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Foreword

This Record contains papers presented at the Third International Symposium on Snow Removal and Ice Control Technology held in Minneapolis, Minnesota, September 1992, and recommended for publication through TRB's peer review process. The papers were prepared by engineers, meteorologists, professors, and researchers from Canada, Denmark, Finland, Japan, Norway, Sweden, Switzerland, the United Kingdom, and the United States. The papers contain information on the state-of-the-art research and technology applications to improve snow removal and ice control operations in transportation systems. They are grouped under the following headings: policy and management, materials and application techniques, environmental considerations, drift control, snow and ice removal equipment, pavement surface condition, safety and operations, visibility, road weather systems, and weather forecasting. This volume was published with support from the Federal Highway Administration.

PART 1

Policy and Management

Snow Removal and Ice Control Technology on Swiss Highways

ULRICH SCHLUP

Winter road maintenance in Switzerland is vital because of the alpine nature of the country. The basic requirement of winter maintenance is to maintain the highway capacity and the safety of the roads without harming the environment. A successful program begins with a well-trained staff; it also depends on meteorology; road sensors; equipment for removing snow, spreading salt, and controlling ice; maintenance centers; and economic operation.

Switzerland is situated in the heart of Europe, in the central alpine region. The southernmost tip of Switzerland has roughly the same latitude as Minneapolis, Minnesota. Two-thirds of the country is mountains, some of which reach more than 4500 m (14,000 ft) in altitude.

The Swiss national highway network is situated at altitudes between 200 and 1200 m (650 and 4,000 ft). Some passes, which must be kept open all winter, even reach 2000 m (6,500 ft). This helps explain why Switzerland, along with other alpine countries that have the same problems, has always been among the pioneers in winter road maintenance technology.

The importance of winter maintenance is also clear in the expenditures of the road maintenance centers. For a four-lane highway, the yearly cost per kilometer reached $50,000 last year ($80,000/mi). The cost for winter activities (which, of course, varies from year to year depending on the weather) runs between 16 and 36 percent, or $8,000 to $18,000/km ($13,000 to $29,000/mi).

REQUIREMENTS FOR MODERN WINTER ROAD MAINTENANCE

Up-to-date winter road maintenance is not just a costly affair—it also brings many benefits. Without it, routine daily activities, business and private, would simply not be possible in a Swiss winter. Winter activities on the Swiss highways have three principal requirements:

- Maintain the highway capacity: full capacity from 7:00 a.m. until 10:00 p.m., and reduced capacity in between;
- Maintain the safety of road users at all times; and
- Avoid damaging the environment.

Put into concrete terms, this means

- Fast and complete snow removal, starting the moment that the snow no longer melts on the road surface;
- Effective ice control whenever slipperiness on the road surface occurs; and
- Minimum use of salt—the ecologists say to use none at all.

When analyzing the various tasks and the different demands, one soon realizes that a single item will not solve the problem. Applied alone, the most powerful vehicle, the most efficient alternative thawing agent, or the newest road sensor that tells the future will not bring the expected results; it will only be a disappointment. Winter road maintenance must be a whole philosophy, one that considers and makes use of every promising aid available.

Successful winter maintenance starts with a well-trained staff that has been instructed in every item from basic meteorology to minimal salt dosage with a sophisticated, electronically controlled spreader. Next comes the use of local weather forecasts or any weather information that gives an accurate forecast of snowfall or ice formation. Road sensors are a must. Automatic salt spreading equipment on structures must be considered. The equipment must be up to its tasks and in top condition. The various assignments with their respective equipment must be organized, and the standby planned. Finally, it is important to have a maintenance center with a practical layout to avoid unnecessary movement and loss of time.

METEOROLOGY AND ROAD SENSORS

No maintenance crew can do its job in time if it doesn't know, some hours in advance, what kind of weather and road conditions to expect. In Switzerland several public services are at the disposal of road users:

- A general weather forecast issued by the Swiss Meteorological Institute. The forecast is updated five times a day and is available on radio, videotex, and telephone.
- A forecast of road conditions. It is also issued by the Meteorological Institute at 6:00 p.m. on radio and made available on videotex and telephone.
- Actual road conditions. These are issued by the automobile clubs, updated twice a day, and made available on radio, videotex, and telephone.
- Special warnings about dangerous road or weather conditions, such as freezing rain. These are given directly to the maintenance centers by the meteorological office.

Missing in all this information, nevertheless, is an accurate, local forecast for the coming 2 to 6 hr. [Local here means the

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Swiss Federal Highways Office, Monbijoustrasse 40, Berne 3003 Switzerland.

area of activity of a maintenance center—about 50 km (30 mi) of highways.] To fill this gap, the appropriate tools have been developed, some of which are still being researched.

The maintenance centers have an on-line connection to the national weather radar, so they get the newest radar picture every 10 min on a PC monitor. With a loop function it is possible to run through a batch of 12 pictures and follow a precipitation front as it has moved in the past 2 hr. With some experience, the responsible person can estimate the speed, direction, and intensity of the front and make decisions accordingly.

There are still some difficulties, though. It is, for instance, not possible to distinguish snow from rain on the radar picture, and to predict the direction and speed of a front remains a bit of a gamble. One possibility for overcoming these difficulties is to blend wind speed and direction, as well as actual measured snow depth or rainfall on the ground, directly onto the radar picture.

Another tool, introduced two winters ago, is a system called SWIS (Street Weather Information System). The principle is simple. The data from all road sensors in a certain area are transmitted to the meteorological office, where a meteorologist, with all the other weather information at his or her disposal, makes a forecast for that specific area. The forecast is transmitted on the monitor in the center, using a standardized mask (Figure 1). This local forecast is for 24 hr, segmented in 6-hr periods. When necessary—necessity is clearly indicated by the actual road sensor data—the forecast is updated after 6 hr.

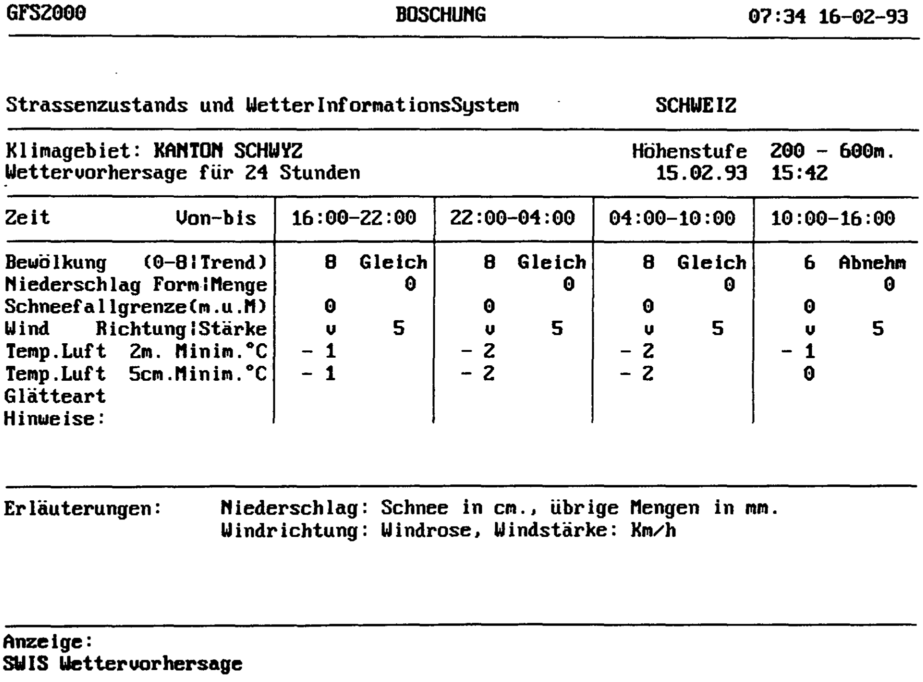
The experiences with the system are extremely promising, but there are difficulties. First, the extremely small-scale forecasts are not always very accurate, and second, the forecasts require additional staff at the meteorological office.

In a research project, physicists found valid relations between air temperature, temperature above ground, dewpoint, and psychometer temperature to predict quite accurately the formation of ice on a hard surface. And, when considering the temperature profile to detect an inversion, it appears possible to forecast freezing rain—at least under certain conditions. This discovery is very interesting, because the Swiss Meteorological Institute has access to more than 60 automatic measuring stations, which deliver these data every 10 min. All that is left to do is to analyze the data and, when a critical situation is found, tell the maintenance people where it is and what is happening.

In the last few years, the major part of the Swiss highway network was equipped with road sensors. The chosen system, GFS 2000, is manufactured in Switzerland. Roughly 200 sensors are installed, which means an average of one sensor per 8 km (5 mi). They are generally installed at places where freezing occurs earlier than elsewhere: on bridges with thin slabs, at the exits of tunnels, on shady stretches, and so on. This should allow the person in charge to intervene locally when freezing is not generally expected.

The results from the sensors are quite satisfactory. However, the best sensor is only a tool. The decision about what must be done is made by the person in charge.

There are two other facts to bear in mind when considering the installation of a road sensor system. First, the forecast of road conditions is not possible with road sensors alone: the best sensor gives only the reading of an actual state at a certain point of the road surface. Second, every sensor system needs regular service, and even then it will occasionally produce false information. It is vital that a manufacturer's serviceman can be called to the spot within a reasonable time; otherwise, the system is of limited value.



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GFSZ000                              BOSCHUNG                         07:34 16-02-93
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Strassenzustands und WetterInformationsSystem                  SCHWEIZ
------------------------------------------------------------------------------------
Klimagebiet: KANTON SCHWYZ                                  Höhenstufe  200 - 600m.
Wettervorhersage für 24 Stunden                               15.02.93  15:42
------------------------------------------------------------------------------------
Zeit              Von-bis | 16:00-22:00 | 22:00-04:00 | 04:00-10:00 | 10:00-16:00
------------------------------------------------------------------------------------
Bewölkung    (0-8!Trend)  |   8  Gleich |   8  Gleich |   8  Gleich |   6  Abnehm
Niederschlag Form!Menge   |           0 |           0 |           0 |           0
Schneefallgrenze(m.u.M)   |   0         |   0         |   0         |   0
Wind     Richtung!Stärke  |   v     5   |   v     5   |   v     5   |   v     5
Temp.Luft  2m. Minim.°C   | - 1         | - 2         | - 2         | - 1
Temp.Luft  5cm.Minim.°C   | - 1         | - 2         | - 2         |   0
Glätteart                 |             |             |             |
Hinweise:                 |             |             |             |

------------------------------------------------------------------------------------
Erläuterungen:       Niederschlag: Schnee in cm., übrige Mengen in mm.
                     Windrichtung: Windrose, Windstärke: Km/h


------------------------------------------------------------------------------------
Anzeige:
SWIS Wettervorhersage
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FIGURE 1 SWIS prognostic as transmitted onto PC monitor in maintenance center.

Sensor technology is in progress. A major step was taken lately by developing a freezing-point temperature sensor. It works by cooling down the sensor surface until the humidity on the surface freezes. The corresponding temperature is measured and indicated on the monitor in the maintenance center as the freezing point. The advantage is obvious, as the remaining salt on the road surface is taken into account. The road master knows the temperature at which the surface of the road in question is likely to freeze and can react accordingly.

In the last two winters about 40 sensors of this type have been installed on the highways. Switzerland has had two rather mild winters, so a final judgment of the sensor cannot be given, but it is expected that the experience will confirm the convincing theory.

EQUIPMENT

The importance of top-quality equipment for winter activities can hardly be overemphasized. In Switzerland the highways are not kept white. The principal roads too are kept bare, with the exception of higher regions or during the night hours. Furthermore, Swiss legislation requires that snow removal be carried out with mechanical means before any thawing agents are used. The equipment for snow removal is chosen accordingly. Decisive factors are as follows:

- Speed of a snow-removal team on the highway. It is important to maintain an average speed between 50 and 60 km/hr (30 and 40 mph) to avoid being overtaken by the traffic.
- Minimization of the remaining snow behind the vehicle.

Obviously, the second object is harder to achieve. In past winters a newly developed machine called a Jetbroom was tested. It is a two-axle vehicle with an attached sweeper and blower unit between the axles (Figure 2). The sweeper brush has a length of 4.30 m (14 ft), which in diagonal position gives a cleaning width of 3.90 m (about 13 ft). The blower duct, mounted in front of the brush, blows the loosened snow out sideways. The results achieved with the Jetbroom are gen-

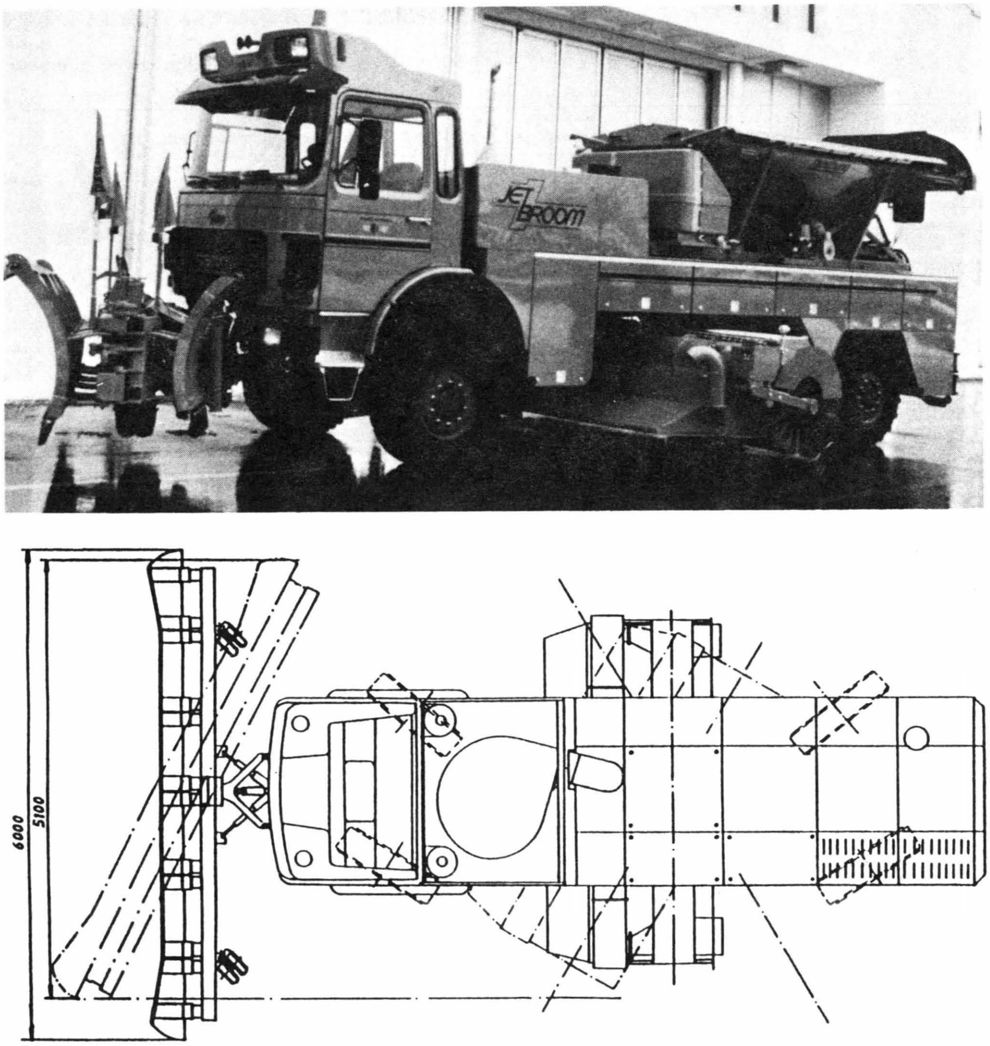

FIGURE 2 Jetbroom with attached sweeper and blower unit between axles: photograph (*top*) and diagram (*bottom*).

erally promising. Because the vehicle is remarkably more expensive than a normal truck, the manufacturer has developed suitable attachments for summer use to achieve a better all-year use.

An important piece of equipment is the salt spreader. The Swiss legislation only licenses spreaders that guarantee to maintain the chosen amount of salt per square unit, independent of speed. This decree forced the centers to replace all the old spreaders. The Federal Highways Office used the opportunity to promote the wet salt technique.

The common wet salt technique consists of mixing dry salt and brine on the spreader disc. The brine is stocked in containers in front or at the sides of the spreader. The brine is a calcium chloride–water solution with a concentration between 15 and 30 percent. In a few cases, sodium chloride is used instead of calcium. The brine is prepared in the maintenance center. The necessary installation consists of a mixing tank and a storage container (Figure 3). The storage capacity is usually about 6 months' consumption or more. The stored brine has a concentration near the maximum. The desired concentration for a particular operation can be obtained by adding fresh water, a process that is electronically controlled.

The use of wet salt on the road offers several advantages. First, the dosage of thawing agents can be reduced. A survey in all Swiss highway maintenance centers showed that with the wet salt technique, the average dosage can be reduced up to 25 percent compared with the use of dry salt. Next, wet salt starts the deicing process immediately, which means that the road surface is free of ice faster than when using dry salt. Finally, preventive salting is much more efficient with wet salt. It adheres to the road surface and cannot be blown away by the wind, as often happens with dry salt.

A disadvantage is the higher investment cost. Slipperiness on the road surface has been reported elsewhere, but not in Switzerland.

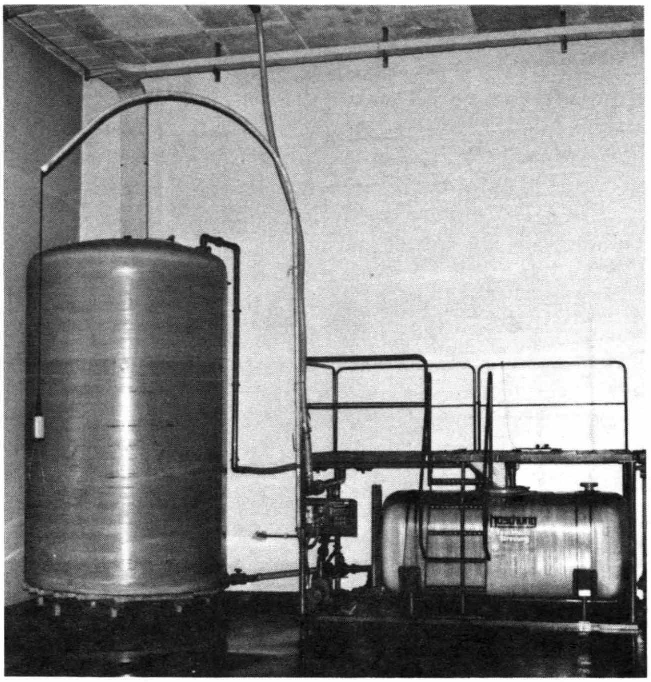

FIGURE 3 Wet salt installation: storage container (*left*) and mixing tank (*right*).

The automatic spray system for thawing agents must be mentioned. Many maintenance centers have a stretch of highway that regularly freezes earlier than the rest. It may be a long bridge or a stretch exposed to the wind or climatic peculiarity. If it happens to be at the far end of the operational area, it either reduces driver safety or causes excessive costs. Because it is not economical to launch an early separate spreading action for a short, faraway stretch, the whole length of the highway is normally done—"it must be done sooner or later, anyway," goes the reasoning. This may be so, but it may not—and the salt is on the road and the hours are spent, sometimes not in the most cost-efficient manner.

The installation of an automatic spray system offers a solution here. Not only is it economical in the long run, but it offers a higher security for the road user. In Switzerland two such installations are in operation, both on long and exposed bridges, and a third is being built. The latest generation of this device has overcome its earlier shortcomings. The distributor case with the spray nozzles is built into the pavement, and the necessary pressure is built up at the site (Figure 4). The pressure is sufficient to burst through any pack of dirt or snow that might occur.

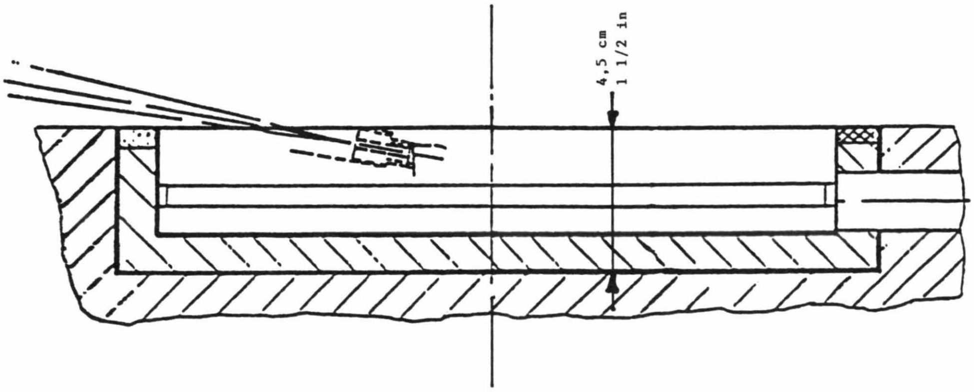

FIGURE 4 Automatic spray system: distributor case with spray nozzles built into pavement.

MAINTENANCE CENTERS

What was said about the importance of top-quality equipment also applies to the centers. It is very difficult to do a good job with an outmoded device, or with an old and unpractical center. Time is the most important factor in successful snow removal and ice control. Thus the maintenance crews need a home base, where the necessary activities do not lead to a loss of time.

A look at a professional fire department base reveals the decisive factors to save time; they are equally valid for a road maintenance center:

- An efficient alarm system;
- A spacious garage that allows the trucks to be parked beside one another, with plows attached and spreaders mounted;
- Motor-driven garage doors;
- A protected garage exit that cannot be blocked by any amount of snow;
- Crew quarters and lavatories adjacent to the garage;
- The supervisor's or road master's office overlooking the whole area of activity;
- Traffic lights, if necessary, to give precedence to the center exit.

The list is not complete. Other parts of the center need special consideration: salt storage in silos allows a much faster filling of the spreaders. According to the disposition of the silos, several trucks can be filled at the same time and, important for economical reasons, the drivers can do it themselves, without additional help. A well-equipped workshop in the center guarantees that any trouble or breakdown of a truck or engine can be seen to without delay, and a diesel oil and gasoline station in the center facilitates the refuelling during operations and in the evenings before closing.

Of equal importance is, of course, the organization of the work, the relief, and the standby. Only in exceptional cases is a night standby foreseen in Switzerland. One or several crews are on call at their homes. There they get the alarm of the ice detection system automatically by telephone. On a laptop they can read back the latest sensor data and react accordingly. Of course, they can also be called by a police patrol.

STAFF TRAINING

Behind every activity there is the person. A successful operation on the road, even with the most sophisticated equipment, requires a well-trained crew. It is the faculty and the skill of all concerned—the head of the center, the crew leaders, the mechanics, and the drivers—on which a successful operation depends. Therefore, instruction and training is essential, and even more so, the more complex and sophisticated modern tools become. It is an important task for the head of the center to set up a training program for all the activities of the unit. A few examples are driving of new vehicles, handling of new equipment, using the appropriate salt dosage for any given road condition, implementing the wet salt technique, removing snow on highway junctions, and installing signalization for maintenance work on the highway. Furthermore, the director must ensure that specialists, mechanics, and electricians are getting the necessary instruction to keep up with developments in their fields.

