collector (Figure 12) will include provision for heating. The entire pneumatic deployemnt system for the power collector has been eliminated and replaced by an outward spring-loaded pantograph to apply collector brush pressure to the power rail.

One note on the use of glycol deicing solutions: they are not compatible with salt deicing chemicals. When these chemicals mix with glycol, the resulting solution is highly conductive of electricity. Phase-to-phase arcing can cause damaged power collectors and rails, and poses a fire safety hazard in the presence of combustible materials. In Morgantown, though salt is not used on the guideway, the city uses it on the roads. As a result, fiberglass panels had to be installed by WVU to prevent deicing salt applied to a nearby highway from being splashed by passing cars onto the system guideway and power rail.

III. Steering

Another significant area of winter weather impact is the steering and switching systems of the vehicle (Figure 13). The vehicle steers by following a rail along the left or right side of the guideway. Guidewheels at the front of the vehicle are applied against the rail with nominal force of 800 newton (180 lbs.) The linkage to which the guidewheels are attached moderates the hydraulic pressure counteracting the force of a 1780 newton (400 lb.) bias spring to maintain the 800 newton (180 lb.) force against the guidewheels. The 1780 newton (400 lb.) spring causes the movement of the steering wheels and linkage until the 800 newton (180 lb.) force has been established. Switching from guideway into station ramping is accomplished by hydraulically repositioning the bias spring such that the steering force is removed from the left side and re-applied to the right side.

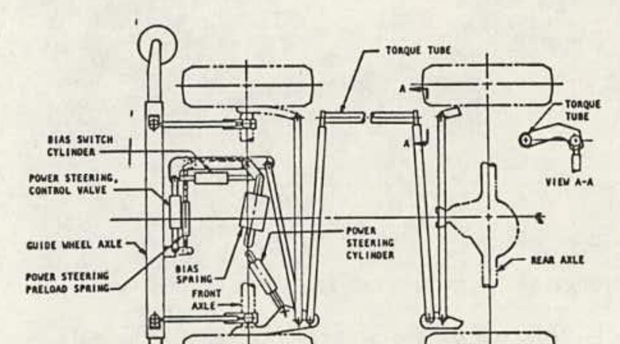


FIGURE 13: PRESENT STEERING AND SWITCHING SYSTEM

Cold temperatures increase frictional resistance in the steering linkage bushings and reduce the quickness with which steering corrections occur. The internal clearances of hydraulic components, particularly the steering control valve, diminish and the valves operate more slowly or bind. The principal remedy for high friction in linkage bushings has been a change to water-insoluble greases which are not as quickly displaced by the action of turbulent air with entrained water passing through the chassis.

The binding of steering control valves, bias actuators, preload springs, and sliding joints in the guide axle has been largely eliminated by local heating with strip heaters (Figures 14 and 15). Altogether, these measures have been found effective in maintaining system operability down to -15°C (5°F.)