In addition, the Swiss Federal Highways Office started a course of instruction for heads of centers and crew leaders. One course takes 2 days. The last course program included basic meteorology, Part 1 (atmosphere, pressure, temperature, formation of clouds and precipitations, cold and warm front, prognostic), reading weather radar pictures for use in winter maintenance, and ice detection systems (functioning, alarms, use of data, errors). The reaction to the course was very positive. A continuation program for three consecutive years is in preparation.

Continual instruction and training is the only way to meet with the ever-increasing demands in winter maintenance. It not only enables the staff to keep up with their task, but it motivates them to do it better, which is the decisive asset.

ECONOMY

In Switzerland, the national highways are owned and operated by the cantons (Swiss states), and the federal government subsidizes their expenditures between 55 and 95 percent. The subsidy is not paid out as a global sum but in proportion to the expenditure of every canton.

Ten years ago operational accounting for all highway maintenance centers was introduced; it enables the federal administration to analyze the economy and the efficiency of any center. Operational accounting shows the hours of drivers, mechanics, vehicles, engines, and such used for winter maintenance on a given stretch of highway. It also shows the operating cost of any given truck or engine. It is therefore possible to compare these data with those of a neighboring center or with a given average or standard. The results are discussed with the head of the center or the person in charge, and, if necessary, a different strategy is developed or different goals are set for the next year.

An interesting fact is that all the heads of centers are the first to compare their own results with the given average. If theirs are lower in cost, they are pleased; if theirs are higher, they will look for the reasons and do something about it. It is a necessary competition that is only healthy for a public agency.

Personal experience of 10 years of activity in the field of winter maintenance on federal level can be summed up as follows: maintain a close look at new developments and test every promising device, but do not expect miracles. An excellent job can be done only when all factors blend into an integral whole.

Goals and Methods of Winter Maintenance in Finland

KALEVI KATKO

Finland is situated so far north that the snowy part of winter lasts for 4 to 6 months. The most important goal of winter maintenance is to ensure the safe and efficient flow of traffic at all times on all roads. Environmental aspects such as the use of salt are also significant issues. To ensure that these goals are met, quality standards for the activities have been established according to maintenance categories. The classification assures the road user that the friction numbers on the winter road surface are kept high enough. Maintenance equipment and its auxiliary devices have been continuously improved. To reduce the need for salt, it is important to remove snow and slush mechanically by plows. When the temperature is between −6 and 1°C (22 and 34°F), salt—liquid, prewetted, or dry—is used for antiskid treatment. Rates as low as 8 to 12 kg/lane-km (30 to 45 lb/lane-mi) of liquid salt can be enough for deicing. Soon Finland plans to reduce the number of miles of main highways that adhere to the bare-pavement policy; main highways with average daily traffic between 1,500 and 3,000 will be evaluated individually to achieve an optimal balance between the users' needs and the environment.

Finland, which is situated in northern Europe between the 60th and 70th parallels of latitude, has 4 to 6 months of snow in the winter, and the depth of snow cover ranges between 40 to 80 cm (15 to 30 in.). On the narrow coastal strip by the Baltic Sea, the winter is shorter and the snow melts several times during the winter. Temperature changes can be sizable and quite sudden. The freezing weather typical of the midwinter [temperature under −10°C (14°F)] can last from a few days to as long as 2 or 3 weeks. Snow falls on many days during winter, in amounts usually no more than 15 cm (6 in.). The most problematic weather for road maintenance personnel is mild, varying weather conditions, when the temperature varies between −6 and 3°C (22 and 38°F). This is generally when Finland receives the most snow.

OBJECTIVES OF WINTER MAINTENANCE

Despite the long winter, society must keep rolling. Thus, the main objectives for winter maintenance are to

- Ensure the smooth flow of traffic on all roads at all times;
- Provide traffic safety; and
- Minimize harmful effects on the environment.

The standards are grounded mainly in traffic volume–based maintenance classifications; the divisions are given in Table 1. For each maintenance category, a condition standard has been defined, and when the road condition falls short of this standard, it must be returned to the required level within a specified time by means of appropriate maintenance activities. Slipperiness, snowiness, and evenness are regarded as variables of the condition standards. The current standards are based on thorough studies that were carried out in the 1980s. The definitions of the condition standards are given in Table 2. Each maintenance class is defined by a given condition standard. Table 3 shows the target condition values for each maintenance class. It also presents the cycle times, which is the amount of time that is allowed for a road that has fallen short of the condition standard to be restored to the level of its target condition.

Road maintenance tries to keep the main part of the road system within the first maintenance class clear of snow and ice throughout the winter. However, as indicated in Table 2, a thin layer of snow is allowed between traffic ruts. This helps to reduce the use of salt. On these highways deicing is done mainly with sodium chloride, but salt is used only during the most slippery traffic conditions, when the temperatures are between −6 and 1°C (22 and 34°F). The friction is at its lowest during these temperatures. In colder weather the friction is generally good. When the temperature goes below −6°C, deicing is done primarily by using sand with a little salt, but only in the most problematic places such as intersections, curves, and hilly sections of the road. Although salt would be effective at lower temperatures, the limit for using salt has been set at about −6°C to reduce environmental problems. Colder weather requires more salt to be effective.

Correctly timing maintenance measures in changing weather conditions is of primary importance. The Finnish National Road Administration (FinnRA) has a weather monitoring system and night patrol operations at the road maintenance areas designed for this purpose. The road weather service system, which has about 150 road weather stations and covers the main highways of the entire country, provides advance warning of weather changes. Maintenance supervisors have skid testers in their cars, which can be used to assess the need for maintenance measures. Monitoring of the existing conditions as they relate to the condition standards is a central part of the system. The maintenance engineers of the road district monitor quality standards in a centralized way.

FinnRA is very satisfied with the system, but it must improve the dissemination of information to road users; new district information centers are being tested today. The cooperation of maintenance supervisors must be better guaranteed than it is.

ENVIRONMENTAL EFFECTS

In recent years the chloride content of the groundwater has risen in some places because of salting. In the future this may

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Finnish National Road Administration, District of Central Finland, Matarakuja 4, P.O. Box 58, Jyvaskyla 40101 Finland.

TABLE 1 Maintenance Classifications

Class	Traffic Volume (ADT)	Length (%)
I Super Divided	(Freeways)	0.6
I Super	6,000 or more	2.1
I	1,500 to 6,000	11.0
II	200 to 1,500	42.4
III	Less than 200	40.6
IV	(Pedestrian and bicycle paths)	3.3

NOTE: ADT = average daily traffic.

TABLE 3 Target Condition Values and Cycle Times by Maintenance Class

Maintenance Class	Target Condition		Cycle Times (hr)	
	Day	Night	Deicing	Snow Removal
ISD, IS	4	4	2	2.5
I	4	3	2	3
II	3	2	4	4
III	2	1	6	6
IV	2	2	4	4

NOTE: ISD = I Super Divided, IS = I Super.

TABLE 2 Definition of Condition Standards

Quality class variable	Target Value				
VARIABLE I, SLIPPERY CONDITION	1	2	3	4	5
- Skid number	0,00-0,15	0,15-0,25	0,25-0,30	0,30-0,45	0,45-0,10
- Road surface - Texture	Very icy driving or otherwise very slippery	Dry ice or snow path	Coarse ice or snow path in cold weather	Bare and wet or paths between traffic ruts	Bare and dry
II SNOW CONDITION (10, 20 and 30 mm = 0.4, 0.8 and 1.2 in)					
- Dry frozen snow	> 50 mm	≤ 50 mm	≤ 30 mm	≤ 20 mm	-
- Thawing snow	> 40 mm	≤ 40 mm	≤ 25 mm	≤ 15 mm	-
- Slush	> 30 mm	≤ 30 mm	≤ 20 mm	≤ 10 mm	-
- Drifting snow	Easy passage may be difficult some places, car may become stuck in a snowdrift	Projections over the road or moderate snow layer at the road edges, driving speed must sometimes be reduced	Projections here and there over the road, driving speed has to be reduced in some cases	Projections here and there to the middle of the outermost traffic lane, generally no need to reduce the driving speed	
III EVENNESS (10, 20 and 30 mm = 0.4, 0.8 and 1.2 in)					
- Ruts	> 30 mm	< = 30 mm	< = 20 mm	< = 10 mm	
- Other roughness	Path very uneven, possible projecting bumps, driving speed must be reduced and uneven spots avoided	Plenty of worn spots or disturbing holes, driving speed must be reduced in some places	Path even possible unevenness does not actually disturb driving	Thickness of path strips on the road portion under traffic < = 10 mm	

cause problems in providing drinking water to communities. The increased salt concentration of drinking water may be a health risk, at least to some groups of people. It also makes the drinking water taste bad and causes some corrosion damage to the water system. Other negative effects include rust damage to cars and damage to the growth of trees and other plants. To keep the environmental problems at a minimum, the department has

- Considered environmental issues in the development of goals for winter maintenance so as to keep the use of salt at a moderate level;
- Identified risk areas and evaluated the use of salt on those sections on a case-by-case basis;
- Increased the accuracy of salt application and reduced the amounts used by means of new technology and training;
- Monitored closely the use of salt; and
- Systematically followed the impact on the environment.

EQUIPMENT AND DEVICES IN USE

The main principle in the development of equipment and auxiliary devices is to improve the quality and efficiency of winter maintenance work. Such improvements will decrease the time during which the road conditions are below the target standard. The basic unit used on the main road network is the truck. The improved system of hydraulics designed for it provides the driving power for many auxiliary devices. The hydraulically operated auxiliary devices have been developed by FinnRA so that they are suitable and efficient for each road category.

The snow removal activity on the road network that must be kept bare (first maintenance class) primarily includes plowing snow, wet snow, and slush. Salting is often done at the same time. To accomplish that, the truck is equipped with a double-blade plow, wing, and a rear (or liquid) spreader (Figure 1). The snowplow has been developed so that it throws snow very well, and it has also been designed with another blade behind it that is made of rubber (Figure 2). The rubber blade is divided into four parts because of ruts in the road surface. The rubber material and its four-part structure enable the blade to clean the wet snow or slush left by the first blade. A road that is as clean as possible requires less salt than one that has been plowed less efficiently. When dry snow is plowed, it is not necessary to use the second blade, so the blade is hydraulically lifted clear of the roadway. The salt is spread by a rear or a liquid spreader on two lanes at the same time. The truck, however, normally operates on the right lane and salt is sprayed sideways also on adjacent traffic lane.

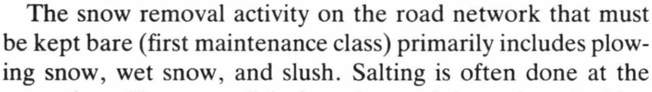

FIGURE 1 Finnish winter fighter with the plow, wing, and liquid salt spreader.

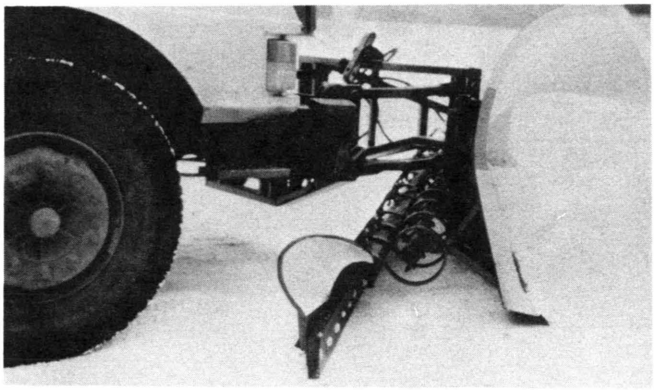

FIGURE 2 Finnish double-blade plow.

On road networks of lower maintenance class categories, FinnRA uses the telescope plow, which has an adjustable plowing width and an underbody plow for removing packed snow from the road. Antiskid treatments consist of sand or salted sand.

The hydraulic auxiliary devices are so easy to handle that it is possible for one driver to operate the truck with all three auxiliary devices operating simultaneously on the road.

SALT USE

For environmental reasons, strong efforts have been made to reduce the amount of salt that is spread. As reported, the amount of salt used is influenced by the quality of snowplowing and by the salting methods. The main principle is to salt a road surface that is as clean as possible and to use the right method of application for the conditions.

FinnRA uses liquid, prewetted, and dry salt. Liquid salt is now in extensive use, especially in southern Finland. In the northern regions it is used to remove ice coatings during fall. Liquid salt usually consists of 23 percent sodium chloride.

Sodium chloride is mainly used for dry salt applications. Water, liquid sodium chloride, or liquid calcium chloride is used for prewetting salt. The use of prewetted salt has greatly increased in Finland. Its use is usually possible through the entire winter. A 5 to 10 percent concentration is typical for prewetting.

The amount of salt used in one-time spreading by the different methods is as follows:

Salt	*Amount [kg/lane-km (lb/lane-mi)]*
Liquid	8 to 12 (30 to 45)
Prewetted	20 (70)
Dry	25 to 50 (90 to 180)

The differences in application rates are significant. It should be remembered, however, that liquid salt is suitable only for preventing ice film or as an antiskid treatment on a very small snow residue. The amount of salt in difficult circumstances can be even twice as much as mentioned (such as in colder temperatures or spreading under snow). However, all these methods are needed to achieve the optimum results for both traffic safety and environmental concerns.

DEVELOPMENT VIEW

In Finland all are concerned about the environmental effects of salting, which is why officials are examining ways to reduce the number of miles of main roads that are kept deiced through the winter. The condition value for roads with average daily traffic between 1,500 and 3,000 will be reviewed. Already on a third of these roads, a lower target condition value of 3 is applied for antiskid treatments, although the value is still 4 for snowiness and evenness. New roads will be evaluated individually to achieve an optimal balance between users' needs and the environment. However, roads must be treated in a unified way throughout Finland so that the standard of traffic safety is consistent and so that the road users are not surprised by a change in conditions.

Proposal for New Winter Road Maintenance Strategy: MINSALT

LENNART AXELSON

The MINSALT project has resulted in a proposal for a new winter maintenance strategy that shows how winter road maintenance can be organized so that its objectives can be attained. By adopting the proposed strategy, it is possible to reduce salt consumption. The overall goal of road maintenance is to help maintain the country's total resources at a high level of efficiency. The objectives can be broken down into several road maintenance aims, including a high standard of traffic safety, good trafficability and high degree of availability, low vehicle costs, and a good environment. Ways that these aims can be achieved on rural areas and in municipalities in the winter are explained. Proposed measures, methods, and resources are also presented.

Salt is satisfactory as a means of improving skid resistance, but it also causes problems, such as increased corrosion on vehicles and roadside structures of steel and damage to concrete structures, trees, and other vegetation, especially in municipalities. The use of salt (or sodium chloride) as a deicing material is therefore being questioned more and more by the road users, the general public, and politicians.

For this reason, the Ministry of Transport and Communications commissioned the Swedish National Road Administration, the Swedish Association of Local Authorities, and the Swedish Road and Traffic Research Institute to draw up a detailed research program aimed at reducing the harmful effects of salt in winter road maintenance. This research program, which was implemented during 1985–1991, is called MINSALT.

The purpose of the MINSALT project was to find out whether and how the harmful effects of salt in winter road maintenance could be reduced without a deterioration in traffic safety. The Ministry of Transport and Communications decided on three ways of minimizing the harmful effects of salt:

1. Extend the regions in which salt is not used.
2. Use new methods for snow and ice control.
3. Devise a new strategy for snow and ice control.

PROPOSAL

The MINSALT project has resulted in a proposal for a new winter road maintenance strategy that, in the light of the results of research and the experience gained from the MINSALT project, shows how winter road maintenance can be organized so that its objectives can be attained. By adopting the proposed strategy, it is possible to reduce salt consumption by about 20 to 40 percent.

The overall objective of road maintenance is to help maintain the country's total resources at a high level of efficiency. This objective can be broken down into the following aims:

- A high standard of traffic safety
- Good trafficability and a high degree of availability
- Low vehicle costs
- A good environment

RURAL AREAS

In rural areas the aims can be achieved by meeting the standard requirements (described in functional terms) of roads in the winter given in Table 1. As for pedestrian pavements and bicycle paths, they should be even, nonslippery, and free from loose snow.

The standard requirements mean that

- Road users must be informed about the winter road maintenance objectives of the National Road Administration.
- Road users must be informed about current road maintenance measures and the latest weather, road, and traffic conditions.
- The standard of winter road maintenance should be so uniform that road users do not notice the difference between road maintenance areas, districts, and counties.
- The standard of maintaining pedestrian and bicycle paths should be such that pedestrians and cyclists do not prefer to use the road.

National and Regional Roads

The standard requirements cannot always be met on account of prevailing traffic and weather conditions, but as far as is practicable, the following requirements apply to national and regional roads. If there is a danger of slippery road conditions, antiskid measures should be taken to prevent them. Deicing and antiskid measures should be carried out before peak traffic periods, and the time for these measures on national and regional roads should be 1 and 2 hr, respectively.

Snow deeper than 3 cm (1.2 in.) should not be allowed to remain on the road during a snowfall, and after the snow has stopped, the road should be free from snow in no more than 2 hr for the national roads and 3 hr for the regional roads Strings of slush should not be left on the road. Snow should

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TABLE 1 Standard Requirements for Rural Areas

	Road		
Functional Goal	National	Regional	Local
Uniform standard of trafficability	X	X	X
Dry road, free from snow and ice	X	X	
Even surface, free from loose snow			X
Good road user information and information on weather and road conditions	X	X	X

be cleared from the hard shoulder when the roadway is free from snow.

Local Roads

As far as is practicable, the following requirements apply to local roads. When precipitation causes extreme slipperiness, the roadway should no longer be slippery within 4 hr after the precipitation has stopped. Snow deeper than 8 cm (3.2 in.) should not be allowed to remain on the road during the snowfall. The roadway should be cleared from snow not more than 8 hr after the snow stopped falling.

Procedures

Functional Requirements

The following procedures can be adopted to meet the functional requirements, although local conditions may call for other solutions:

- Neighboring road maintenance area should be contacted each time snow-clearing or deicing measures are undertaken.
- If possible, winter road maintenance boundaries between neighboring road maintenance areas should be located where traffic speeds are lower, such as intersections, interchanges, or population centers, or where a safe turning space can be arranged.
- When planning deicing routes, the time difference between units meeting at the boundary should not exceed 30 min for the salted road network. Coordination between different units should take place. Practical considerations rather than administrative boundaries should be the determining factor, so that "invisible" boundaries are reached. If conditions are favorable for overlapping, such a measure should be considered.

Deicing and Snow-Clearing Methods

Adoption of the following measures, methods, and resources is proposed. It is important to use the right method at the right time. Where chemical deicing is concerned, the method used should be the one with the lowest salt consumption. For preventive salting, the salt should always be prewetted with 80 to 100 L of water per tonne of salt (22 to 27 gal of water per 2,200 lb of salt) if equipment for spreading a saline solution or prewetting salt with a saline solution is not available. This means that the dry salt is prewetted in a simpler manner by spraying a saline solution or water over it as it is loaded onto the spreading vehicle. Prewetted salt should not be spread wider than 4 m (4.3 yd), regardless of the road width, because of large salt losses in connection with wider spreading. The application rate compensates for the actual width to be deiced.

Salting in conjunction with snowplowing should be carried out only when there is a danger of compaction or freezing. When salting and snowplowing are combined, the salt should be spread only on the width of the road that has been cleared of snow.

Chemical deicing should normally not be done on local roads, as the standard requirements for local roads says. If possible, salt-free abrasives such as crushed stone aggregate of 2 to 5 mm (0.08 to 0.20 in.) should be used. The lowest temperatures for chemical deicing should be −12°C (10°F) on national roads, −8°C (18°F) on regional roads, and −3°C (27°F) on local roads. At temperatures lower than these, the material with the best adhesion, having regard to durability and availability, should be chosen.

Sand mixed with salt should not be used when it is possible to use crushed limestone, natural sand, or crushed stone aggregate. If sand mixed with salt is to be used, it should be mixed with 20 to 50 kg of salt per m^3 of sand (22 to 55 lb of salt per 1.3 yd^3), and not later than in July. The longer time taken to melt the salt, the higher the quality of the product.

Snow-clearing equipment should be adapted to the prevailing snow and temperature conditions. Snow should be cleared from the roads as quickly as possible. If possible, salting should be delayed until the snow has stopped falling.

MUNICIPALITIES

Road safety should be of a high standard for all road user categories. To reduce the number of casualties and minimize the cost of accidents to the community, deicing for pedestrians must be given priority. Having good traffic system availability calls for a high standard of deicing of pedestrian paths. Otherwise it will not be possible to satisfy the transportation needs of the elderly and the handicapped. Highly frequented pedestrians routes to bus and tram stops, civic centers, central city areas, and so forth should be even, skidproof, and free from loose snow.

The business sector in particular demands good trafficability on main roads and important streets. In principle, these roads and streets should be deiced by the time the morning rush hour starts and to the same standard and with the same standard requirements as the National Road Administration maintains on adjoining roads. Cooperation between the National Road Administration and the local authorities should therefore be developed, especially in regard to information on weather and road conditions, deicing vehicle turn-outs, and other measures.

Antiskid treatment is highly dependent on good weather information and good forward planning to prevent operational problems. On important through routes and main streets, preventive antiskid measures are an important means of achieving high standards of road safety and trafficability.

A suitable way of carrying out preventive salting is with prewetted salt or a saline solution. This will produce better results with a smaller quantity of salt.

The use of a saline solution should be avoided on icy roads and extremely wet roads and during snowfall. It is important to limit the use of salt wherever possible so that deicing can be carried out in a manner that is least harmful to the environment. Salting should therefore be used primarily as a preventive measure. Salt should not be used to melt snow. Salting in connection with snow clearance should be resorted to only when there is danger of snow compaction. Salt should be used restrictively on main roads and major streets lined with trees. Care should also be taken when salting near concrete structures.

If dry salt is spread on the roads, salt spreaders on which acceptable application rate settings are possible should be used. As a rule, sand spreaders are not suitable for salting. Salt should not normally be spread on less important main streets. If possible, such streets should be treated with crushed stone aggregate or the like without the admixture of salt. Removing the salt from the sand used for gritting greatly reduces the amount of salt spread on municipal street networks.

Pedestrian and bicycle paths should normally be treated with salt-free materials. Materials that ensure good skid resistance should be chosen for bicycle paths as long as they are not so flaky as to damage bicycle tires. Heated sand might be a good alternative to crushed stone on pedestrian paths.

PART 2

Materials and Application Techniques

Methods and Materials for Snow and Ice Control on Roads and Runways: MINSALT Project

KENT GUSTAFSON

The harm caused by salt can be reduced by using methods and materials, both chemical and mechanical, that more effectively counteract slippery conditions. New deicing methods and agents have been tested in several different projects in the Swedish MINSALT project in efforts to find ways of improving skid resistance that do not have the negative effects of salt. In regard to chemical deicing—that is, salting—methods have progressed from spreading dry salt to spreading prewetted salt and saline solutions, and from spreading curative when icy conditions have already formed to spreading preventive as an anti-icing measure. Spreading prewetted salt or a saline solution has been done for many years, and it is now a fairly well known technique; test results are mostly positive. The methods are presented, and results and experience from some winter use are shown. Several deicing agents were tested as alternatives to sodium chloride, but calcium magnesium acetate was investigated most intensively. The studies were concerned with melting properties, corrosion to metals, and effects on cement concrete. For runway deicing there is a search for alternatives to urea, which has a negative effect on the environment. Liquid potassium acetate has been tested in the laboratory and the field, and the experience is mostly positive; it is now used on some airports in Sweden.

The harm caused by salt can be reduced by using methods and materials, both chemical and mechanical, that more effectively counteract existing or probable slippery conditions. New deicing methods and agents have been tested in different projects in the 5-year study of the Swedish MINSALT program. Projects were conducted during 1985–1990 to find ways of improving skid resistance that do not have the negative effects of salt. The results from the MINSALT projects have been reported in different papers and are summarized in a final report (*1*).

CHEMICAL DEICING WITH NaCl

As for chemical deicing—that is, salting—methods have progressed from spreading dry salt to spreading prewetted salt and saline solutions. Experiments aimed at using NaCl more efficiently included studies of optimum spreading rates under different weather and road-surface conditions. The importance of the road structure, the wearing course, and the salt (origins and gradations) were studied. Possibly the most negative effect of salt is its corrosiveness. Corrosion inhibitors—substances added to the salt to reduce its corrosiveness—were also studied in the laboratory.

Several chemical alternatives to NaCl have been tested. In particular, calcium magnesium acetate (CMA) has been studied more closely in regard to its ice-melting capacity, corrosiveness, and effect on concrete. Studies of alternatives have also included chemicals suitable for runway purposes. Potassium acetate, a liquid deicer, has been tested and is being used at some Swedish airports.

As a rule, deicing by spreading sand on the roads also entails spreading salt, because the sand used for this normally contains about 3 percent salt by weight to permit its storage in cold weather, to facilitate spreading, and to make it more effective on an ice and snow cover. Several possible salt-free alternatives such as limestone products and chippings have therefore been tried out within the scope of the project. Finally, more efficient methods of ice scraping and snowplowing have also been tested. By reducing any remaining layer of ice and snow, the salt dosage needed to achieve an acceptable standard can be minimized.

Prewetted Salt, Saline Solution

Until the mid-1980s, spreading dry salt was the only chemical deicing method in Sweden. Under many conditions, dry salt had limited effect, particularly when spread on dry roads as an anti-icing measure. Studies have shown that much of the dry salt ends up at the side of the road during the actual spreading process and that even more is blown off the road by traffic. One way to make the salting more effective is to wet the salt before spreading. By prewetting the salt sufficiently, the time required for the salt to dissolve is reduced and the salt adheres better to the road surface.

The spreading of prewetted salt or a saline solution has been done for many years; it is now a well-known technique. The salt can be prewetted either when it is loaded onto the spreading vehicle or when it is spread.

Water, NaCl or $CaCl_2$ solutions, or other suitable solutions can be used for prewetting the salt. Water and NaCl solution have been used in Sweden. Water is used for the simpler method of prewetting the salt when loading it, and a saturated NaCl solution is used for prewetting with a salt spreader and when a saline solution is spread. $CaCl_2$ solution has been tested but not used in Sweden on account of its aggressive effect on cement concrete, higher cost, and the fact that no

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difference in its effect on ice and snow could be subjectively discerned in comparative tests with NaCl.

Special spreaders for prewetted salt were developed and put into service during the 1980s (Figure 1). In addition to the hopper for the dry salt, these spreaders have a solution tank [capacity approximately 2 m^3 (about 500 gal—conversions in this paper will be approximate)], pump, spray nozzle, and electrical equipment for regulating the amount of solution. As it is discharged onto the spreader disc or passes through the discharge pipe, the dry salt is sprayed with brine.

A saturated NaCl solution (approximately 23 percent by weight concentration) is used for prewetting the salt and for spreading saline solutions. Two types of saline solution plants are used to prepare the saturated saline solution. One fills a tank with salt and water that is pumped around until a saturated saline solution is obtained. Production volume is 8 m^3 (2,000 gal) of solution at a time. The same container is used for manufacture and storage. The other type of plant forces water under pressure through a bed of salt in a large tank. The saturated solution is then allowed to flow to a 10-m^3 (2,600-gal) storage receptacle. Manufacture of the saline solution is a continuous process, and the amount of salt and water is metered automatically.

As a rule, 30 percent by weight of the saturated NaCl solution is added to the dry salt. The rate of dry salt is similarly reduced by 30 percent at the same time. This means that the amount of salt spread on the road is automatically reduced because the saline solution added to the salt contains a large proportion of water. The actual reduction in the salt dosage is slightly more than 20 percent. Besides this automatic reduction, the higher efficiency of the method as compared with conventional spreading means that the amount of salt spread on the road can be further reduced.

The advantages of using prewetted salt instead of dry salt, as shown by the tests carried out with wet salt spreaders and the results of subsequent practical winter road maintenance applications, include the following:

- The salt is spread more uniformly and less is wasted at the roadside.
- The salt adheres to the road surface better.
- Prewetted salt has a faster and more durable effect.
- Spreading speed can be increased.
- In some cases the road surface dries out quicker.

In summary, the advantages of prewetted salt mean that a smaller amount can be spread to maintain a certain standard and that preventive measures are possible.

Simple Prewetting with Water

Dry salt can also be prewetted in a simpler manner by spraying a saline solution or just water over it as it is loaded onto the spreading vehicle. The advantages of this prewetting method are that conventional spreaders can be used and that little capital needs to be invested in special new equipment.

In Sweden the simpler prewetting technique was tested in a road maintenance area during the winter of 1987–1988. Prewetting was accomplished by spraying water into the loaded salt hopper with a hose (Figure 2). Depending on the method of loading, the solution is added from above, by spraying it over the loaded salt as in the figure, or during the actual loading process, if it uses a conveyor belt.

In the winter of 1988–1989, tests with the simple prewetting method were carried out on a larger scale in about 70 local road maintenance areas. In addition to some special studies, practical experience of the method as used by road maintenance crews has been gathered in two questionnaires; the results are summarized as follows:

- The proportion of water should be 80 to 100 L/t (22 to 27 gal/2,200 lb), in the light of special tests.
- It must be possible to measure the amount of water because the equipment malfunctions if insufficient water is used.
- The method has been tested at temperatures down to about −12°C (10°F), but it is generally used down to −6°C (21°F).

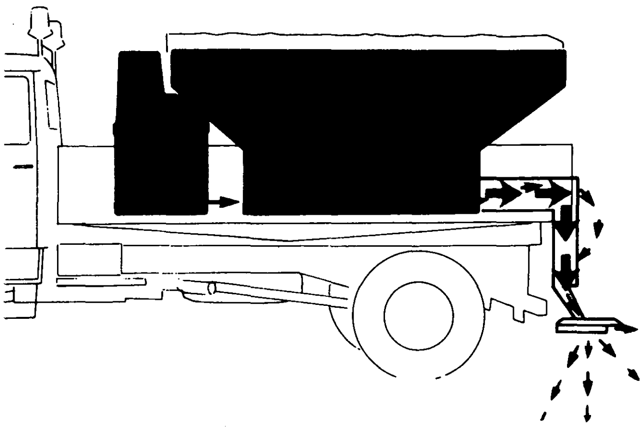

FIGURE 1 Spreader for prewetted salt.

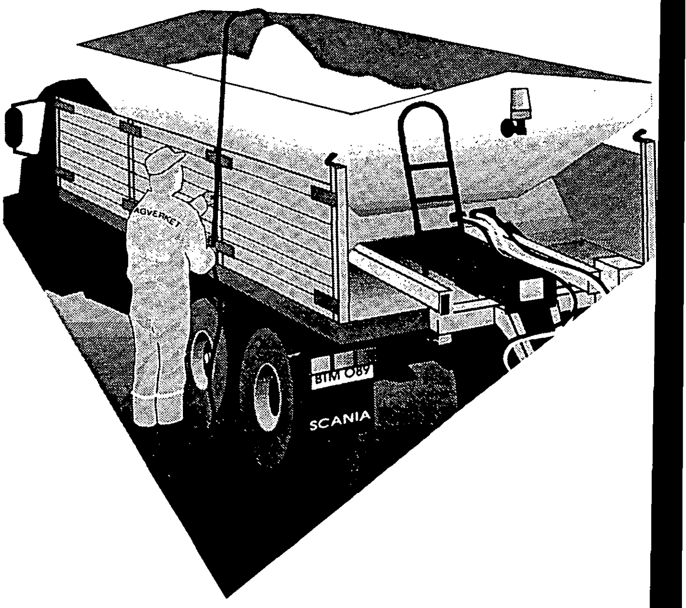

FIGURE 2 Simple prewetting of salt with water.

- Spreading speed has been 50 to 60 km/hr (30 to 38 mph).
- As a rule, 2 to 3 t (4,000 to 6,500 lb) of salt has been prewetted, although tests have been carried out with up to 8 t (18,000 lb). The amount of salt that can be prewetted depends to some extent on the size of the spreader.
- About 90 percent of the road maintenance areas have reported that the method produces good results and that they intend to continue using it.

Simple prewetting with water makes it possible to gain the advantages of prewetted salt with conventional spreaders at an extremely low investment cost, improve the adhesion of the salt so that it stays longer on the road, and increase spreading speed. One limitation of the method is that the spreader should not be loaded with more than 2 to 3 m^3 (70 to 105 ft^3) of salt to ensure that it is thoroughly wet before spreading. However, this is enough for 60 to 90 km (40 to 60 mi) of preventive salting. The limitations of the method make it better suited to road maintenance areas with lower traffic densities on their salted roads. In areas with more trafficked roads, prewetted-salt or saline-solution spreaders are more suitable for chemical deicing and anti-icing measures.

Spreading of Saline Solution

Deicing with a saline solution entails spreading a saturated salt solution containing 20 to 25 percent NaCl by weight. Spreading this solution on the roads therefore corresponds to only about a quarter of the amount of dry salt.

Swedish studies of spreading brine were begun in the winter of 1987–1988 when tests were carried out on a small scale in two local road maintenance areas. This smaller preliminary study consisted of a visual examination to assess spreading efficiency, spreading pattern, effect on the road surface, and refreezing, if any. Brine was tested on a larger scale in the following winters: 1988–1989 in 7 areas and 1989–1990 in another 20 areas.

Two types of spreading equipment for saline solution were tested; both were speed-independent, which means that the amount of solution spread is not dependent on the speed of the vehicle. The normal capacity of the tank of brine is 8 m^3. The brine is spread on the road either by means of nozzles on a spreader arm or by means of two rotating discs (Figure 3). Depending on the spreader, the width can be set between 2 and 10 m (6 and 30 ft) and the application rate between 3 and 18 g/m^2 (40 and 225 lb/lane-mi) of dry salt. The dosage corresponds to 10 to 80 g/m^2 (2 to 16 gal/1,000 ft^2), corresponding to about 5 g/m^2 (60 lb/lane-mi) of dry salt. The road administration bought more spreaders for the 1989–1990 season, so that about 80 spreaders were in use. As in the previous winter, the spreading of saline solution was followed with a questionnaire concerning the methods and spreading equipment used. The 26 local road maintenance areas and 2 municipalities covered by the study gave their views and reported on the results they had obtained.

Summarizing, experience gained during the three winters shows that

- The method is considered to be extremely effective as a preventive measure and for dealing with hoar frost on the roads.

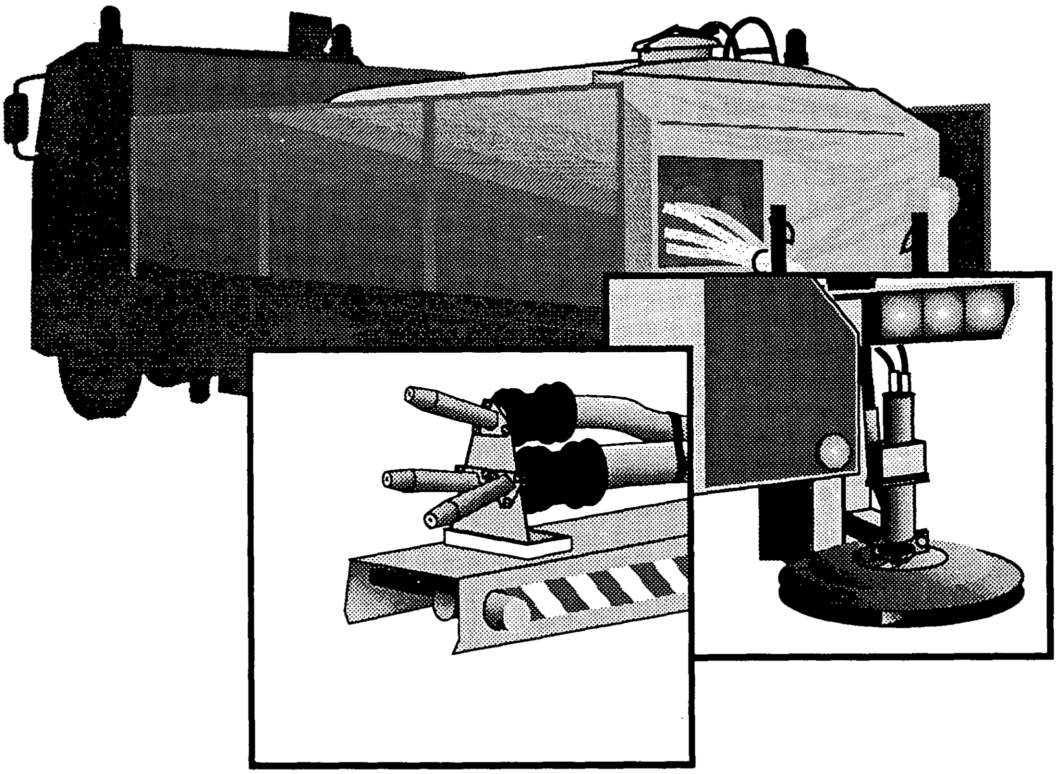

FIGURE 3 Spreaders for saline solution: *left insert*, nozzles; *right insert*, spinners.

- During a snowfall, the method is of doubtful merit. On wetter roads and where ice has already formed, the method is similarly of doubtful merit, or downright unsuitable. Correct dosage is a critical factor. Dilution of the brine resulting in refreezing can be a problem.
- A saline solution of 20 g/m^2 (4 gal/1,000 ft^2) [corresponding to about 5 g/m^2 (about 60 lb/lane-mi) of dry salt] is sufficient in most cases as anti-icing and less severe deicing measures.
- The method has been tested on roads and highways with average daily traffic ranging from 1,500 to 12,000.
- Spreading has been possible at speeds of up to 60 km/hr (40 mph).

CHEMICAL ALTERNATIVES TO NaCl

Calcium Magnesium Acetate

The negative effects of chemical deicing with NaCl have for many years prompted researchers to develop alternative chemical compounds that are neither corrosive nor environmentally harmful and whose efficiency and cost make them suitable for winter road maintenance. The most recent and comprehensive study aimed at finding alternatives to NaCl was carried out in the United States toward the end of the 1970s. Following an evaluation of the tests embracing freezing-point reduction, corrosion, toxicity, cost, environmental aspects, and so forth, CMA was identified as a promising alternative to road salt (*2*).

Studies of CMA were carried out in Sweden before the MINSALT project was initiated. These studies were included in the project once it was under way. To begin with, a small quantity of CMA was manufactured on a laboratory scale, but when it was marketed commercially during the latter part of the project, tests were conducted with the proprietary product. The studies carried out at the Swedish Road and Traffic Research Institute, as well as studies conducted by other research institutes, were chiefly concerned with CMA's melting properties, corrosiveness, and effect on cement concrete.

CMA's freezing-point reduction—the lowest temperature at which melting can occur—varies according to the Ca/Mg ratio between about −10°C (−14°F) and −28°C (−18°F); for NaCl it is about −21°C (−6°F). The lowest and optimum freezing point is obtained with a Ca/Mg ratio of about 3/7 to 2/8 (in mol). The CMA products ICE-B-GON and Clearway CMA have a ratio of 3/7.

The melting effect of CMA does not vary so widely, however, because of the Ca/Mg ratio; it depends more on the shape, size, and density of the particles. Melting ability has been tested on blocks of ice at different temperatures. In Figure 4 the result from one melting test at −2°C (28°F) is shown. The CMA pellets were 2 to 3 mm (0.08 to 0.12 in.) in size. The solubility of CMA is lower than $CaCl_2$ and NaCl but better than urea. It should be noted that CMA has a very slow initial melting reaction, whereas NaCl and especially $CaCl_2$ have a very rapid melting effect. The same relations have been determined at lower temperatures, tests at −6°C (21°F) and −10°C (14°F), but the slower melting effect compared with $CaCl_2$ and NaCl is even more prominent.

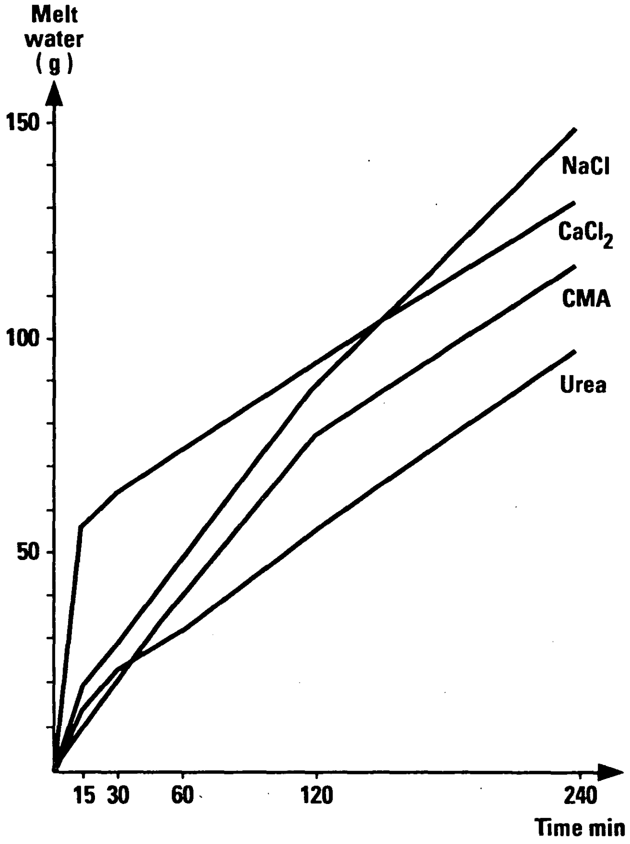

FIGURE 4 Ice melting effect of some deicers in laboratory testing at −2°C (28°F); application rate = 20 g on 114 cm^2 (0.7 oz on 18 in.^{2}).

Perhaps the greatest positive effect of CMA over NaCl is reduced corrosion. Several corrosion studies have been carried out with CMA. Corrosion tests with CMA on car body steel showed that CMA is much less corrosive than NaCl and $CaCl_2$. The weight loss on steel plates, which were covered with a mix of mud and the deicer for 100 days, was considerably less for CMA than for the other deicing chemicals in the test. Immersion tests with aluminum plates also showed promising results for CMA, which was less corrosive than NaCl, $CaCl_2$, and urea. The difference in speed of corrosion was not so marked as with steel, however.

The corroding effect of CMA on magnesium alloy plates has also been tested, since magnesium alloy can be used in aircraft. The immersion test compared CMA with urea and showed that CMA was the more corrosive of the two deicers. The result indicates that to avoid the corrosive effect some kind of surface treatment of the magnesium metal must be accomplished or a corrosion inhibitor be mixed with the CMA.

Several studies concerning the freeze-thaw and chemical effect of CMA on cement concrete have been carried out. As shown by freeze-thaw tests, the chloride salts clearly peak at a concentration of 3 to 4 percent. After declining with slightly rising concentration, the degree of damage increases dramatically for high concentrations of $CaCl_2$ and $MgCl_2$. Here, the chemical effect manifests itself. For NaCl, on the other hand, the degree of damage clearly diminishes with a rising concentration and is extremely small for a saturated solution. According to freeze-thaw tests, CMA's incidence of damage rises in direct proportion to its concentration up to the same level as NaCl's maximum (which occurs at about 3 percent) (Figure 5).

Tests at the Lund Institute of Technology during 1985–1986 were aimed at studying the chemical effect of CMA and other substances on concrete. The specimens in a NaCl solution were little damaged, but the effect on the cement concrete in CMA was considerable. Samples in $CaCl_2$ solution were also heavily damaged, perhaps even faster than with CMA. The tests were carried out with CMA of dubious composition, so the relevance of the results is open to question, especially as current (1992) CMA for road maintenance purposes is a different product altogether and comprises a stable compound without an excess of acid. These tests were therefore duplicated during 1991–1992, but the results have not yet been reported.

To study the effect of deicing agents, and CMA in particular, on concrete under more realistic and varying conditions, field experiments were carried out during 1986–1990. After the period of exposure, the concrete specimens were tested and analyzed with respect to compressive strength, tensile splitting strength, carbonation depth, frost resistance, chloride content, and acetate content. A thin grinding analysis was also carried out.

The results of the tests show that all exposure damage with respect to CMA was less than for NaCl and other chloride salts. In summary, nothing in the analyses performed indicates that deicing with CMA would cause more damage to cement concrete than that caused by NaCl. The spraying of the agents on the specimens during the tests is certainly more intensive than what occurs in ordinary road maintenance work, but it would be unwise to draw too far-reaching conclusions from the results at hand. The periods of exposure were extremely short in relation to the expected lifetime of the structures.

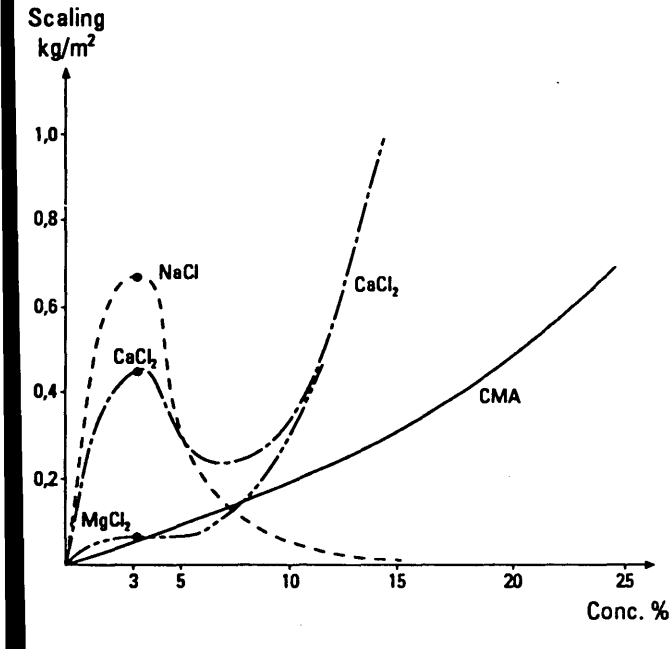

FIGURE 5 Concrete-frost testing according to Swedish Standard 137236: tests with 3 percent solutions of NaCl, $CaCl_2$, $MgCl_2$, and 3 to 26 percent solutions of CMA; weight loss after 56 cycles (*3*).

CMA's biggest drawback as an alternative deicing agent is its price, which is about 15 to 20 times higher than the price of NaCl, and there is nothing to indicate that this can be reduced to any great extent, not even for large-scale production. The dominating expense connected with the use of CMA is the direct cost of production. The principal advantages to be gained from switching to CMA are reductions in corrosion of the vehicle fleet, in chemical aggression on bridges and other cement concrete structures, and in environmental damage (groundwater and vegetation).