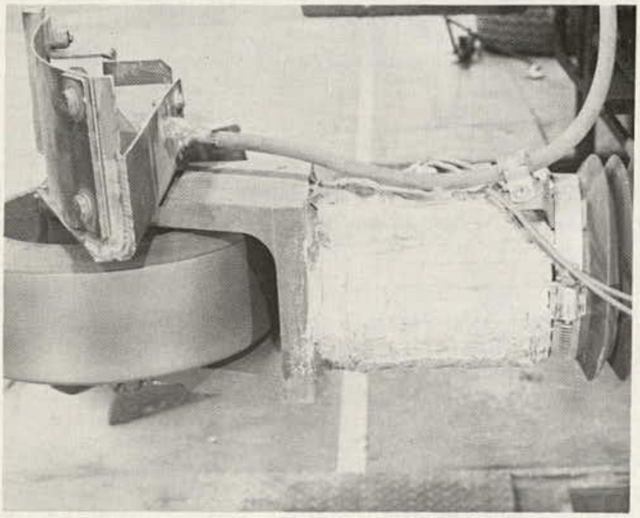


FIGURE 14: ELECTRICALLY HEATED GUIDE AXLE

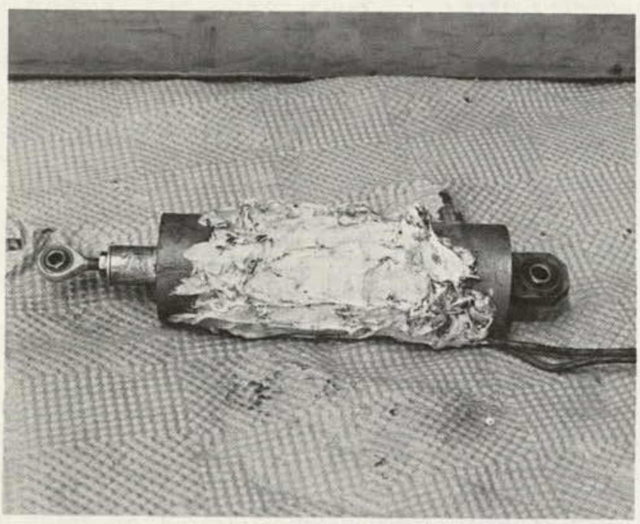


FIGURE 15: HEATED BIAS SWITCHING ACTUATOR

Redesign of the steering system in Phase II (Figure 16) has eliminated the hydraulic steering contol valve and replaced most bushings at steering linkage joints with low temperature, anti-friction bearings. The new steering system has been installed on a vehicle and operated during last winter. On one occasion, this vehicle operated without maintenance and without difficulty throughout a ten inch snowstorm. After twelve hours operation, in

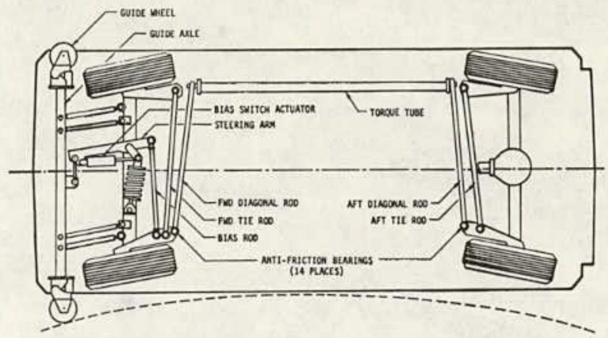


FIGURE 16: PHASE II STEERING AND SWITCHING SYSTEM

severe weather, the vehicle was taken out of service to remove ice accumulated on the chassis which would physically obstruct motion of the steering linkage. Cold chamber testing has demonstrated that the all-mechanical steering system is operable down to -34.4°C (-30°F.)

IV. System Reliability and Costs

Efforts to increase the operational reliability of the Morgantown system in winter weather have been reflected by dramatic improvement in the availability statistics over the last three winters (Figure 17). The average availability for December, January, and February has improved each year, from 73.5% in 1975-76 to 92.1% in 1976-77 to 97.5% in 1977. It is also noteworthy that not a single day of operation was cancelled due to adverse weather during the winter of 1977-78.

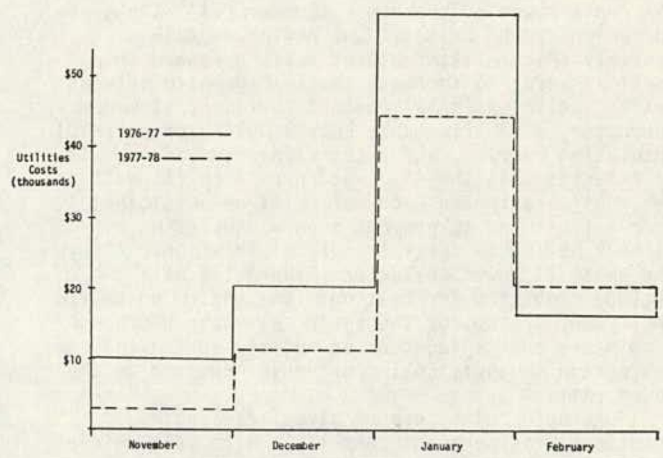


FIGURE 18: GUIDEWAY HEATING SYSTEM UTILITIES

The costs of natural gas and electricity for the guideway heating system are shown in Figure 18 for the last two winters in Morgantown. In total, they are less than 6% of the annual operating costs of the system. This seems a reasonable expense to insure that the system operates as any transit system should, i.e., every day that it is scheduled. In the case of the University, the guideway heating system allows reliable system operations during the