Against this background, the likelihood that CMA will replace NaCl must be considered small. Furthermore, the cost/benefit sides of the balance sheet are somewhat complicated in a changeover to CMA. The use of CMA could result in major savings for the individual motorist in the form of reduced corrosion, whereas the major costs associated with CMA would be borne by the road maintenance authority.

Sodium Formate and Potassium Acetate

Besides CMA, other alternatives have been considered, although in less detail. In some cases, small-scale studies have been conducted. The substances that have been tested are, among others, calcium chloride ($CaCl_2$), urea, sodium formate, and potassium acetate (proprietary name Clearway-1).

Limited laboratory tests concerning melting effect and freezing-point depression were made with sodium formate as small pellets (less than 1 mm). The result showed that sodium formate is comparable to NaCl as a deicer. The same result was shown in a minor field test. Sodium formate as a saturated brine was spread on hoar frost and as an anti-icing measure. In both cases comparison was made to NaCl brine, and no difference between the two deicers could be seen.

Another chemical investigated was a noncorrosive potassium acetate solution (proprietary name Clearway-1) primarily for airfield use. This is a 50 percent by weight aqueous solution with a small amount of corrosion inhibitor added to fulfill the rigorous demands for use on airfields.

Potassium acetate has been tested in the laboratory and on airfields during some winters. It has a very low freezing point, −40°C (−40°F), with a 50 percent by weight solution. Because the acetate is a liquid, it has a very rapid melting effect. The field tests showed that compared with urea the acetate had a more rapid and better melting effect, but there was a question about its long-term effect. Potassium acetate is hygroscopic (draws moisture out of the air), which can lead to longer wet periods, dilution, and perhaps refreezing.

The positive effects of potassium acetate compared with NaCl and urea are reduced corrosion and environmental damage. The major drawback is the price, which is even higher than for CMA. Potassium acetate is not an alternative to NaCl but could be an interesting and effective alternative to urea for airfields.

CONCLUSIONS

The search for a chemical to replace NaCl has shown that there is no economical alternative that can be used any time soon. There are possible compounds such as CMA and sodium formate, but there are also much higher material costs and still questions about some effects connected with these alternatives. NaCl will therefore still be the most used deicer for road purposes.

Salt-spreading methods have progressed from dry salt to prewetted salt and brine. The results from the MINSALT project have led to a proposed strategy that will reduce salt consumption and increase the effectiveness of the salting. This can be accomplished by working more with anti-icing measures, before the icy conditions occur, and less with deicing. Prewetted salt or brine should be used.

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Deicing of Roads in Norway with Brine

ROAR STOTTERUD AND KNUT MAGNE REITAN

Norway's Public Roads Administration (PRA) started a test program for deicing roads with brine in 1989. With limited access to earlier experiences with the method, the PRA wanted to evaluate the suitability of use of brine in Norway. The following was to be achieved by applying brine instead of dry or prewetted salt: (a) instant reaction, (b) increased spreading speed, (c) reduced consumption rates of salt, and (d) faster drying of deicing roads. The follow-up has shown that these objectives have been met. The effects have been judged to be very good when brine is applied in conjunction with preventive actions before expected snowfalls or icy conditions and after the formation of frost or thin layers of ice. During precipitation the effects depend on the intensity and duration of the snowfall. Brine can be used when temperatures are warmer than about −10°C (14°F).

The operational requirements of Norway's Public Roads Administration (PRA) do not warrant the deicing of roads with chemicals even when the friction conditions are poor. However, operational requirements allow the use of salt as a preventive action: before a snowfall, or to remove ice or frost when such conditions occur. In Norway the requirements do not allow the use of deicing agents as a means of snow removal.

Approximately 3500 km (2,200 mi) of national roads in Norway are treated with salt. The total salt consumption associated with these roads is 40 000 Mg (44,000 tons) a year.

When dry salt is spread as a preventive action, experience has shown that approximately 80 percent of the salt blows off of the pavement into the ditch. Much of the salt is therefore wasted and contributes to the environmental problems as well as other problems associated with the use of salt. These problems are to some extent reduced if the salt is prewetted. However, experience has shown that roads treated with prewetted salt take a long time to dry. Motorists have reacted negatively to these conditions.

Despite the modest rates of salt spreading, the PRA, both for environmental and economical reasons, wanted to minimize salt consumption without worsening the driving conditions. This desire was the background for the initiative in spring 1989 for a program to test the use of brine instead of dry or prewetted salt. With limited access to earlier experiences with the method, the PRA wanted to initiate a comprehensive project to evaluate the use of brine as an alternative to current methods.

PURPOSE OF TEST

The basis for the whole project was to evaluate the suitability of brine in Norway. The conditions on roads salted with brine were compared with conditions on roads salted with dry or prewetted salt. Other questions were

- Under what conditions is the use of brine a suitable method?
- What quantities are required during varying
  - Temperatures?
  - Intensity of precipitation?
  - Road conditions?

Further objectives were to attain thorough results from mixing equipment and brine spreaders.

DESCRIPTION OF EQUIPMENT

Brine is by definition a fully saturated solution of sodium chloride in water. The solution achieves a 25 percent concentration with a specific gravity of 1.18 kg/L (9.8 lb/gal). To manufacture the brine, a mixing plant is required. There are two ways to produce brine:

- Batch mixing: the required volumes of water and salt are put into a tank, and the mixture is agitated until the salt is dissolved and the solution is saturated.
- Continuous mixing: the mixing plants have separate tanks for mixing and storage. The water is pumped through a layer of salt on the bottom of the mixing tank. This action is sufficient to achieve a saturated solution, which is pumped into a storage tank.

Four mixing plants have been tried. The production capacity of the batch-mixing plants is approximately 20 m^3/hr (26 yd^3/hr). The continuous-mixing plants produces up to 30 m^3/hr (39 yd^3/hr). One of the continuous-mixing plants is equipped with a storage tank that holds 300 m^3 (392 yd^3).

In one location in a dairy industry district, the local dairy industry delivered brine at no cost. Brine is used in the production of cheese, and the alternative for the industry was to dump the brine into the sewer system and be charged for it. Therefore, the manufacturers of cheese were able to deliver the used brine to the local road station for free. Tests have shown that there were no harmful additives to the brine that could reduce the effect of deicing or further damage the environment.

The brine spreaders that have been tried are based on two principles:

- Disc spreaders: brine is thrown out from one or two discs.
- Nozzle spreaders: several nozzles are placed on a spray bar.

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In addition there is a new type of spreader that can spread both brine and dry or prewetted salt at the same time. The spreader is based on two or three discs or discs in combination with nozzles.

All brine spreaders can spread from less than 10 g/m² (0.033 oz/ft²) to 60 g/m² (0.197 oz/ft²), 5 m (16 ft) in width and up to 55 km/hr (34 mph). With a spreading width of 7 m (23 ft), the equipment can spread at least 40 g/m² (0.132 oz/ft²). The adjustment is continuous or in steps of 5 g/m² (0.017 oz/ft²). Some of the equipment can spread over a width up to 12 m (39 ft).

The equipment has been developed continuously during the project. With good cooperation between the users and the manufacturers of the equipment, new ideas and improvements were tested. The results are that there are now very few problems with the equipment and that the equipment satisfies the specifications.

RESULTS

Frequent measurements on five reference points have given much information that shows that the effect of brine on the road surface depends on weather and road conditions. The effect has also proven to be dependent on the traffic volume and the intensity of precipitation.

The results are divided into three groups depending on the measured coefficient of friction in the first hour after the spreading. The friction is measured with "Digi-slope," which gives the coefficient of friction when the test vehicle brakes at 40 km/hr (25 mph) with locked wheels.

Result	*Coefficient of Friction After Spreading*
Good	Better or equal to 0.40
Adequate	Between 0.30 and 0.40
Poor	Less than 0.30

Documented results were attained from 566 spreadings, of which 76 percent gave good results, 10 percent adequate results, and 14 percent poor results (Figure 1). Under normal conditions the results will be better, because in the project we wanted to find the limits for the use of brine. Therefore, brine sometimes was used under conditions that were unsuitable for use of salt, such as low temperatures and heavy snowfall.

In areas in the southwestern part of Norway where conditions are favorable for the use of salt, 96 percent of the spreadings were successful. In the northern part of Norway where the test stretches were located on the outer perimeter of an area considered suitable for salting, because of more snow, 83 percent of the results were good. Areas with a continental climate with low winter temperatures are not considered as suitable for the use of salt. Nevertheless, more than 70 percent of the brine spreadings were successful in these areas.

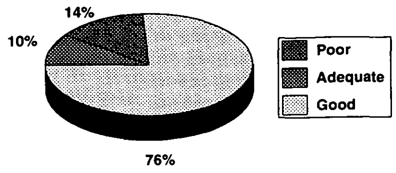

FIGURE 1 Results from all spreadings of brine.

In areas where brine was used for two seasons, the results were better than in areas where people just had one season with experience, showing that it is necessary to have experience with brine to get the best results.

Causes

All conducted spreadings have a reason that is registered. The causes are classified in the following groups:

- Prev. ice (preventive salting against frost and ice),
- Prev. snow (preventive salting against snow),
- Frost (salting on frost and thin layers of ice),
- Snow (salting on snow and during snowfall),
- Freezing rain (salting for freezing rain or rain on frozen surfaces), and
- Miscellaneous (salting for other reasons).

Figure 2 shows results associated with different causes for spreading. The figure shows also the number of spreadings for each cause and includes all test stretches. On average, three out of four spreadings have been successful.

Preventive salting against ice has attained good results from 92 percent of the spreadings. Good results also came from 98 percent of spreadings for frost and thin layers of ice, which shows that brine is ideal under these conditions. Almost every spreading gave the desired effect, and the quantity of salt was reduced to 75 percent that of dry salting. Heavy or long-lasting snowfall after the spreadings is the reason why a few of them gave poor results.

According to the registrations, 74 percent of the preventive spreadings against snow gave good results. In reality, all spreadings gave the desired effect and stopped the snow from adhering to the surface. The measurements showing poor friction were conducted after the snowfall had begun and before the roads were cleared, so friction was measured on a sheet of snow or slush.

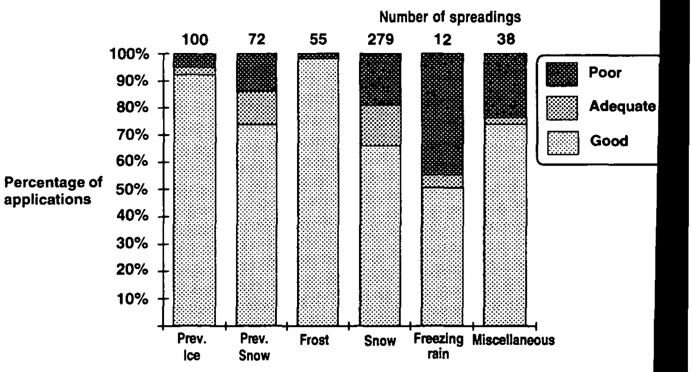

FIGURE 2 Cause for salting, all stretches.

During snowfall, 66 percent of the spreadings gave good results. Considering the fact that 15 percent gave adequate results with coefficients of friction between 0.30 and 0.40, it can be stated that the method also can be used during snowfall.

During freezing rain, 85 percent of the spreadings were successful. The few problems that occurred took place early in the morning with little traffic.

Other causes for spreadings were the occurrence of slush, packed snow, thick packed ice, or any combination thereof. A total of 74 percent of these spreadings were successful, although 24 percent (corresponding to nine spreadings) gave poor results. These spreadings occurred with slush on packed ice.

Weather and Road Conditions

Almost every spreading on dry, moist, and wet roads and on frost gave good results. The results showed reduced effects when slush, snow, or thick ice occurred on the roads. Good results were obtained on thin layers of ice, although the results deteriorated with increasing thickness. Brine must not be used on ice that is so thick that it is impossible to see the surface underneath. Under such conditions, brine will only make the road more slippery.

A total of 77 percent of the spreadings on slush gave good results. The quantity of slush on the surface greatly influences the results: the more slush there is, the more salt is required to keep the friction above 0.40. Even during salting on loose snow on the road, 61 percent of the spreadings gave good results. On hard and packed snow, only 41 percent of the spreadings gave good results. If spreadings classified as adequate with coefficients of friction between 0.30 and 0.40 are included, then an 82 percent success rate was achieved. However, the rate of success depends of the thickness of the packed snow and ice.

From these results it is obvious that application of brine is not suited for melting snow and ice. The results gradually deteriorate with increased quantities of slush, snow, or ice on the road.

The quality of the road condition during spreading is shown in Figure 3. The figure includes all test stretches. Figure 3 shows that problems can occur on days with precipitation and that the application of brine is often insufficient when thick layers of snow and ice occur. The results from salting in conjunction with precipitation will improve considerably with better clearing of snow. Improved clearing combined with salting will also prevent the creation of packed snow or thick ice on the road surface, and thus eliminate most of the troublesome conditions in connection with salting.

Most spreadings occurred on days when precipitation was registered as snow or slush. However, these conditions prevailed only a few winter days, and on only a few of those days the coefficient of friction registered below 0.40. The spreadings that gave good results thus cover most of the winter period as indicated by registration of slippery roads. Under conditions suitable for salting, only 5 percent of the time was for slippery roads (i.e., coefficients of friction below 0.40).

Even on days with snowfall, most spreadings gave good or adequate results. Problems arise during long-lasting snowfalls or intense snowfalls. Spreadings during snowfalls with temperatures below −6°C (21°F) have mainly given poor results. Intense snowfall has also given problems with temperatures as high as −1°C (30°F). Figure 4 gives an indication of when brine is suitable in conjunction with snowfall.

During a snowfall, the better the clearing efforts, the better the results. With frequent clearing and frequent salting, the results are also good during intense snowfalls. Heavy snowfall has an intensity of 3 mm (0.1 in.) water per hour—equivalent to approximately 3 cm (1.2 in.) of dry snow per hour. Accurate snow quantities have not been registered during these investigations, but we have experienced that brine has had a good effect during heavy snowfalls. Problems have occurred when the snowfall lasted for 5 to 10 hr with the same high intensity. The results are a function of

- Intensity of precipitation,
- Temperature of air and road surfaces,
- Traffic volume, and
- Clearing equipment and clearing arrangement.

Since brine is not suitable for melting any quantity of snow, it is important to clear away most of the snow and slush before salting. Frequent clearing with good equipment that can remove snow and slush in the tracks are required. By salting and clearing on the same spot at least every 60 or 70 min, the results from the spreadings have been good even during heavy

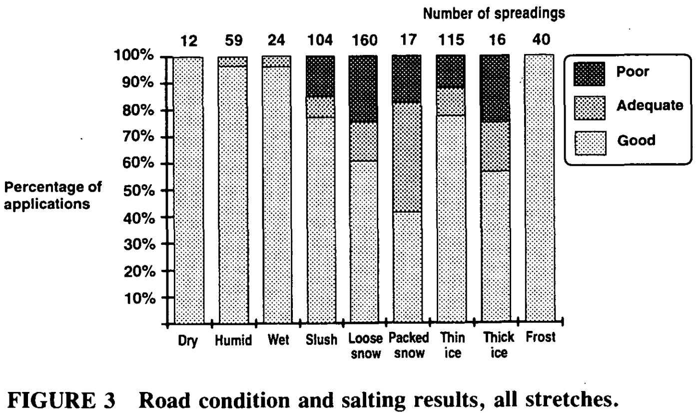

FIGURE 3 Road condition and salting results, all stretches.

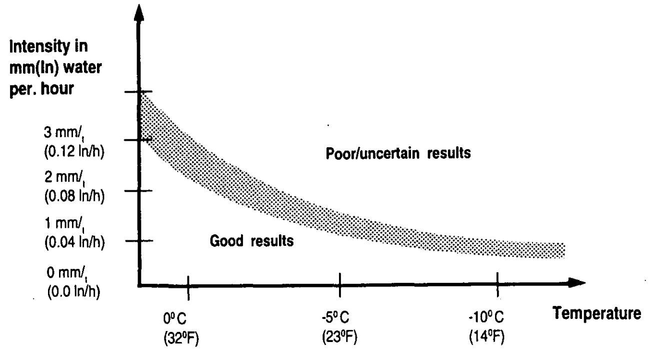

FIGURE 4 Brine during snowfall (1 mm water equivalent to 1 cm dry snow).

snowfalls. Clearing with slush plows that follow the unevenness in the surface has improved the results from using brine.

DURATION OF EFFECTS OF SPREADINGS

The duration of the effects attributed to spreadings depends on traffic volume, temperature, type of precipitation (fog, mist, rain, etc.), salt quantity, and type of surface.

Immediate Effect

The effect of brine is independent of traffic volume. Dry salt must be crushed before it is effective, but brine is already diluted and effective the moment it is spread on the road.

Preventive Spreading

Preventive salting against frost and icing normally lasts for at least 10 hr or until precipitation occurs. Salting in the evenings normally lasts till after the morning rush hour. The effect of salting when the humidity is high can be shorter since the moisture condenses on the road surface and dilutes the brine. Traffic causes the water to evaporate, hence the road will gradually dry up and the salt remains on the surface. The heavier the traffic, the quicker the salt dries up and disappears. Salting during evening hours with decreasing temperatures and reduced traffic volumes might require new spreading before the morning traffic.

The effect of the spreadings are known to last for 2 or 3 days when temperatures are down to −6°C (21°F). When the humidity has reached a low level whereby the moisture does not condense on the road, the brine will not be diluted and consequently have full effect. This occurs even though the traffic volume is not large enough to dry up the moisture on the road surface.

In the autumn and spring, when night frost with hoar frost or ice forming on the road surface is likely to occur, a spreading will last at least until the forthcoming night. Under such conditions the traffic volume is less important than it is in winter. On roads with traffic of 200 to 300 annual average daily traffic, salt can be used as a preventive action during these periods. This makes the method suitable on most roads in periods when slippery roads are least expected by the road users.

Rime and Thin Layers of Ice

Good results are achieved on rime and thin layers of ice with an average winter day traffic (AWDT) of 1,000 or more, of 3 days duration, if no more moisture is added.

Brine will normally melt frost and thin ice on the road surface. However, too little traffic might cause the road to freeze, because friction heat created by the interaction between the surface and tires will evaporate the water on the road—the more heat, the more water evaporates and the quicker the road dries up. The evaporation will remain low with little traffic, and the brine will be diluted and the freezing point will increase, so the likelihood of a good effect increases with the traffic.

Low Temperatures

At temperatures below −6°C (21°F), the effect of the spreading can last for long periods, normally until the precipitation starts or the temperature and the level of humidity rise. The humidity will increase with the temperature, and moisture on the road surface will condense. The brine will be diluted and the freezing point will increase.

The air is normally dry at low temperatures, which causes the roads to dry quicker under these circumstances. This is clearly shown by this winter's measurements. Preventive salting or salting on frost or thin layers of ice have given good results at temperatures down to −12°C (10°F). The AWDT should be more than 1,000, and at decreasing temperatures the hourly traffic volume should be at least 30 when the humidity is high.

Good results can also be achieved with little traffic, provided the amount of brine is small. Twenty grams of brine per square meter (0.066 oz/ft^2) have given good results at −10°C (14°F). By spreading more brine, more water must be evaporated, which in turn requires heavier traffic.

Some measurements have been conducted with sensors that register the freezing point of the liquid covering the road surface. When the brine-spreading vehicle has passed, the freezing point drops immediately to about −12°C (10°F), whereas with dry salt the process is slower and the freezing point rarely goes below −8°C (18°F). These measurements show that the spread brine has a better ability to last than dry salt.

Precipitation

Periods with precipitation require frequent spreadings; thus, frequency is a function of the intensity of the precipitation. With an intensity of 3 cm (1.2 in.) snow per hour, deicing with brine must be conducted with 40 g/m^2 (0.132 oz/ft^2) at least every 60 or 70 min. Clearing of snow and slush is also required before each spreading, keeping the coefficient of friction near 0.40. During light snowfall when the snow remains on the pavement, spreadings should be conducted at intervals of 4 hr or less.

Type of Surface

The effect of brine normally varies little with the type of surfacing. However, experience indicates that the effect is best with certain surface dressings, giving good friction and little splash from the road surface. The effect of both dry salt and brine is poor on porous asphalt. Since diluted salt is collected in cavities and percolates through the surface, leaving the top surface without salt, it will freeze quicker.

RECOMMENDED BRINE QUANTITIES

Humidity is important for the quantities used in connection with preventive salting. The combination of humidity and temperature gives the dewpoint as an expression of when the air is saturated by moisture. When the road-surface temperature is lower than the dewpoint, moisture from the air condenses on the road surface. Greater brine quantities are required when this occurs. This is simplified in Table 1 to distinguish only between humidity above or below 85 percent. Dewpoint apparatus in combination with road-surface temperature will give a reliable indication of the danger of having condensation on the road.

SPEED OF SPREADING

The speed during spreading of brine should not exceed 55 km/hr (34 mph). Trials have been carried out at greater speeds with adequate results, but it is more difficult to achieve full width of the spreading at higher speeds. Another possible problem is brine whirling up behind the spreading vehicle when the speed is too high, covering the windshields of the following cars with brine.

Compared with other methods, the brine method is superior with respect to spreading speed:

Method	*Maximum speed [km/hr (mph)]*
Brine	55 (34)
Prewetted salt	40 (25)
Dry salt	30 (19)

TABLE 1 Recommended Brine Quantities

Climate and Road Conditions	Brine Quantity [g/m² (oz/ft²)]
Preventive action against ice	
Dry road, humidity below 85%	10-15 (0.033-0.050)
Dry road, humidity above 85%	15-20 (0.050-0.066)
Wet road	15-20 (0.050-0.066)
Preventive action against snow	40 (0.132)
On hoar frost and thin ice	15-20 (0.050-0.066)
On snow and during snowfall	40-60 (0.132-0.197)

The spreading vehicles cause less hindrance to the traffic at high spreading speeds, and the range per spreading unit is larger. Thus, it is possible to spread the same length of road in a shorter period of time than when spreading of dry or prewetted salt.

EFFECT AND PRINCIPLE OF SPREADING

The effect of brine on the road is independent of the type of spreading equipment. Both disc and nozzle spreaders spread the brine evenly on the road surface. The disc spreader spreads the brine in a sickle manner. This has sometimes created "washboards" during spreading in snowfall. The nozzles spread the brine in jets and have good coverage in the preadjusted area.

Sidewinds will affect the width of the spread. With a spreading width of 7 m (23 ft), sidewinds can vary the actual width up to 1 m (3.3 ft). One factor in favor of nozzle spreaders in areas with rough weather is the ability of nozzles on a boom to spread brine on the pavement even in strong winds. Spreadings from side nozzles and discs can be blown away before they actually hit the pavement. Dry salt spreaders are no alternative under such conditions.

Splash from brine can be a problem for oncoming vehicles. Disc spreaders have created the largest problem in this respect, particularly spreaders with one disc that spread in lanes with opposite traffic.

CONSUMPTION OF SALT

The consumption of salt depends on climate conditions, quantity of precipitation, and the length of the winter period. On the test stretch in northern Norway the consumption was 16.4 Mg/centerline-km (29.1 tons per mile). The reason for the high consumption was mainly much snow and a long winter period (5 to 6 months). In southwestern Norway, where most of the spreadings were preventive against ice forming during the night, the consumption was 2.7 Mg/centerline-km (4.8 tons per mile). This type of salting consumes one quarter of the salt required by the use of dry salt. This test stretch is comparable with two routes that were salted with dry salt. The consumption on these dry salt routes were 7.5 Mg/centerline-km (13.3 tons per mile) and 14.5 Mg/km (25.7 tons per mile).

The use of brine reduces overall salt consumption on the test stretches by approximately 35 percent when compared with dry or prewetted salt. Table 2 shows salt consumption

TABLE 2 Salt Consumption with Brine and Prewetted Salt as a Percentage of Dry Salt Consumption

	Consumption (%)		
Cause for Salting	Brine	Prewetted Salt	Dry Salt
Prev. ice/Frost	25	70	100
Prev. snow	33	75	100
Ice/Frost	30	75	100
Snow	100	100	100

with brine and prewetted salt as a percentage of consumption with dry salt. Consumption is shown for the most important causes for salting. The numbers are only approximates; nevertheless, they show that considerable quantities of salt can be saved by changing from dry or prewetted salt to brine.

SUMMARY OF EXPERIENCES

Preventive Action Against Ice

Brine is well suited for preventive action against ice. It is effective immediately, lasting for at least 12 hr, and all the salt remains on the road. It can be used in temperatures down to −10°C (14°F) and in quantities of 10 to 20 g/m^2 (0.033 to 0.066 oz/ft^2). In this capacity, brine is better than dry or prewetted salt.

Frost

Brine is also well suited for use on frost; it too is better than dry or prewetted salt. It has an immediate effect and remains effective for 12 hr; all the salt remains on the road. Brine can be used down to −10°C (14°F), but when the humidity is above 85 percent, it should not be used below −6°C (21°F). Quantities are to be 10 to 20 g/m^2 (0.033 to 0.066 oz/ft^2). There is a danger of freezing when traffic is less than 30 vehicles per hour.

Thin Layers of Ice

Brine is better on thin layers of ice than dry or prewetted salt is. After 5 min it becomes effective and remains so for at least 12 hr. All the salt remains on the road. Just as on frost, brine can be used down to −10°C (14°F) but should not be used below −6°C (21°F) when humidity is above 85 percent. It should be used in quantities of 10 to 30 g/m^2 (0.033 to 0.099 oz/ft^2). There is a danger of freezing when traffic is less than 30 vehicles per hour.

Preventive Action Against Snow

To be effective against snow, brine should be spread out before the snowfall. It will take effect immediately; the duration of its effect depends on traffic volume and precipitation. All the salt remains on the road. It can be used down to −6°C (21°F), in quantities of 40 to 60 g/m^2 (0.132 to 0.197 oz/ft^2). Brine is better than dry salt and equal to prewetted salt.

Snowfall

Brine generally gives good results in snowfall. It takes 30 min to become effective and stays effective from 1 to 4 hr, depending on traffic volume and precipitation. All the salt remains on the road. Brine can be used for temperatures down to −6°C (21°F); recommended quantities are 40 to 60 g/m^2 (0.132 to 0.197 oz/ft^2). However, inadequate clearing can create packing, and in this use brine requires about 50 percent more spreading runs than dry or prewetted salt in a long-lasting snowfall. Overall, brine requires a greater effort to achieve the same effect as dry or prewetted salt.

Freezing Rain

Brine is adequate in light precipitation but not suited to heavy precipitation. It should be used in quantities of 40 to 60 g/m^2 (0.132 to 0.197 oz/ft^2) for the same effect as dry and prewetted salt.

Packed Snow and Thick Ice

Brine is unsuitable for packed snow and thick ice.

Current Status of U.S. Anti-Icing Technology Development

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Limited experience has shown that application of a chemical freezing-point depressant on a highway pavement before, or very quickly after, the start of ice or snow minimizes the formation of an ice-pavement bond. State highway agencies in the United States have not adopted anti-icing practices despite the potentially greater effectiveness and reduced costs associated with the practice. The Strategic Highway Research Program (SHRP) of the National Research Council has funded a multiyear study entitled *Development of Anti-Icing Technology*. The overall objective of the research program is to develop a better understanding of the conditions under which anti-icing will be effective and to develop various anti-icing techniques that will have the greatest potential of success over the range of conditions experienced in the United States. Winter maintenance personnel in nine state departments of transportation participated in anti-icing experiments during the 1991–1992 winter. The overall aspects of the SHRP study are covered, and some preliminary research results achieved during that winter are presented.

Limited experience has shown that application of a chemical freezing-point depressant on a highway pavement before, or very quickly after, the start of ice or snow minimizes the formation of an ice-pavement bond. This reduces the task of clearing the highway to bare-pavement conditions and requires less chemical amounts than is generally required under conventional deicing practices. State highway agencies in the United States have not adopted anti-icing practices despite the potentially greater effectiveness and reduced costs associated with the practice. The main reasons for the lack of acceptance concern the uncertainty about the most favorable conditions for anti-icing and the way that anti-icing should be conducted. The imprecision with which icing events can be predicted, the lack of confidence about the condition of the pavement surface, and the public's perception of wasted chemicals further complicates the situation. Some early anti-icing attempts have failed because of these uncertainties.

Technological developments in weather forecasting and in the assessment of pavement surface conditions now offer the potential for successful implementation of anti-icing treatments. Sensors embedded in the pavement surface can measure the temperature representative of the surrounding pavement and detect the presence of water or ice and a chemical freezing-point depressant. Signal information coming from these sensors has given maintenance managers the means to observe real-time pavement surface conditions and, when used with available algorithms, to provide a reasonable prediction of pavement surface conditions for up to 12 hr. Improved weather forecasting targeted specifically to local or regional road conditions also gives the manager a way to predict the state of the pavement surface. In addition, the availability of better communications enables this information to be relayed rapidly to maintenance forces and the public.

There is a need to develop a better understanding of the conditions under which anti-icing will be effective and the ways to conduct anti-icing efficiently to ensure the greatest probability of success. Several hurdles to the successful implementation of anti-icing need to be investigated and overcome. For example, the use of chemicals in solid form for anti-icing treatments demands precise timing of the application to minimize loss from traffic action. The use of prewetted salt has reduced loss during application due to particles bouncing off the pavement. The use of prewetted salt also may be effective in reducing the amount of material that is blown off the road by traffic. In addition, the influence of time between an application of salt and the onset of freezing precipitation is not fully understood.

Limited experience has shown that anti-icing requires as little as 10 to 20 percent of the normal chemical application rate for deicing. Highway agencies have found that reducing the conventional application rate to quantities on the order of 50 lb/lane-mi is not generally possible with present-day spreading equipment that is designed for deicing application rates of 300 to 500 lb/lane-mi and higher.

Liquid freezing-point depressants have the attractive feature of enabling precise control of uniform application over a wide range of rates. However, effective techniques for using liquids remain to be developed.

In early 1991, the Strategic Highway Research Program (SHRP) of the National Research Council funded a multiyear study entitled *Development of Anti-Icing Technology* under a SHRP contract. The study was designed to identify solutions that overcome these obstacles to successful implementation of anti-icing practices in winter maintenance operations. The overall objective of the research program is to develop a better understanding of the conditions under which anti-icing will be effective and to develop anti-icing techniques that will have the greatest potential of success over the range of appropriate conditions.

To achieve this objective, the research program was divided into two parts. The first part is to determine the effectiveness of anti-icing treatments from field testing of various treatment approaches on in-service highways because of the expected

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great influence of traffic. The field tests are being conducted in different locations to evaluate the influence of a wide number of variables. These tests are being performed in cooperation with state highway agencies (SHAs). Also to be performed in this part of the study is an analysis of the relative cost of anti-icing versus deicing, considering such factors as accidents, time delays, and costs of material, equipment, and labor.

The second part of the study is to determine the optimum application rates for several anti-icing treatments over a range of environmental conditions. Also to be performed in this part of the study is a survey of the worldwide spreader equipment market. The purpose of this survey is to determine the capabilities of spreader equipment to apply controlled quantities of solid, prewetted solid, and liquid deicing chemicals at minimum application rates required for effective anti-icing treatments.

This paper describes some of the activities associated with the field testing of in-service highways during the first contract year. These activities included the development of a research design, field observations, and analysis of anti-icing effectiveness. Some preliminary results achieved during the 1991–1992 winter are also presented.

RESEARCH DESIGN

The research design consisted of several steps, including

- Selecting participating SHAs and evaluation sites;
- Determining variables to be evaluated, including anti-icing strategies and site characteristics; and
- Choosing and purchasing equipment needed by the participating SHAs to conduct the anti-icing experiment.

Nine SHAs were identified as being interested in participating in the testing of in-service highways. A liaison in each state was contacted by telephone to determine the extent of cooperation and participation in the study. Information was also obtained on the winter maintenance treatment strategies used, spreader equipment available, weather forecasting services used, and the locations of any roadway weather information systems (RWISs) used. Visits to each of the nine state agencies were made following the initial contact. During these visits, specific information was obtained on the current snow and ice control practices used by each agency, the proposed test and control sections to be used in the study, the type of material and spreader equipment typically used in the study areas, the frequency of storm events, and the meteorological support and pavement sensors available at each site. Published information was also obtained from each state on its particular snow and ice control practices, and photographs were taken of the proposed test and control locations.

The test sections selected during the visits were segments of highways that were close to a maintenance truck station and could be used for the anti-icing experiments. A segment of highway near each test section was also chosen to serve as a control for the experiment. Each control section matched its associated test section, as best as possible, in regards to area type, pavement type, and average daily traffic (ADT). The control sections were to be treated in accordance with the conventional snow and ice control policy of the particular state.

Data collected during the state visits were analyzed and assembled into a recommended research design for testing various anti-icing treatment strategies. Table 1 presents the geographical distribution of test sites used in the study. A total of 14 test sites were selected in the nine states.

The information obtained as a result of the various surveys (telephone, site visits, and literature) is summarized in the research design in Table 2. This table gives the independent variables—geographic area, state, area type, pavement type, and ADT—and the estimated number of winter events at each site. For each unique combination (total of 23), the recommended treatment strategy, consisting of the type of chemical to be used and the treatment timing, is provided. Of the 23 experimental conditions, 8 were to take place before the storm (3 on portland cement concrete pavement and 5 on asphaltic pavement) and 15 at the beginning of the storm (5 on portland cement concrete pavement and 10 on asphaltic pavement). Because of practical restrictions and safety considerations, the research design could not be balanced with respect to pavement type and treatment strategy.

Considerable equipment and support items were provided to the participating SHAs for use in the anti-icing experiments. The items included

- Ground-oriented spreader controls;
- Prewetting equipment for trucks;
- Fixed liquid deicer spray systems and associated tanks;
- Storage tanks, pumps, and liquid deicing chemicals;
- A complete RWIS;
- A system upgrade for an existing RWIS;
- Local weather forecasting service;
- Friction testers;
- Salinity detection instruments; and
- Radiometers.

In general, each test section except the one in Maryland contained RWIS pavement and atmospheric sensors so that informed decisions could be made about pretreatment timing, application rate, and so forth. Maryland was given a handheld radiometer with which to measure pavement temperatures. The intention here was to see if decisions about the timing of anti-icing treatments could be made with a relatively inexpensive pavement-temperature sensing device.

TABLE 1 Geographic Distribution of Test Sites

Geographic Area	State	No. of Test Sites
Mountainous states	California Maryland	2 1
High plains states	Colorado Nevada	2 1
Plains states	Missouri Ohio	2 2
Lake effects states	Minnesota New York	2 1
Maritime state	Washington	1
Totals	9	14

TABLE 2 Recommended Research Design

Geographic area	State	Area type	Pavement type	ADT	Estimated number of winter events	Treatment strategy: Type of chemical to be used	Treatment strategy: Treatment timing
Mountainous	California	Rural	DGA	31,100	40	a) Liquid $MgCl_2$ b) Rock salt prewetted w/Freezgard Plus	Pre-storm
Mountainous	California	Rural	PCC	31,100	40	a) Liquid $MgCl_2$ b) Rock salt prewetted w/Freezgard Plus	Pre-storm
Mountainous	California	Rural	DGA	2,200	120	Rock salt prewetted w/liquid $MgCl_2$	Pre-storm
Mountainous	Maryland	Rural	OGA	1,600-2,000	40	Straight rock salt	Beginning of storm
High Plains	Colorado	Rural	PCC	29,500-30,100	25	Rock salt prewetted w/liquid NaCl or $MgCl_2$ after loading	Beginning of storm
High Plains	Colorado	Suburban	DGA	33,000	25	Rock salt prewetted w/liquid NaCl or $MgCl_2$ after loading	Beginning of storm
High Plains	Nevada	Suburban	DGA	39,000	6	Rock salt prewetted w/Freezgard	Beginning of storm
Plains	Missouri	Rural	DGA	39,500	15	Rock salt prewetted w/liquid $MgCl_2$ or $CaCl_2$	Beginning of storm
Plains	Missouri	Rural	DGA	11,800	15	Rock salt prewetted w/liquid $MgCl_2$ or $CaCl_2$	Pre-storm
Plains	Ohio	Suburban	DGA	34,000-45,000	30	Rock salt prewetted w/liquid NaCl	Beginning of storm
Plains	Ohio	Rural	DGA	23,000-58,000	30	Rock salt prewetted w/liquid NaCl	Beginning of storm
Lake Effects	Minnesota	Rural	DGA	5,800	18	Rock salt prewetted w/liquid $CaCl_2$	Pre-storm
Lake Effects	Minnesota	Rural	PCC	5,800	18	Rock salt prewetted w/liquid $CaCl_2$	Pre-storm
Lake Effects	Minnesota	Urban	DGA	35,000	18	Rock salt prewetted w/liquid CMA or KOAc	Beginning of storm
Lake Effects	Minnesota	Urban	PCC	35,000	18	Rock salt prewetted w/liquid CMA or KOAc	Beginning of storm
Lake Effects	New York	Suburban	DGA	19,900-45,700	40-50	Rock salt prewetted w/liquid $CaCl_2$	Beginning of storm
Lake Effects	New York	Suburban	PCC	45,700-53,500	40-50	Rock salt prewetted w/liquid $CaCl_2$	Beginning of storm
Maritime	Washington	Rural	DGA	21,000	10	a) Rock salt prewetted w/liquid NaCl b) Rock salt prewetted w/liquid NaCl + CMA	Beginning of storm
Maritime	Washington	Rural	PCC	21,000	10	a) Rock salt prewetted w/liquid NaCl b) Rock salt prewetted w/liquid NaCl + CMA	Beginning of storm

During the planning stages for the study, it was decided that pavement friction and salinity measurements should be made on the test and control sections throughout the winter testing period. It was important that the devices used to make the measurements be suitable for use by maintenance personnel during bad weather. The devices also had to provide meaningful results.

PAVEMENT FRICTION MEASUREMENT

Before the beginning of the project, the Minnesota Department of Transportation (Mn/DOT) began investigating the usefulness of the Coralba friction tester for making pavement friction measurements. The Coralba is a Swedish friction measurement device used on some European and Scandinavian airport runways. The device can be installed in a pickup truck or passenger vehicle and is connected to the brake system. It provides a measure of friction between the tire and pavement during a braking operation. The friction value obtained from a test is displayed on a dash-mounted unit.

Mn/DOT performed a limited amount of testing with the device before the study. After the study began, a protocol was developed for friction testing to determine if a correlation could be established between the Coralba friction tester measurements and ASTM E-274 skid trailer results. The testing with both systems was conducted in summer 1991 at the St. Cloud, Minnesota, test track and on I-35 and TH-53 in the Duluth, Minnesota, area. The correlation of the Coralba friction tester with ASTM E-274 skid measurements is described in the following.

A total of 106 individual measurements were made with the Coralba and 41, with the skid trailer. These were taken on three sites, including three pavement types (asphalt, concrete, and new concrete). Measurements were made at 32.2, 48.3, and 64.4 km/hr (20, 30, and 40 mph) on wet pavement (three measurements were made on dry pavement but were not included in subsequent analyses). The Coralba was used in two modes—with and without lockup—resulting in 58 and 48 measurements, respectively.

For each of the 24 unique combinations (site, pavement type, speed, and device), the mean, standard deviation, and coefficient of variation were calculated for the skid numbers and the Coralba measurements in both modes. These statistics are given in the last three columns of Table 3.

Data obtained at 32.2 km/hr (20 mph) with the Coralba could not be compared with skid data because the skid trailer was not used at that speed. However, the 32.2-km/hr (20-mph) Coralba measurements were compared when using the device in either lockup or no lockup mode.

There is a direct proportional relationship between skid and Coralba measurements. However, since most of the measurements were made at higher skid numbers (over 53 SN) and only two were made at less than 18 SN, a linear regression

TABLE 3 Skid and Coralba Measurements, Statistics

Obs.	Site	Pvt type	Speed (mph)*	Device	Lockup ?	Pvt	Mean	Standard Deviation	CV*1 (100%)
1	I-35	New conc.	30	Coralba	no	wet	0.51	0.04	8.65
2	I-35	New conc.	40	Coralba	no	wet	0.55	0.03	6.08
3	I-35	New conc.	29.7	Skid	yes	wet	65.92	1.26	1.91
4	I-35	New conc.	30	Coralba	yes	wet	0.46	0.05	10.06
5	I-35	New conc.	40	Coralba	yes	wet	0.50	0.04	8.58
6	I-35	New conc.	40.4	Skid	yes	wet	62.26	1.35	2.17
7	NBL TH 53	Asphalt	30	Coralba	no	wet	0.44	0.04	8.13
8	NBL TH 53	Asphalt	40	Coralba	no	wet	0.42	0.04	9.63
9	NBL TH 53	Concrete	20	Coralba	no	wet	0.33	0.07	19.97
10	NBL TH 53	Concrete	30	Coralba	no	wet	0.36	0.06	15.78
11	NBL TH 53	Concrete	40	Coralba	no	wet	0.39	0.06	14.50
12	NBL TH 53	Asphalt	30	Coralba	yes	wet	0.45	0.03	6.29
13	NBL TH 53	Asphalt	30.3	Skid	yes	wet	57.66	2.63	4.56
14	NBL TH 53	Asphalt	39.0	Skid	yes	wet	59.32	2.33	3.94
15	NBL TH 53	Asphalt	40	Coralba	yes	wet	0.47	0.03	5.57
16	NBL TH 53	Concrete	20	Coralba	yes	wet	0.30	0.10	33.23
17	NBL TH 53	Concrete	30	Coralba	yes	wet	0.35	0.04	12.12
18	NBL TH 53	Concrete	30.3	Skid	yes	wet	58.14	1.90	3.27
19	NBL TH 53	Concrete	40	Coralba	yes	wet	0.32	0.04	13.74
20	NBL TH 53	Concrete	40.9	Skid	yes	wet	53.28	3.21	6.02
21	St. Cloud	Asphalt	30	Coralba	yes	wet	0.25	0.02	9.80
22	St. Cloud	Asphalt	30	Skid	yes	wet	17.74	0.96	5.40
23	St. Cloud	Asphalt	40	Coralba	yes	wet	0.22	0.03	11.87
24	St. Cloud	Asphalt	40	Skid	yes	wet	15.10	0.94	6.21

Note 1: CV = Coefficient of Variation = 100 * Standard Deviation/Mean
* 1 mph = 1.609 km/hr

would be misleading and therefore was not performed. Instead, the Spearman nonparametric rank correlation coefficient was calculated for each of the three possible comparisons.

The calculated correlation coefficients and their corresponding tabulated critical values (in parentheses) are

- Skid versus Coralba lockup mode ($N = 8$): $R = 0.905$ (critical $R = 0.714$)
- Skid versus Coralba no lockup mode ($N = 6$): $R = 0.657$ (critical $R = 0.886$)
- Coralba lockup versus no lockup mode ($N = 7$): $R = 0.857$ (critical $R = 0.750$)

To test whether these correlation coefficients are significantly different from zero, the calculated coefficients were compared with the corresponding tabulated coefficients with $N - 2$ degrees of freedom and a two-sided significance level of 5 percent, assuming a 95 percent confidence level. If the calculated R exceeds the tabulated R, one concludes that the correlation coefficient is significantly different from zero.

The results are summarized as follows:

- The correlation between skid and lockup Coralba measurements is significantly different from zero at the 95 percent confidence level—that is, Coralba and skid measurements increase or decrease together.
- The correlation between lockup and no-lockup Coralba measurements is significantly different from zero at the 95 percent confidence level as well.
- However, the correlation between skid and no-lockup Coralba measurements is not statistically significant.

On the basis of these results, it was decided that the SHAs would use Coralba friction testers during the winter testing. The testers were to be operated in a lockup mode at 64.4 km/hr (40 mph). However, testing could be conducted at 48.3 km/hr (30 mph) for safety considerations. It was also decided that the testers should not be operated at 32.2 km/hr (20 mph) because of the high variability in the Coralba measurements obtained at that speed (see the coefficients of variation in Table 3).

SALINITY MEASUREMENTS

A brief technical survey was made of scientific instruments that could be used for measuring residual anti-icing chemicals on pavement surfaces. The survey identified three manufac turers of conductivity meters. Boschung Company, Inc. of Switzerland was chosen for its Sobo-20 salinity tester. The primary reasons for this choice were that the Sobo-20 has a built-in conductivity cell and that the unit was specifically designed for the quantitative measurement of chloride solutions on roads. A Sobo-20 unit was purchased for evaluation.

Studies were conducted to evaluate the utility of the Sobo-20 salinity tester for the semiquantitative measurement of salt-based chemical deicer solutions. These studies consisted of evaluating the type of response and range of detection for solutions of five chemical deicers.

- Sodium chloride (NaCl)
- Magnesium chloride ($MgCl_2$)
- Calcium chloride ($CaCl_2$)
- Potassium acetate ($KOOCCH_3$)
- Calcium magnesium acetate ($Ca/MgOOCCH_3$)

When making a measurement, a precise volume of a measuring liquid is pumped into a measuring cell on the road surface. The conductivity obtained with the measuring liquid, which dissolves remaining salt on roads, gives the quantity of remaining salt in ounces per square yard. The measuring apparatus has a temperature compensation feature.

The instrument consists of two parts: (a) the measuring chamber, with built-in conductivity cell, which spreads the measuring liquid from the vessel or tank onto the road; and (b) the electronic displayer, which is a data processing device with display scale and storage of the measurements.

The liquid solution for dissolving the residual salt contains the pure liquid components distilled or demineralized water (85 percent) and technical acetone (15 percent).

The freezing point of the solution is approximately −5°C (23°F). The mixture may be prepared by the user or bought at a drug store. It should be noted that the accuracy of the measurement is guaranteed only with the aforementioned composition of the measuring liquid.

Five series of deicer surface tests were conducted to determine the Sobo-20 meter readings for selected surface concentration levels of deicer chemical. The experimental test procedures consisted of the following steps:

1. Carefully weighed amounts of a deicer solution (10 or 20 percent deicer by weight) were applied to the surface of a stainless steel pan.
2. The amounts of deicer solution applied to the test surface were selected to yield the following equivalent deicer concentration levels: 1.7, 3.4, 8.5, 17.0, 25.4, 33.9, and 50.9 g/m^2 (22, 44, 110, 220, 330, 440, and 660 lb/lane-mi).
3. The required amounts of 20 percent deicer solution by weight (20, 40, 100, 200, 300, 400 and 600 mg) were applied to attain the deicer surface concentration levels just specified.
4. After the proper amount of concentrated deicer solution is applied on the stainless test surface, the sampling/testing chamber of the Sobo-20 was placed over the deicer sample.
5. The measuring fluid was forced into the measuring chamber, and the Sobo-20 reading was recorded on its electronic meter.
6. After the measurement was completed, the solution was collected and the conductivity was measured with an ElectroMark Analyzer Model 4400 (Markson Science Inc.) conductivity meter.