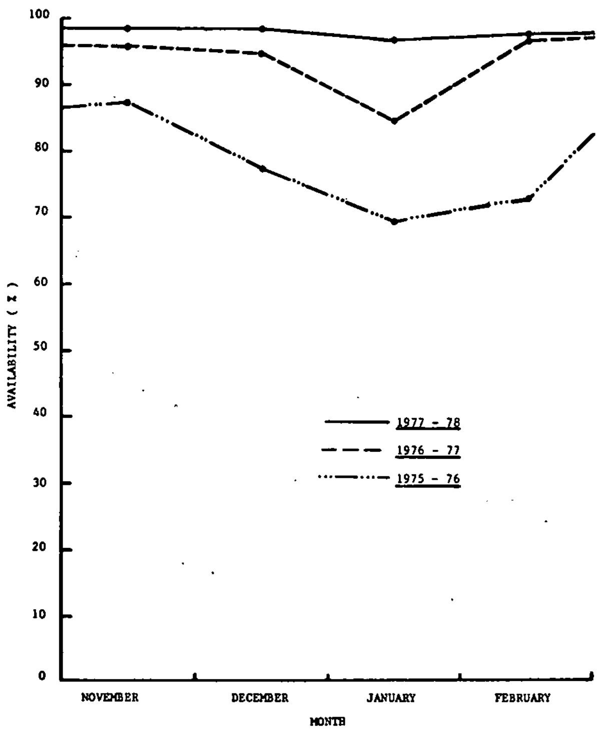


FIGURE 17: PEOPLE MOVER WINTER AVAILABILITY

portion of the school year when 40% of all the year's trips are made.

In conclusion, one can see that the Morgantown People Mover system works very well during the winter. To do so, it requires a heated guideway, deicing equipment and chemicals for the power rail, and local heating of power collectors and critical steering system components. These measures reflect the subsystems which require attention if operation in cold and snowy weather is to be achieved. The techniques used in Morgantown may be applicable for other automated systems but their suitability should be evaluated in light of the particular control principles and vehicle design of that system.

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Snow Removal and Ice Control Research Objectives for the Future

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The concluding session devoted time to a discussion of research needed over the next 10 years to improve present capability for removing snow and ice from highways, and for ensuring an all-weather capability for guideway systems, communication facilities, and aircraft and their ground facilities. Discussion was led by Dr. Ronald A. Liston, CRREL. Discussions during the other sessions also revealed areas of study that needed to be initiated or expanded, although not all of these were brought up in the concluding session.

Most discussion revolved around highway snow and ice control. The scope was enlarged, however, to approach the problem as one of increasing winter traction and trafficability, whether by reducing or eliminating snow and ice accumulation, or by improving the coefficient of friction between tires and the winter surface. To this end, it was recommended that research be directed to improve tire designs and materials, and the work done by Caltrans showing that graphite fiber tire additives significantly increase the friction coefficient was cited.

Continuation of current research underway until it is translated into practice was recommended. This includes development of physical and non-chloride chemical approaches to snow removal and ice disbonding, and the operational procedures required to integrate new materials and techniques into an effective, cost-saving system. Further work on electronic monitoring of road surface conditions in high traffic density areas to provide real-time information for traffic control and treatment level was suggested. Fundamental work on the mechanism by which disbonding agents weaken or destroy the ice-pavement bond, followed by determination of optimum chemical application rates and development of methods of applying precisely metered quantities in a controlled pattern, will have relevance to both highway and guideway practice.

Decision makers need better information and methodology to make economic determinations of snow-removal system operation and effectiveness. As an example, an economic model for impact of delays of variable durations on local or regional economy, and the cost function for the various treatment levels will enable selection of the least-cost option. System optimization by computer modeling needs further work and refinement and translation into a practical format for wide use by large and small winter maintenance organizations.

Traffic speeds and accident rates for traffic of specified density and mix as a function of depth of snow on the road are not well known. An improvement in this information, coupled with improved values for costs of delay time, will permit selection of an optimum time for commencing snow clearance or other remedial action. Traffic action can remove light snowfalls or some types of snow, but the conditions under which this can occur are not clearly known. Research on the response of snow to trafficking by rubber tires will provide answers to this question.

Improvement in the design of snow clearing equipment, both displacement plows and rotary plows (snowblowers) was recommended.

Non-chemical, or at least non-chloride, methods of snow and ice control on advanced guideway systems were stated as pressing needs which require research. Automatic controls on present and future guideway systems are intolerant of snow and ice, and either design of components to avoid accumulation, or development of positive means of removal, are proper research objectives.

Data on traction of high-pressure rubber tires such as are used on automated guideway systems, as well as on buses and trucks, are not readily available. An effort to gather together scattered data, and to perform the research necessary to fill in the gaps, was recommended. It was also recommended that joint participation by rail, airport, guideway, and other non-highway transportation modes in winter operations conferences such as represented by this symposium be continued.

Recent standards for errant vehicle restraints have virtually eliminated the use of cable guard in many Snow Belt states in favor of metal plate beam guardrail. Plate beam guardrail is often placed at the top of embankments and this, combined with its approximate height of 2 ft creates aerodynamic conditions ideal for causing snow drifts on adjacent pavement. The safety device itself creates a winter hazard. Study is needed to develop effective vehicle restraint designs with aerodynamic characteristics that will not cause the drifting of snow.

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