The results of the Sobo-20 tests for five series of deicer solutions are presented in Figure 1. Comparative evaluations of test results revealed interesting information about the intensity and linearity of Sobo-20 response/deicer weight relationships according to deicer type and concentration range.

Sodium chloride gave the highest Sobo-20 conductivity readings per unit weight and the most linear response. In addition, the results obtained during this study were in agreement with the values reported by the manufacturer for sodium chloride.

The four other deicers ($MgCl_2$, $CaCl_2$, KOAc, and CMA) gave nonlinear Sobo-20 reading/deicer weight relationships at surface concentration levels greater than 25.4 g/m^2 (330 lb/lane-mi).

The intensity of the Sobo-20 response per unit weight varied by deicer type in the following order: $NaCl > MgCl_2 > CaCl_2 > KOAc > CMA$. Generally, the order of the degree of response was expected.

The analytical range of the Sobo-20 varied according to the ionic strength of the deicer electrolyte. The strong electrolyte deicers (NaCl, $MgCl_2$, and $CaCl_2$) gave Sobo-20 readings at the lowest concentration level tested (22 lb/lane-mi), but the lowest detectable concentration level, for the weak electrolyte deicers (KOAc and CMA), was 8.5 g/m^2 (110 lb/lane-mi). Because the analytical range of the standard Sobo-20 lacks the sensitivity to detect and analyze KOAc and CMA at surface concentration levels below 8.5 g/m^2 (110 lb/lane-mi), the manufacturer was contacted and asked to provide a more sensitive range. A modified electronic meter that replaces the full scale with a 1/10 scale and would provide an analytical range from 0.34 to 5.1 g of NaCl per square meter (4.4 to 66.0 lb/lane-mi) was ordered and found to detect and measure the presence of KOAc and CMA at the lower concentration levels. Accordingly, the analytical ranges of Sobo-20 for the five target deicers are as follows:

- For NaCl, $MgCl_2$, and $CaCl_2$
  - –1/2 scale: 22 to 330 lb/lane-mi
  - –Full scale: 44 to 660 lb/lane-mi
- For KOAc and CMA
  - –1/2 scale: 110 to 330 lb/lane-mi
  - –Full scale: 220 to 660 lb/lane-mi

On the basis of these results, the Sobo-20 salinity meter appeared to be the most promising technique for measuring residual anti-icing chemicals on pavement surfaces. Consequently, it was decided the standard Sobo-20 would be used during the winter testing by those participating SHAs that would be using NaCl, $CaCl_2$, and $MgCl_2$, or mixtures of these strong electrolytes. It was further decided that a modified electronic meter with increased sensitivity for lower concentration levels of KOAc and CMA should be obtained and provided to any SHAs that would be using KOAc and CMA.

FIELD OBSERVATIONS

It was necessary to develop training materials and to train the maintenance personnel in the nine participating SHAs before the anti-icing experiments began. Winter maintenance training materials were obtained from various sources including several departments of transportation. These materials were

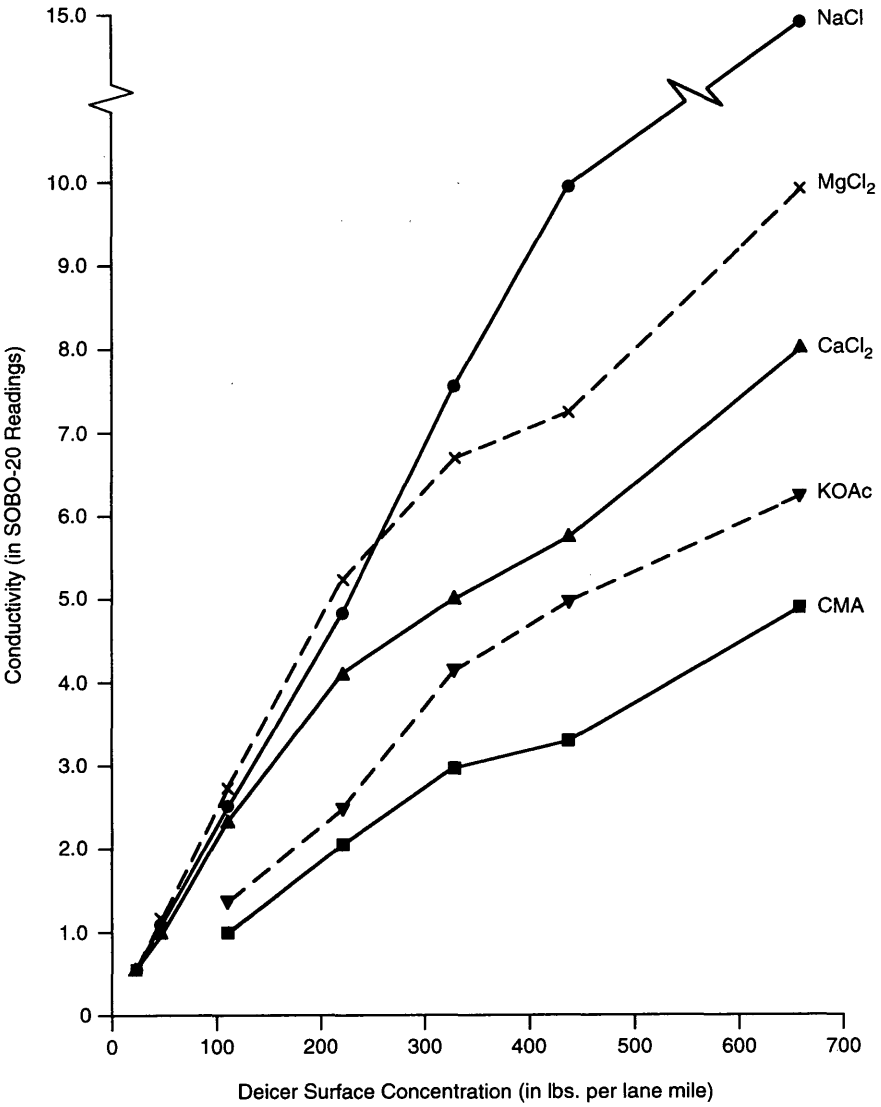

FIGURE 1 Sobo-20 reading versus deicer surface concentration.

reviewed for application to the study, and parts were found to be of direct value. Operating instructions on several types of spreader control equipment were obtained during the state visits. These documents were also reviewed for their applicability to the study. Finally, various forms and procedures for documenting winter maintenance activities and pavement sensor readings were obtained and reviewed. The development of the needed forms and procedures was greatly enhanced by incorporating many of the features found in the materials collected.

Appropriate materials assembled from the various sources were combined into manuals for training the winter maintenance personnel. Portions of the training manuals varied from state to state. The variations incorporated specific state requirements for winter maintenance activities, reflected site-specific geographic and climate considerations, and pertained to the type of chemical (solid, prewetted, or liquid) spreaders to be used in the testing.

The training materials covered all aspects of the H-208 program, including a background on the scope of the project, basic meteorology, and snow and ice control chemicals; a description of the design, operation, and the use of RWISs; and information specifically related to the implementation of the study in each jurisdiction including the role of supervisory and operating personnel, data collection, and so on. Hands-on training was also furnished for both the Sobo-20 and the Coralba friction tester. The training material developed for Maryland was different from the other eight states because of the absence of a RWIS in that state.

Itemized operating, calibration, and maintenance instructions were prepared also for the Sobo-20 and Coralba instruments. These instructions were intended to simplify the data collection during winter storm events and to ensure the quality of the information collected.

Also included in the training was a series of data recording forms designed specifically for use in the research program. These forms provided the proper format in which to record weather and pavement conditions, spreader equipment operation, and Sobo-20 and Coralba readings. Suitable forms were also prepared for instrument calibration and, for Maryland, the recording of measurements collected using the radiometer.

Using these materials, on-site training was provided to all SHAs participating in the project. Although modified in certain cases, the training was originally designed for 1½ days, with classroom work held on the first day and hands-on training provided during the morning of the second day.

Finally, during the training provided to state winter maintenance personnel, some adjustment of the test and control sections were necessary to more closely conform to their routine treatment practices. A first cut was made during the initial state visit to select an appropriate test and control section. The boundaries of these sections were further refined during the training session. Also, discussions were held with supervisory personnel to identify the specific equipment (e.g., truck or trucks) to be used for anti-icing on the test section and deicing on the control section.

The training of the winter maintenance personnel in the nine SHAs began near the end of November 1991 and was completed during the early part of January 1992.

The first anti-icing experiment was run in Maryland near the end of January 1992. The official end of the anti-icing experiments for the 1991–1992 winter was the end of March 1992. At that time, 57 storm events had been recorded by the participating states, despite the late start of the anti-icing experiments during the 1991–1992 winter. More than 70 percent of the events were recorded by maintenance personnel from the departments of transportation in Maryland, Minnesota, Nevada, and New York. No storm events were recorded at four sites because of the extremely mild winter after the program became operational.

ANALYSIS OF MAINTENANCE FIELD DATA

A complete analysis of the maintenance field data collected by the states was begun at the end of the 1991–1992 winter. The analysis is intended to determine a preliminary estimate of the cost-effectiveness of anti-icing treatments relative to conventional deicing.

Examples of the analyses being conducted of the maintenance field data are given in Figures 2 through 5. These figures pertain to Storm 8 recorded on February 16, 1992, for US-395 in Nevada. Figures 2 and 3 provide a chronological history of the meteorological events, pavement conditions, and maintenance activities associated with the storm, including the amount of material applied to the driving lane (DL) and passing lane (PL). Figure 2 pertains to conditions related to the test section, and Figure 3 contains similar data for the control section. Figures 4 and 5 are graphical presentations of the

DATE: FEBRUARY 16, 1992

TEST							APPLICATION							CORALBA	SOBO			
DATE	TIME	TRK I.D.	PVMT TEMP (°F)	AIR TEMP (°F)	ROAD COND	WTHR COND	MATERIAL APPLIED	RATE (lbs/ ln-mi)	LANES TREATD DL	LANES TREATD PL	AMOUNT APPLIED (lbs) DL	AMOUNT APPLIED (lbs) PL	TRMT	FRICTION VALUE @40 mph	READNG WT	READNG CL	EQUIVALENT (lbs/ln-mi) WT	EQUIVALENT (lbs/ln-mi) CL
Feb 16	05:00		31	31	15	5								NONE*				
Feb 16	05:05		31	31	15	5												
Feb 16	05:10	2769	31	31	15	5	Lq. MgCl2	102	1		682		C					
Feb 16	05:15		31	30	15	5												
Feb 16	05:25		31	30	15	5												
Feb 16	05:35	2769	31	30	15	5	Lq. MgCl2	102		1		682	C					
Feb 16	05:45		32	30	25	5												
Feb 16	05:55		32	30	25	5												
Feb 16	06:15		31	30	25	4												
Feb 16	06:25		31	29	25	4												
Feb 16	07:10	2769	31	29	10	5	Lq. MgCl2	102	1		682		C					
Feb 16	07:15		31	28	10	5												
Feb 16	07:30		31	28	10	5												
Feb 16	07:45	2769	31	29	25	5	Lq. MgCl2	102		1		682	C					
Feb 16	07:55		31	29	25	5												
Feb 16	08:00		31	30	25	5												
Feb 16	08:15		31	31	25	5												
Feb 16	08:25		32	31	25	7												
Feb 16	08:30		33	31	25	7												

Codes:

WEATHER	ROAD CONDITION
1 – DRIZZLE	30 – DRY
2 – RAIN	25 – WET
3 – FR. RAIN/SLEET	20 – SLUSH
4 – LT. SNOW	15 – SNOW
5 – SNOW	10 – SNOW/ICE PACK
6 – BLOWING SNOW	5 – ICE
7 – NONE	45 – OTHER

TOTAL LBS MgCl2 TO PL: 1,364

TOTAL LBS MgCl2 TO DL: 1,364

TOTAL LBS MgCl2 APPLD: 2,727

* No friction values taken for test.

Notes:
1 Pavement and Air Temperature data from Sensor #5 located at US 395 and Business 395 junction.
2 Nevada DOT did not have a SOBO unit for test or control sections.
3 Treatment methods are P, C, A, P+C, P+A, C+A. P = Plowing; C = Chemical; A = Abrasives.
4 Under SOBO Heading, WT=Wheel Track, CL=Center Lane
5 Section length is 6.68 miles.
6 Pavement type is Portland Cement Concrete (PCC).

FIGURE 2 Chronological history of Nevada Storm 8 for test section.

DATE: FEBRUARY 16, 1992

TEST							APPLICATION							CORALBA	SOBO			
		TRK I.D.	PVMT TEMP (°F)	AIR TEMP (°F)	ROAD COND	WTHR COND	MATERIAL APPLIED	RATE (lbs/ ln-mi)	LANES TREATD		AMOUNT APPLIED (lbs)		TRMT	FRICTION VALUE @40 mph	READNG		EQUIVALENT (lbs/ln-mi)	
DATE	TIME								DL	PL	DL	PL			WT	CL	WT	CL
Feb 16	05:00	2286	31	31	15	5	Sand/Salt*	1,385		1		9,252	C+A	NONE**				
Feb 16	05:05		31	31	15	5												
Feb 16	05:15		31	31	15	5												
Feb 16	05:25		31	30	15	5												
Feb 16	05:35		31	30	15	5												
Feb 16	05:45		32	30	15	5												
Feb 16	05:55		32	30	15	5												
Feb 16	06:00	2286	31	30	15	5	Sand/Salt*	1,385		1		9,252	C+A					
Feb 16	06:15		31	30	15	4												
Feb 16	06:25		31	29	20	4												
Feb 16	07:15		31	28	15	5												
Feb 16	07:20	1821	31	28	15	5	Sand/Salt*	2,126	1		14,199		C+A					
Feb 16	07:30	2286	31	28	15	5	Sand/Salt*	1,385		1		9,252	C+A					
Feb 16	07:45		31	29	15	5												
Feb 16	07:55		31	29	15	5												
Feb 16	08:00		31	30	15	5												
Feb 16	08:15		31	31	25	5												
Feb 16	08:25		32	31	25	7												
Feb 16	08:30		33	31	25	7												

Codes: WEATHER	ROAD CONDITION
1 – DRIZZLE	30 – DRY
2 – RAIN	25 – WET
3 – FR. RAIN/SLEET	20 – SLUSH
4 – LT. SNOW	15 – SNOW
5 – SNOW	10 – SNOW/ICE PACK
6 – BLOWING SNOW	5 – ICE
7 – NONE	45 – OTHER

TOTAL LBS SAND/SALT MIX TO PL:	27,757
TOTAL LBS SAND/SALT MIX TO DL:	14,199
TOTAL LBS SAND/SALT MIX APPLIED:	41,956
TOTAL LBS SAND–PL:	23,039
TOTAL LBS SALT–PL:	4,719
TOTAL LBS SAND–DL:	11,785
TOTAL LBS SALT–DL:	2,414
TOTAL LBS SAND APPLIED:	34,823
TOTAL LBS SALT APPLIED:	7,133

Notes:
1 Pavement and Air Temperature data from Sensor #5 located at US 395 and Business 395 junction.
2 Nevada DOT did not have a SOBO unit for test or control sections.
3 Treatment methods are P, C, A, P+C, P+A, C+A. P = Plowing; C = Chemical; A = Abrasives.
4 Under SOBO Heading, WT=Wheel Track, CL=Center Lane
5 Section length is 6.68 miles.
6 Pavement type is Portland Cement Concrete (PCC).

* Salt/Sand mix is 83% Sand; 17% Salt
** No friction value taken for test.

FIGURE 3 Chronological history of Nevada Storm 8 for control section.

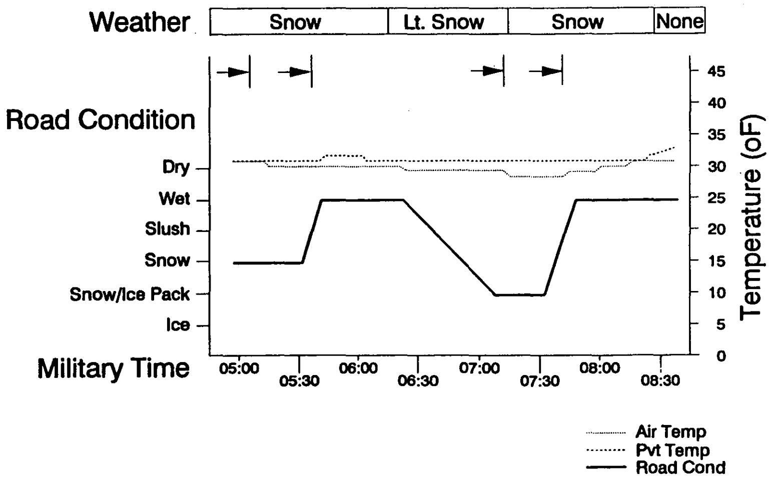

FIGURE 4 Time history of weather, pavement, and air temperature conditions for test section on US-395 in Nevada, Storm 8; arrows denote liquid Freezegard applications (application rate = 102 lb/min, total application = 2,727 lb).

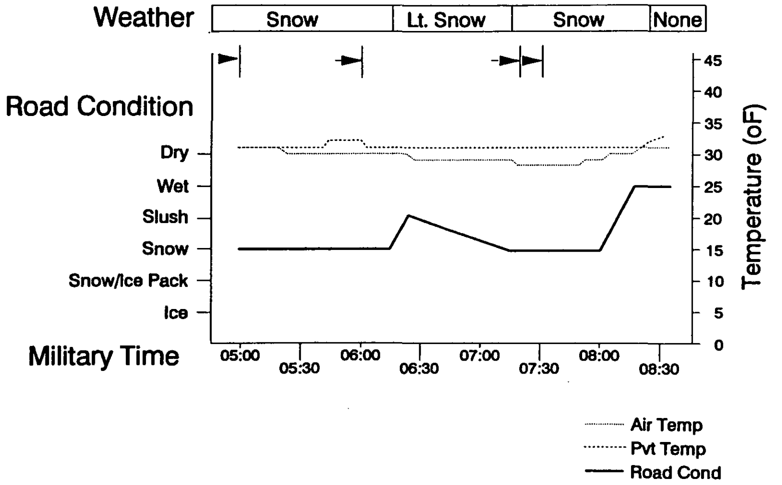

FIGURE 5 Time history of weather, pavement, and air temperature conditions for control section on US-395 in Nevada, Storm 8; arrows denote sand/salt applications (mix is 83 percent sand, 17 percent salt; total application = 41,956 lb).

weather, pavement conditions, and air temperature as a function of time for the test and control sections, respectively. For Nevada Storm 8, more than 2.6 times as much deicer was applied to the control section as was applied to the test section [3236 kg NaCl versus 1237 kg $MgCl_2$ (7,133 lb versus 2,727 lb)]. On a total material basis, more than 15 times as much material was applied to the control section as was applied to the test section [19 031 kg versus 1237 kg (41,956 lb versus 2,727 lb)].

Similar tabulations and plots for Maryland Storm 6 are given in Figures 6 through 9. During this storm, 1.6 times as much deicer was applied to the test section as was applied to the control section when the deicer amounts were normalized with section length [35.5 g/m^2 NaCl versus 21.7 g/m^2 NaCl (461 lb/mi versus 282 lb/mi)]. However, on a total material weight basis, about 2.0 times as much material was applied to the control section as was applied to the test section when the material amounts were normalized with section length (731 g/m^2 versus 35.5 g/m^2 [9,490 lb/mi versus 461 lb/mi]).

Some interesting comparisons can be drawn between the Maryland test and control sections even though more salt was used on the test section than on the control section. For instance, a maintenance truck had to make five passes on the control section but only three passes on the test section. Also, the pavement condition of the test section only deteriorated to a slush state while the pavement condition of the control section deteriorated to a snowy condition. The salt application rate of 5.9 g/m^2 (77 lb/lane-mi) applied to the test section was

DATE:FEBRUARY 4, 1992

TEST

							APPLICATION							CORALBA	SOBO			
			PVMT	AIR				RATE	LANE		AMOUNT			FRICTION			EQUIVALENT	
		TRK	TEMP	TEMP	ROAD	WTHR	MAT'L	(lbs/	TRTD		APPLIED (lbs)			VALUE	READING		lbs/ln−mi	
DATE	TIME	I.D.	(°F)	(°F)	COND	COND	APPLIED	ln mi)	SB	NB	SB	NB	TRMT	@40 mph	WT	CL	WT	CL
Feb 4	14:00		42	40	30	7								0.51	0	0.5	0	22
Feb 4	16:30	86068	35	33	25	2	Rock Salt	77	1	1	845	845	C	0.20	0.5	5	22	220
Feb 4	22:00	86068		27	20	3	Rock Salt	77	1	1	845	845	C					
Feb 4	22:30	86068		26	25	4	Rock Salt	77	1	1	845	845	C					
Feb 4	23:00			27	30	7												
Feb 5	08:00		22	20	30	7								0.30	2	2.5	85	110
Feb 5	08:30			20	30	7												

Codes: WEATHER	ROAD CONDITION
1 – DRIZZLE	30 – DRY
2 – RAIN	25 – WET
3 – FR. RAIN/SLEET	20 – SLUSH
4 – LT. SNOW	15 – SNOW
5 – SNOW	10 – SNOW/ICE PACK
6 – BLOWING SNOW	5 – ICE
7 – NONE	45 – OTHER

TOTAL LBS ROCK SALT TO NB: 2,534

TOTAL LBS ROCK SALT TO SB: 2,534

TOTAL LBS ROCK SALT APPLIED: 5,069

Notes: 1 Length of section is 11 miles.
2 Pavement type is DGA (Dense Graded Asphalt).
3 Air and Pavement temperature were obtained from Raytek Raynger PM−4 forms and MD Highway Administration Weather Condition Reports.
4 Treatment methods are P, C, A, P+C, P+A, C+A. P=Plowing; C=Chemical; A=Abrasives.
5 Under SOBO Heading, WT=Wheel Track, CL=Center Lane.

FIGURE 6 Chronological history of Maryland Storm 6 for test section.

DATE: FEBRUARY 4, 1992

CONTROL							APPLICATION							CORALBA	SOBO			
		TRK	PVM TEMP	AIR TEMP	ROAD	WTHR	MAT'L	RATE (lbs/	LANE TRTD		AMOUNT APPLIED (lbs)			FRICTION VALUE	READING		EQUIVALENT lbs/ln-mi	
DATE	TIME	I.D.	(°F)	(°F)	COND	COND	APPLIED	ln-mi)	NB	SB	NB	SB	TRMT	@40 mph	WT	CL	WT	CL
Feb 4	14:30		41	39	30	7								0.50	0	0	0	0
Feb 4	16:30				25	2												
Feb 4	17:00	86218	35	32	25	2	Sand/Salt*	188	1		1,880		P+A+C	0.26	0.5	3	22	135
Feb 4	17:30	86218		30	20	3	Sand/Salt*	188		1		1,880	P+A+C					
Feb 4	20:00	86218		27	15	7	Sand/Salt*	188	1		1,880		P+A+C					
Feb 4	21:30	86218		30			Sand/Salt*	188		1		1,880	P+A+C					
Feb 4	22:30	86218		29			Sand/Salt*	188	1		1,880		P+A+C					
Feb 5	08:30		20	18	30	7								0.26	3	4	135	180

TOTAL LBS MAT'L TO SB: 3,760

TOTAL LBS MAT'L TO NB: 5,640

TOTAL LBS MAT'L APPLD: 9,400

*Sand/Salt Mix is 70% Sand, 30% Salt

TOTAL LBS SAND TO SB: 2,632

TOTAL LBS SALT TO SB: 1,128

TOTAL LBS SAND TO NB: 3,948

TOTAL LBS SALT TO NB: 1,692

TOTAL LBS SAND APPLIED: 6,580

TOTAL LBS SALT APPLIED: 2,820

Codes:

WEATHER	ROAD CONDITION
1 - DRIZZLE	30 - DRY
2 - RAIN	25 - WET
3 - FR. RAIN/SLEET	20 - SLUSH
4 - LT. SNOW	15 - SNOW
5 - SNOW	10 - SNOW/ICE PACK
6 - BLOWING SNOW	5 - ICE
7 - NONE	45 - OTHER

Notes:
1 Length of section is 10 mi
2 Pavement type is DGA (Dense Graded Asphalt).
3 Air and Pavement temperature were obtained from Raytek Raynger PM-4 forms and MD Highway Administration Weather Condition Reports.
4 Treatment methods are P, C, A, P+C, P+A, C+A. P = Plowing; C = Chemical; A = Abrasives.
5 Under SOBO Heading, WT = Wheel Track, CL = Center Lane.

FIGURE 7 Chronological history of Maryland Storm 6 for control section.

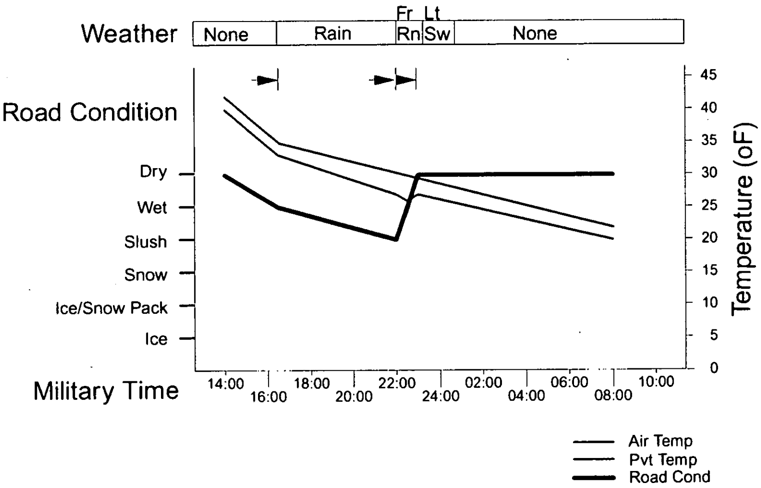

FIGURE 8 Time history of weather, pavement, and air temperature conditions for the test section on Maryland Route 495, Storm 6; arrows denote rock salt applications (application rate = 77 lb/min, total application = 5,069 lb).

apparently enough to prevent the pavement from reaching a snowy state. However, the 25.4 kg (56 lb) of salt plus 59.9 kg (132 lb) of abrasives applied per lane mile on the control section was not enough to prevent the pavement from reaching a snowy state.

The first treatment application for each storm event made by the maintenance forces on the test and control sections was classified as either an anti-icing or a deicing operation. A general definition of an anti-icing operation is one in which a maintenance treatment involving a deicer is applied to the highway before a bond is established between frozen precipitation, or frost, and the pavement surface. Conversely, a deicing operation is one in which a treatment of a deicer is applied to the top of an accumulation of snow, ice, or frost that is bonded to the pavement surface. The exact point at which frozen precipitation is either bonded, or not bonded, is very difficult to establish. In practice, a friction measurement (or Coralba reading) could help define that point in the development of the storm. The Coralba measurements, in general, were not made in the field at the appropriate time or were not reliable enough to assist in this determination for all storms. It appears that the friction measurements were

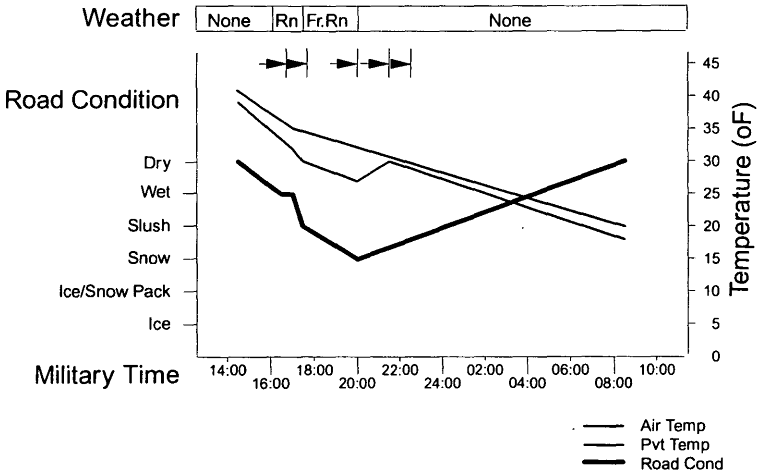

FIGURE 9 Time history of weather, pavement, and air temperature conditions for the control section on Maryland Route 495, Storm 6; arrows denote sand/salt applications (mix is 70 percent sand, 30 percent salt; application rate = 190 lb/min, total application = 9,400 lb).

made as part of the storm documentation and not as part of a decision making process concerning the reapplication for deicing/abrasive materials.

Consequently, it was necessary to develop criteria to help decide the classification of the first maintenance treatment. As developed, this classification of the first maintenance operation depends on the pavement temperature, the pavement condition, and the type of precipitation. Air temperature is not directly included in the criteria but is implicitly assumed to be below 40°C. The pavement conditions identified as appropriate for anti-icing operations are dry, wet, and one with very minor accumulation of snow or sleet on the pavement shoulder or roadway. The pavement conditions identified as appropriate during deicing operations include slush, snow and ice pack, and ice. These criteria, along with ancillary information (such as Coralba readings, Sobo-20 readings, and maintenance personnel observations), were used in classifying the first maintenance treatment of each storm.

Tabulations and plots similar to those displayed in Figures 2 through 9 are being developed for the other storm events recorded during the 1991–1992 winter.

Coralba friction measurements and Sobo-20 salinity measurements were made by some of the states during the 1991–1992 winter in an attempt to better define the pavement conditions before and during selected storm events. Coralba friction measurements were made by five states during 27 storm events; Sobo-20 measurements were made by four states during 24 storm events.

During several storms, some of the states made salinity measurements using the Sobo-20 device before the first (anti-icing) application treatment. Most of the time these pretreatment measurements resulted in zero salinity values. However, in a few storms, the pretreatment measurements indicated that there was a minor salinity level, possibly a carryover from previous storm treatments.

Cases were noted in which a low salinity measurement value was followed by an application treatment. In other cases, a low salinity measurement value was not followed by an application treatment. The same application treatment combinations were noted also for high salinity measurement values. Thus, it appears that the Sobo-20 measurement value levels were not used consistently to make decisions about reapplication treatments.

CONCLUDING REMARKS

The activities conducted so far under the program have suggested methods that can be used by winter maintenance personnel for measuring pavement friction and residual chemicals before, during, and after storm events. Such tools can provide maintenance supervisors with added knowledge of the pavement conditions for their decision making.

The analysis of the 1991–1992 winter maintenance field data is starting to reveal some interesting results concerning anti-icing operations in the United States. The balance of the analysis results will be used to help guide the continued anti-icing experiments planned for the 1992–1993 winter.

ACKNOWLEDGMENTS

The work reported herein was conducted under Contract SHRP-90-H208. L. David Minsk is the SHRP Research Manager for the contract. Funding for the study was provided by the SHRP, National Research Council, National Academy of Sciences.

Quality, Quantity, and Availability of West Virginia Oil and Gas Well Brines for Highway Deicing Purposes

RONALD W. ECK AND WILLIAM A. SACK

Research findings over the last decade have indicated that use of natural brines as highway deicing agents was technically feasible and cost-effective in a variety of situations. The principal remaining concern related to brine availability. An in-depth evaluation of oil and gas field brines on a statewide basis was undertaken. Published information was limited, so a survey was conducted of oil and gas producers in the state to obtain information on the quantity and quality of brine produced. Data collected were compiled as a microcomputer data base to be used by the West Virginia Division of Highways. Selecting brine parameters for analysis and acceptable concentration levels for those parameters was somewhat difficult, since there are no generally accepted guidelines for oil and gas brines. The two most important issues involving a brine's suitability for highway deicing are melting effectiveness and the level of potentially harmful constituents. The data base was implemented to determine brine quantity estimates on a statewide basis. Almost 2.2 million L/year were identified. All counties producing suitable brines were clustered in the west-central and north-central portions of the state. On the basis of current brine availability, the most promising applications are as an additive to abrasives rather than application of straight brine directly to the pavement.

Brines (either prepared or natural) have received considerable attention as a snow and ice control material since they act fast and do not blow off the road. A number of state and local highway agencies use natural brines from geologic formations beneath the earth's surface. Since West Virginia is a significant producer of oil and gas and associated brines, it was appropriate to examine the use of brines on West Virginia highways.

The significant quantities of brines produced in West Virginia are difficult to dispose of in an environmentally acceptable manner since the brines are much more concentrated than seawater. The currently preferred method of brine disposal is via injection wells; however, this is often a very expensive method in the Appalachian region. Since there is, at present, no completely satisfactory and cost-effective method of disposing of waste brine, brine is often disposed of directly into ground or surface waters with potential water quality deterioration.

During the past decade, several research projects have been undertaken in West Virginia to address questions associated with the use of natural brine as a deicing agent. Both laboratory and field testing programs have been conducted on brines alone and on brine as an additive to abrasive materials and deicing salts. Findings indicated that use of natural brines as a highway deicing agent was technically feasible and appeared cost-effective in a variety of situations (*1*). On the basis of the research, the West Virginia Division of Highways (WVDOH) had enough information to begin acquiring equipment and building facilities to implement a brine usage program. The principal concern remaining related to the availability of brine. Thus, an in-depth evaluation of oil and gas field brines on a statewide basis was undertaken.

The overall goal of this research was to evaluate the quality and quantity of oil and gas field brines across the state in anticipation of a larger-scale use of brines. Specific objectives established to meet this goal are

1. To expand the necessarily limited brine quality information collected in Phase I to include brine availability information statewide,
2. To work with oil and gas producers to determine current brine production and brine quality from major fields and to estimate the production life of these fields, and
3. To develop, from existing information and analyses conducted as part of this research, a microcomputer-based brine availability (quantity and quality) data base.

BRINE AVAILABILITY INFORMATION

To obtain data on the quality and quantity of brine, several federal and state agencies and trade associations were contacted, including the Environmental Protection Agency (EPA), the West Virginia Department of Natural Resources, the West Virginia Department of Energy, the West Virginia Geologic and Economic Survey, the West Virginia Oil and Natural Gas Association, and the Independent Oil and Gas Association of West Virginia. However, only the West Virginia Geologic and Economic Survey was able to provide much useful data on brine quality.

The quantity of brine produced from a given well depends on a variety of factors, including the geological formation tapped and its depth, and the well's location, construction age, and operation (*2*). Many wells produce little brine when first put into production but then produce more with time others yield large quantities of brine initially. Brine produced per well is extremely variable.

Clearly, the best source of hard data on brine production is the oil and gas industry. The investigators were able t

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obtain estimates of brine available for deicing from 13 companies, as will be discussed, but a comprehensive listing of brine produced statewide was not available. A 1987 survey of actual brine production included approximately 15 percent of the gas wells and 10 percent of the oil wells in the state (*3*). Assuming that the amount of brine produced in the wells reported is representative of produced water from all active wells in the state gives an estimate of 844 million L of brine.

Even if the figure of 844 million L of brine production per year is a reliable estimate, only part of the brine would be available or suitable for use on roadways. Brines unsuitable for use include those that are too weak or that contain undesirable levels of contaminants. It is also likely that brines from a number of wells would not be cost-effective for use because of their remote location or low production, resulting in unacceptably high transportation costs.

As a result of discussions with various state agencies and trade associations, it was found that there are an estimated 1,800 producer-operators in West Virginia with between 30,000 to 45,000 wells. However, most of the wells may be classified as stripper wells that produce only small amounts of oil or gas, and some are inactive. In addition, most of the operators are relatively small companies with fewer than 25 wells.

Discussions with representatives from the oil and gas industry were carried out to ascertain what type of information on brine quantity, well location, and brine quality they would be willing and able to provide. We found, with few exceptions, that most companies did not have significant information on brine quality. In addition, most companies were unwilling to provide information on quantity or quality for individual wells. Most were, however, willing to report the quantity of brine available from a group of wells in a given geographic area.

A brine survey form was prepared to gather data from each company for the data base. The information requested for each brine source included county, formation or zone, quantity of brine available from October to April, estimated production life, well group location, and distance that the company was willing to haul the brine to a WVDOH maintenance station.

Initial contacts with each oil and gas producer were made by phone. During the initial call, the purpose of the project was explained and a request for participation was made. If the company representative agreed to cooperate, a brine survey form and accompanying explanation was sent along with a request for the form to be filled out and returned to the investigators as soon as possible. Samples were also requested.

Of the 71 telephone contacts made during the study, 18 companies completed the brine survey form. Of the remaining 53 companies, 4 had been sold or were no longer in business. Thus, 49 companies rejected participation in the project either explicitly (stated a reason) or implicitly (did not respond). The most common reason given for rejection was production of only a small quantity of brine. Of the 18 companies that returned the survey forms, only 14 actually provided samples of brine for analysis.

CHOICE OF CONSTITUENTS AND FORMULATION OF BRINE RANKING SYSTEM

One of the early project tasks was choosing which constituents would be determined for each brine. A closely allied task was choosing acceptable concentration levels for some of the parameters. The two most important issues regarding a brine's suitability for highway deicing are melting effectiveness and the level of potentially harmful constituents.

Discussions were held with state regulatory personnel in West Virginia and Pennsylvania to aid in choosing constituents. Consideration was also given to the EPA Drinking Water Standards and to typical levels of various constituents normally found in brines. The final choice of acceptable levels was based on the judgment of the researchers. It was decided to limit the list of constituents to 10 because of time and resource constraints.

Table 1 presents the 10 constituents chosen for analysis and provides a rationale for the choice in each case. Also included are the acceptable levels where pertinent. It may be noted that different acceptable levels have been specified for use in road spreading and for addition to abrasives. This is because brine application rates for road spreading are based on 142 kg total dissolved solids (TDS) per two-lane kilometer, whereas brine application rates for use with abrasives are expected to range from about 3 to 9 kg TDS/two-lane-km (*4*). Since the brine application rate for abrasives is only about 5 percent of that for road spreading, higher acceptable levels of iron, sulfate, barium, lead, and oil and grease are shown for brine added to abrasives.

In areas where a variety of brine sources are available for use, it appears prudent to use the brines with the best melting effectiveness and lowest concentrations of undesirable constituents. Hence, a ranking system was devised for both brine spreading and brine addition to abrasives applications. The system was based on concentrations of total dissolved solids, barium and lead. A point system was used that allows a maximum value of 7 (most desirable) and minimum value of 1 (least desirable). Thus, a brine with high TDS (above 250,000 mg/L) and low lead and barium levels would earn a high rank of 7 points. But a brine with relatively low TDS (less than 200,000 mg/L) and high lead and barium levels would receive a low rank of 1 point. The system is clearly arbitrary in nature, but it is simple, easy to use, and can be readily applied to new brines.

BRINES ANALYSIS AND RANKING

As noted earlier, brine samples were obtained from 14 oil and gas producers. Seventy samples were analyzed from 23 counties and 25 different formations or zones. On the basis of meeting the acceptable criteria chosen (Table 1) for TDS, barium, lead, and oil and grease, 32 of the 70 brines sampled were found to be suitable. Of the 32 brines, 19 were acceptable for both spreading and adding to abrasives, whereas the other 13 could be used only as abrasive additives. Detailed data on the composition of each brine are presented in the project final report (*5*).

Range and mean constituent values were determined for the suitable project brines. TDS levels varied from 150,000 to 311,200 mg/L. In general, the stronger brines originated from deeper formations. As would be expected, the major elements determined (chloride, sodium, and calcium) increased as the TDS increased.

TABLE 1 Brine Constituents Analyzed and Acceptable Levels Chosen

Parameter	Rationale	Acceptable Level[a]	
		Road Spreading	Added to Abrasives
Total Dissolved Solids	A high TDS improves melting efficiency and reduces volume of brine required	150,000 (min)	150,000 (min)
Chloride	Same as TDS	NLS[b]	NLS
Sodium	Same as TDS	NLS	NLS
Calcium	Improves melting at lower temperatures	NLS	NLS
pH	Low pH may accelerate corrosion of equipment and impact surface runoff	NLS	NLS
Iron	May cause staining of concrete roadways	For values >500, restrict to use on asphalt	NLS
Sulfate	High sulfate levels attack concrete	For values >400, restrict to use on asphalt	NLS
Barium	Health effects	30 (max)	100 (max)
Lead	Health effects	6 (max)	7 (max)
Oil and Grease	Potential for slippery conditions and environmental impact	35 (max)	160 (max)

a all values in mg/l except pH
b NLS - no limit specified

Calcium levels varied from 13,440 to 35,630 mg/L and averaged 23,910 mg/L. The presence of calcium is desirable in that calcium salts lower the freezing point more than sodium salts, allowing the use of a calcium-based deicing agent at a relatively lower temperature. Iron ranged from 22 to 1010 mg/L, with an average value of 319 mg/L. The high variability in iron is probably due to sample handling during collection and analysis. On exposure to air, ferrous iron will slowly oxidize to ferric iron and precipitate. When used for road spreading, brines with iron concentrations of greater than 500 mg/L are restricted to use on asphalt to avoid staining of concrete.

Sulfate levels, which varied from 20 to 1080 mg/L (average 361 mg/L), are of interest because of potential attack of concrete. It is recommended that brines with sulfate levels above 400 mg/L be restricted to use on asphalt when brine is used for road spreading. Because of dilution with meltwater, actual runoff sulfate levels are not expected to cause concrete to deteriorate.

Lead in project brines varied from 2.7 to 6.4 mg/L, with an average of 4.3 mg/L. It is thought that these levels are environmentally acceptable for a variety of reasons. First, there is a large amount of dilution by meltwater available. For example, assume the average brine containing 212 560 mg/L TDS and 4.3 mg/L lead was applied at a loading rate of 142 kg TDS/two-lane-km in a road spreading application. Also assume that there was 3.2 mm of precipitation on the highway for dilution. It can be shown that the runoff lead concentration at the edge of the roadway would be approximately 0.16 mg/L. In addition, as the runoff moves toward a water course, significantly greater dilution would occur as meltwater from the surrounding terrain mixes with runoff from the roadway. The preceding discussion assumed a road spreading application rate of 142 kg TDS/two-lane-km. For an application in which brine is added to abrasives, it was noted earlier that the application rate would be extremely small (5 percent of that used for spreading) and hence lead levels would be insignificant.

Barium in project brines varied from 0.2 to 98.5 mg/L, with a mean of 20.5 mg/L. As noted in Table 1, acceptable brines for road spreading and for use as abrasives additives should have barium levels of less than 30 and 100 mg/L, respectively, for health considerations.

It should be noted that dry deicing agents also contain trace constituents such as lead and barium. A variety of dry sodium and calcium chloride deicing agents were analyzed during Phase I (*6*) for comparison with trace elements in natural brines. Results were expressed as milligram of constituent per kilogram of TDS. The lead in the dry agents averaged 6.7 mg/kg in sodium chloride and 500 mg/kg in calcium chloride samples tested, whereas barium averaged 114 mg/kg in two sodium chloride samples tested. Using the average values for project brines gives 20.2 and 96.4 mg/kg of lead and barium, respectively, in the dry deicing agents. Hence, trace elements in dry deicing agents used may actually exceed those in natural brines in some cases.

Oil and grease concentrations ranged from 2 to 160 mg/L, averaging of 41 mg/L. Brine used for spreading will be restricted to an oil and grease level of less than 35 mg/L to avoid slippery pavement conditions.

DEVELOPMENT OF BRINE DATA BASE

Information Requirements and Report Capabilities

To evaluate the potential for brine usage in a given part of the state, information is required about brine quality, brine quantity, location, and estimated production life of the field. In addition, a list of oil and gas companies in an area willing to provide brines would be required. Storage and handling costs must also be carefully considered. It was anticipated that the oil and gas companies would deliver brine to most WVDOH maintenance stations at no cost, but it is clear that the distance between the brine source and the nearest maintenance station is an important consideration in selecting a particular brine.

To use this brine information, certain data are also needed from the user. User inputs would include the location of the maintenance station at which brine is desired, the quantity required (based on past history of rock salt usage), and the method of brine application desired (e.g., road spreading, salt prewetting, stockpile freezeproofing, or adding to abrasive mixtures). Although not part of the information requirements per se, any system for accessing and manipulating brine data must incorporate such user inputs.

It was initially anticipated that brine quantity and quality information could be acquired on a well-by-well basis. Discussions with oil and gas producers indicated that because of the sensitive nature of the data, producers will not usually provide data on individual wells but would be willing to provide data on groups of wells producing from a particular formation. Thus, the data base described herein is based on well groupings. Given the potentially large volume of data to be andled, the need for frequent updating, and the need to serve different users, a computerized data base was created.

Two types of reports were envisioned. The first report, which would identify brine producers, is intended for use at he managerial level, either at the WVDOH main office in Charleston or at the district headquarters. For each WVDOH district, the report would list the brine producers in each county making up that district. An address and telephone number would be provided for each producer along with an estimate of the quantity of brine available in gallons per year.

The second report, which would identify specific brine sources, is intended for use by county maintenance personnel in making arrangements for acquiring brine. The oil and gas producers in each county who have agreed to cooperate would be listed with an address and telephone number. The location of the haul point and the zone or formation from which the well group produces should be indicated along with the quantity, quality, and transportation information.

PC-FILE +, a general-purpose data base manager, was selected as the most appropriate for project purposes. The software runs on all of the IBM series of personal computers, as well as all compatible and most "nearly compatible" computers. It is designed to work with any printer. PC-FILE + requires a 384K or larger MS-DOS computer with two double-sided disk drives or one double-sided disk drive and a hard disk, an 80-column display, and MS-DOS or PC-DOS Version 2.0 or later.

The main data base, which contains the information items discussed earlier, was designated as BRINE. Table 2 provides a list of the fields that make up the BRINE data base. To ensure that any particular brine is acceptable for use on highways, BRINE includes only those brines that have been found to be acceptable.

Several reports were developed that would be useful to WVDOH users. The PRODUCER list includes, for each WVDOH district, the brine producers in each county making up that district. An address and telephone number are provided for each producer along with a cooperation code and the quantity of brine available in gallons per year. The cooperation code is designated as either "P" or "H." A "P" indicates that the company is willing to provide brine but that WVDOH must make arrangements for transportation. An "H" indicates that the company is willing to haul brine (at no cost) a reasonable distance to WVDOH maintenance facilities.

The SOURCE list is typical of the report that might be requested by county maintenance personnel in making arrangements for acquiring brine. The oil and gas producers in each county who have agreed to cooperate are listed with an address and telephone number. The location of the haul point for a well group is given in a form that would be identifiable to the system user, such as a town or a highway intersection. The zone or formation from which the well group produces is also indicated along with the quantity of brine produced in gallons per year and estimated production life. The haul that a producer is willing to make at no charge to WVDOH is presented in terms of either a distance or a haul time, as provided by the producer in response to the questionnaire. Finally, an analysis of the brines is presented in terms of the 10 parameters selected as being useful in identifying suitable brines for highway purposes.

Identification and Ranking of Suitable Brines

Haul distance is obviously a factor to be included in any ranking system for selecting brine sources. However, as the

TABLE 2 Fields Making Up Brine Data Base

Field Name	BRIEF EXPLANATION
Sample Number	ID Number assigned by researchers
Company	Oil/Gas producer
Contact	Individual providing data
Address	Street address
P.O. Box	Post office box number
City	City
State	State
Zip Code	Zip code of city
Area Code	Telephone area code
Phone Number	Telephone number
Formation	Geologic formation from which produced
Location	Geographic location of well grouping
District	WVDOH District number
County	County
Quantity	Quantity of brine available
Estimated Life	Estimated life of well grouping
Cooperation Code	Producer willingness to haul brine
Storage	Producer willingness to store brine
Haul Distance	Distance producer willing to haul
Haul Time	Trip length producer willing to haul
pH	pH of brine
TDS	Total dissolved solids of brine
Chloride	Chloride content of brine
Sodium	Sodium content of brine
Calcium	Calcium content of brine
Iron	Iron content of brine
Barium	Barium content of brine
Lead	Lead content of brine
Sulfate	Sulfate content of brine
Oil & Grease	Oil & grease content of brine
Station	WVDOH maintenance stations within haul distance
Comments	Remarks

project progressed, it became apparent that haul distance did not affect the brine selection decision in the way the researchers had envisioned at the proposal stage. Thus, as will be described, inclusion of haul distance in the ranking system is implicit as opposed to explicit.

Currently, a number of oil and gas producers are hauling (or paying to have hauled) brines considerable distances to dispose of them. Review of questionnaire responses tended to support this statement, with companies indicating haul radii of 2 or even 3 to 6 hr. The radius of haul would vary depending on the type of highway over which the haul is made. For example, a truck can travel significantly farther in 2 hr over an Interstate highway than it can over a two-lane, two-way highway with sharp curves and steep grades.

Because of the considerable haul distances involved and the wide range in these distances, a traditional economic analysis of hauling cost versus distance does not apply. Hauling brine to a particular maintenance station is an either-or situation. This complicates any attempt to incorporate hauling considerations as part of the ranking system for a specific brine.

The ranking system developed can be considered as a two-step process. First, suitable brines for which the distance from the well group to a WVDOH maintenance station is less than or equal to the haul distance indicated by the producer are identified. That is, the data base includes a list of the brine sources within a reasonable haul distance of each maintenance station. Second, the quality ranking system is then applied to each of the brines feasible for a given maintenance station. As with the quality ranking system, haul considerations have been incorporated into the ranking system by the researchers and do not need to be considered by data base users.

Identifying feasible brines for particular maintenance stations was essentially a manual process. Existing WVDOH salt stockpile locations were plotted on a state highway map. The centroid of each well grouping was also plotted on the basis of the location indicated on the producer's questionnaire response. For each centroid, a circle was plotted with radius equal to the indicated haul distance. Where producers indicated a haul time instead, the time was converted to a distance using the following factors:

- Interstate highways: average speed = 72 km/hr
- Two-lane highways: average speed = 40 km/hr

From this plot, it was a straightforward process to identify the maintenance stations within the economic haul circle for each well grouping. The list of these maintenance stations, for each brine source, was then incorporated into the BRINE data base.

DATA BASE IMPLEMENTATION

The brine analysis information, for those producer-furnished samples that were deemed appropriate on basis of the criteria presented earlier, was input to the data base. In addition, those maintenance stations within the economic transportation distance, as determined by the haul distance analysis, were entered appropriately. The data base was then implemented to determine brine quantity estimates statewide.

Brine Quantity Estimates

To determine the availability of brine statewide, a printout was generated from the data base showing the quantity of suitable brines in each of the producing counties. These results are shown in Table 3. The 32 samples, each representing a different well group, came from 14 of the 55 counties in the state.

The quantities were plotted on a state map in order to visualize the geographic distribution of suitable brines. Except for Raleigh County in the southern part of the state and Nicholas County in the center of the state, all of the brine-producing counties are clustered in the west-central and north-central portions of the state, that is, between the Ohio River and the Clarksburg-Buckhannon area. Previous work, both by this research team and others, has shown that there are other significant brine-producing areas in the state, for example, Monongahela-Preston counties, Randolph-Tucker counties, and Kanawha-Clay counties. Brines from these areas were not included on the map because either the brines are not suitable for highway purposes or producers from those locations did not respond to the survey.

As provided in Table 3, this study identified slightly more than 2.1 million L of suitable brines available statewide each year. This quantity can be considered as the minimum amount of brine available. Other producers of suitable brines will certainly come forward once the WVDOH begins using brines for highway purposes. However, even if additional brine becomes available, it is fair to say that certain parts of the state will not be candidates for implementing a brine usage program. These areas include the northern panhandle, the eastern panhandle, and the southeastern and the southwestern parts of the state.

Brine Feasibility at Selected Locations

Information from the data base was used to evaluate the feasibility of brine usage at selected maintenance stations in brine-producing areas of the state. In consultation with WVDOH maintenance personnel, several scenarios for using brine were developed and evaluated. The scenarios were:

- Application to Interstate 79 in central West Virginia
- Application in urban areas
- Application in vicinity of brine sources
- Application of brine-treated abrasives

All scenarios assumed an average West Virginia winter: 18 storms a year with three salt applications per storm. In addition, it was assumed that the brine strength was 200 000 mg/L TDS requiring an application rate of 85 kg/two-lane-km to apply 142 kg TDS/two-lane-km. Obviously, brine strength will vary depending on the source. Survey results indicated that most suitable West Virginia brines are in the range of 160 000 to 250 000 mg/L.

It was determined that, given the haul distances involved, the Interstate system is not an attractive setting for using brines. A special truck would be needed to carry the large quantities of brine involved.

The second scenario involved straight brine application in densely populated areas, where distances are not great but the need to act quickly is important. Results indicated that there is almost enough brine within a reasonable haul distance of Charleston, Clarksburg, and Parkersburg to handle two of the three urban ares. Although the scenario appears feasible for the two urban areas that might be chosen, negligible brine would be left statewide for other highway applications.

In the third scenario, a county having well groupings where sufficient quantities of brine are available would become a candidate for application of straight brine on paved roadways. There are only five areas in the state where such a large quantity of brine exists in a relatively concentrated area. In the five counties (or groups of counties) that have brine sources close enough to make this approach practicable, conversion

TABLE 3 Quantities of Suitable Brines Available in Each Producing County

County	Well Groups	Liters per year
Doddridge	1	55,640
Gilmer	3	151,000
Harrison	5	224,150
Jackson	1	31,800
Lewis	4	334,000
Mason	1	31,800
Nicholas	3	111,280
Raleigh	2	22,260
Ritchie	1	158,970
Roane	5	395,200
Tyler	2	152,900
Upshur	2	26,390
Wirt	1	318,000
Wood	1	98,560
TOTAL	32	2,112,000

to brine would save only 5 to 10 percent of a candidate county's salt usage.

The final scenario involved treating a standard abrasive hopper spreader with brine as a substitute for conventional rock salt. Assuming that 6.7 kg TDS/two-lane-km would be added to the abrasive material, a 3.8-m^3 (5-yd^3) truck would be treated with 568 L of brine each time it left the maintenance yard. Analysis indicated that nine counties have sufficient brine within a reasonable haul distance.

The most promising of the four scenarios is its addition to abrasives for enhanced melting action. Nine counties were identified with sufficient brine for abrasive treating needs, and a one-winter pilot study or field trial in one or two of these counties was recommended. To implement this recommendation, a sample agreement between the WVDOH and CNG Development, a local producer, to conduct a field trial was developed. The agreement is written so that CNG Development will provide brine and storage tanks to the WVDOH Weston Maintenance Station in Lewis County. Although the sample agreement is written for a specific company and location, it can be readily modified for use with other companies and locations. The agreement is written so as to be a companion document to a set of pollution prevention guidelines and conditions; both documents are contained in the project final report (*5*).

Pollution prevention guidelines and conditions were prepared for submission to the West Virginia Department of Natural Resources and are designed for use during brine application to cinder abrasives to enhance melting action during a field trial at the Weston Maintenance Station in Lewis County. The rate of brine application with the cinder abrasives will be quite low (approximately 7 kg TDS/two-lane-km), so the potential for any environmental problems is extremely limited.

CONCLUSIONS

Data on the quality of brines in West Virginia were not readily available. Useful historical data were obtained but suffered from limitations such as the date of the data, limited geographic coverage, or the exclusion of important constituents. It was concluded that there was a need for systematic collection of brine quality data from each oil and gas producer. The West Virginia Department of Energy is planning to collect such data within the next few years.

Similarly, no comprehensive data are available on the quantity of brine produced in West Virginia. The best source of such data is the oil and gas industry. Until a government agency such as the West Virginia Department of Energy specifies a mandatory data collection program, producers will most likely be unable or reluctant to provide brine production data. However, the brine availability data base compiled as part of this research will be of use to the West Virginia Division of Highways in the near term.

Choosing brine parameters for analysis and acceptable concentration levels for these parameters was somewhat difficult since there are no generally accepted guidelines relative to oil and gas brines. In the researchers' opinions, the two most important issues regarding a brine's suitability for highway deicing are melting effectiveness and the level of potentially harmful constituents. The parameters evaluated in this study were total dissolved solids, chloride, sodium, calcium, pH, iron, sulfate, barium, lead, and oil and grease. Since the brine application rate required for abrasives is only about 5 percent of that for road spreading, higher acceptable levels of iron, sulfate, barium, lead, and oil and grease were indicated for brine added to abrasives.

Traditional economic analyses of hauling cost versus distance do not apply to the transportation of brines. The transportation of brine from the wellhead to a particular WVDOH maintenance station is an either-or situation. Thus, inclusion of haul distance in the brine ranking system is implicit (i.e., invisible to the user) as opposed to explicit.

The data base was implemented to determine brine quantity estimates on a statewide basis. Almost 2.2 million L per year of suitable brines were identified. In general, all of the counties producing suitable brines in this study are clustered in the west-central and north-central portions of the state.

Perhaps the major overall conclusion drawn from this research is that based on current brine availability, the promising applications are as an additive to abrasives rather than an application of straight brine directly to the pavement. Previous studies (*4*) on West Virginia brines have shown that they are also suitable for prewetting of rock salt and stockpile freezeproofing.

The quantity of available brine identified should be considered as a minimum. Once the beneficial use of brines for highway purposes is demonstrated, other producers of suitable brines will certainly come forward. However, even under these circumstances, the northern panhandle, the eastern panhandle, and the southeastern and southwestern parts of the state are unlikely candidates for implementing a brine usage program.

ACKNOWLEDGMENTS

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Anti-Icing Activities in Finland: Field Tests with Liquid and Prewetted Chemicals

TAPIO RAUKOLA, RAUNO KUUSELA, HEIKKI LAPPALAINEN, AND ANTTI PIIRAINEN

Preventive ice control methods were discussed and even promoted in the 1970s in Finland. Because of bad results, such practice did not become generally used. At the end of the 1980s, the liquid and prewetted salting methods were introduced in Finland; these methods made preventive ice control feasible. In field studies preventive methods were tested in practice using liquid NaCl (23 to 25 percent). Salt residues were measured after the applications with Sobo 20 to find out how long the residues are effective on the roadways. The tests included a comparison between liquid NaCl and liquid $CaCl_2$ (at 32 percent). The spreading patterns were studied with prewetted salt at different rates of application and at different spreading speeds. A few anti-icing tests conformed to each other: preventive treatment was successful. In the residues, there was no difference between how well the NaCl and $CaCl_2$ stayed on the roadways. Quite often the salt residues diminished more during the first 200 vehicles than afterward. It is recommended to treat the most heavily trafficked highways with liquid salt preventively, when the road is expected to freeze. Spreading patterns were found to be at their best when the spreading width for a road 7 m (23 ft) wide is less than 5 m (about 16 ft)—3 to 4 m is good—and the speed is not more than 30 to 40 km/hr (19 to 25 mph). If these limits are exceeded, more salt is wasted to the slopes. Six road master districts were involved in these tests, all of which were executed on trafficked highways.

Black ice increases the risk of traffic accidents tremendously—20 to 25 times over the risk on a dry surface. It is therefore worthwhile to reduce such conditions as much as possible. In the 1970s it was recommended that preventive actions with dry, granular salt be used. Some areas tried it but were disappointed with poor results, and motorists thought that the maintenance personnel were out of their minds.

Large-scale use of liquid and prewetted salting methods began a few years ago in Finland. Since then, the investments in the equipment have been substantial; they include mixing units, spreaders, and tanks for spreading and storing brines. The increase in the number of spreaders illustrates this (Table 1).

FIELD TESTS

Spreading the liquid and prewetted salts has been the first effective method for highway maintenance personnel to carry out anti-icing activities, because the wet agents stick to dry surfaces and it is possible to control the rate of application. (In this paper, "anti-icing" means a preventive treatment, and "deicing" means a curative treatment.) One advantage of liquid salt is the minimization of total salt used. The first experiences showed about a 20 percent savings in tonnage used on the heavily trafficked Finnish areas. The cost savings were not realized because of the expense of the equipment.

Most of the maintenance people still remember failures of earlier experiments, and they are reluctant to fail again. Therefore, it was decided to implement field tests to show the effectiveness of brines in preventing ice from forming on highways (*1*).

Objective

The objective of testing was to develop recommendations for anti-icing activities. The recommendations were to include advice on how early treatments can be done, the rates that should be used, the condition under which the method can be used, the risks, the type of equipment that is best, and the differences between sodium and calcium chlorides.

Implementation

Normally black ice forms during weather conditions occurring mostly in October and November. Unfortunately, there were only a few good occasions for testing in 1991 because the fall was much milder than normal. It will be necessary to continue field tests to collect more data to make final conclusions.

The anti-icing tests were carried out in two maintenance areas: a NaCl spinner spreader was used in the Orivesi area (Figure 1), and a $CaCl_2$ spray bar spreader was used in the Karstula area (Figure 2). The two areas are about 140 km (90 mi) apart as the crow flies. Spreading equipment was calibrated before tests, and traffic counts were made in 15-min increments during residue tests.

Working Pattern

Anti-Icing

Results were evaluated in the traffic lanes after the applications. Salt residue tests were taken in many places on tes

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TABLE 1 Spreaders Available for Liquid and Wet Salt Application

Period	Liquid Spreaders	Pre-wetting Spreaders
89-90	2	50
90-91	32	80
91-92	85	100
92-93*	125	125

** includes 40 spreaders on order*

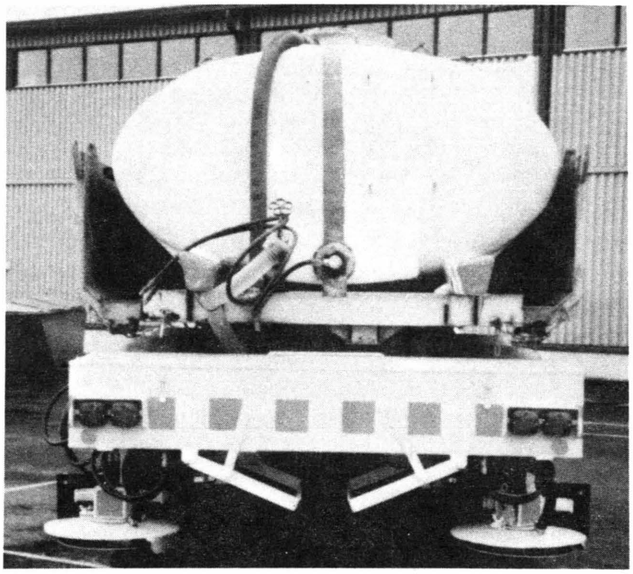
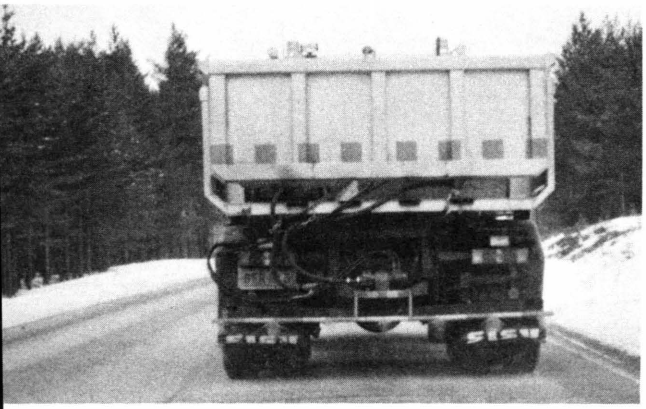


FIGURE 1 Liquid spinner spreader in Orivesi.



IGURE 2 Liquid spray bar spreader in Karstula; accessory onsists of thin spray bar and nozzles, pump, and hydraulics.

ections and control roads. The personnel in the Orivesi area ound that the anti-icing method worked great and started to se it on a large scale immediately.

Treatments were applied when the forecasts predicted reezing or when the first signs of freezing could be seen. For orecasted snowfalls, an anti-icing treatment was made once efore the occurrence. Chloride quantities were measured soon after spreading and usually some time after. The results of salt residue tests can be used to estimate how much salt was left when freezing occurred at that location. The night patrolman and the supervisor reported the time of freezing on the control sections and whether the test sections remained unfrozen. The measurements were taken as described in Figures 3 and 4.

Residue Tests

About the same measurement pattern was used as described in Figure 3. Wide-shoulder roads were used as test roads to see how much of the salt flew over the edge markings.

Instruments

The Sobo device was used to define how much chloride existed on the test pavements (Figure 4). It works well to measure

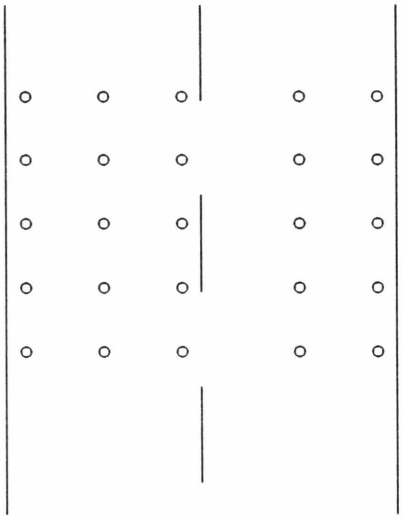


FIGURE 3 Location of salt measurements on lanes and beside road markings.

FIGURE 4 Sobo 20 measurements in progress.

both sodium and calcium chloride quantities on the basis of electric conductivity definitions. The specific resistances of both agents are about the same.

Sobo uses liquid acetone and distilled water mixture for measurements. The readings are from 0 to 45 g/m². The accuracy of Sobo varies depending on salt gradations: Sobo records only about 50 percent of very coarse salt, about 75 percent of fine-graded salt, and about 100 percent of brines. On dry surfaces the Sobo gives somewhat lower readings than on wet ones. If the electrodes of the Sobo get dirty, readings become far too low, so the electrodes must be cleaned frequently.

Spreading Equipment and Liquid Concentrations

Both spinner and spray bar spreaders were used for testing: spinners were used with liquid sodium (Figure 3), and spray bars were used mainly with liquid calcium chloride (Figure 4). The concentration of liquid sodium chloride was targeted at 23 to 25 percent. Liquid calcium chloride was applied at a 32 percent concentration. From these data, an application rate of liquid calcium chloride would be roughly 20 percent less than the liquid sodium chloride to have the same results for salt per square meter.

RESULTS

Anti-Icing

Orivesi

The Orivesi test section was a three-lane section on Highway 9. When the maintenance staff enlarged the anti-icing treatments to cover the entire section of the highway, additional measurements were taken. The control roads were in the same vicinity as the test sites. The average daily traffic of the test road is about 6,100.

Case 1: November 16, 1991 The anti-icing treatment was applied to all salt-classified highways (those with a bare-pavement policy) at 4:20 p.m. at a rate of 20 g/m² liquid NaCl, or 5 g/m² salt. Two of the nearby low-volume roads were frozen 2 to 3 hr later. At that time, 4 to 5 g/m² salt remained on the test section and its condition remained unfrozen. Hoar frost started to build up 12 hr after the treatment (at 4:00 a.m.), but the test road did not freeze until between 8:00 and 9:00 a.m. Another treatment was made 17 hr after the first treatment. The residue was 1 g/m² salt on the liquid salt test road (Figure 5). The road temperature was 0°C (32°F) at 4:00 p.m. and −7°C (25°F) at 8:00 the next morning. The dew-points were −0.2 and −4.6°C (31.6 and 24°F), respectively.

Case 2: November 22, 1991 The anti-icing treatment was applied at 2:10 p.m. to the wet highway surface at a rate of about 11 g/m² liquid NaCl, or 3 g/m² salt. After 3 hr, all control roads with no salt were frozen and the others remained wet. At the freezing time, the salt residue on the test section was 1 g/m² (Figure 6). The road temperature was −1.4°C (29.5°F) at 5:00 p.m. and −3.6°C (25.5°F) at 8:30 p.m.

Case 3: November 23, 1991 The forecast at 8:45 p.m. was for ice buildup in 9 hr. The anti-icing treatment was started at 10:30 p.m. at a rate of 11 g/m² liquid NaCl, or 3 g/m² salt, onto the wet surface. Other roads were treated with prewetted NaCl at a rate of 5 g/m². The control roads were frozen at about 3:00 a.m. Salted roads remained wet (Figure 7). The road temperature at 10:00 p.m. was 2.5°C (36.5°F), and skies were partly clear.

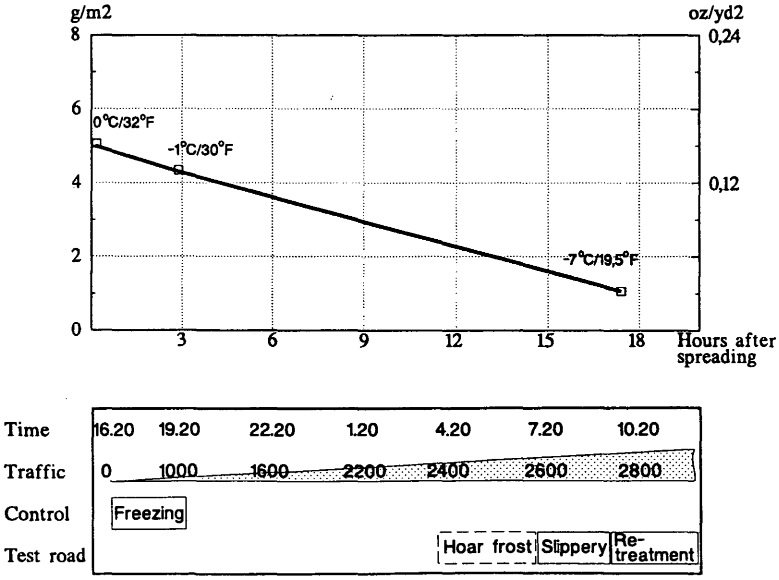


FIGURE 5 Average salt residues on November 16, 1991.

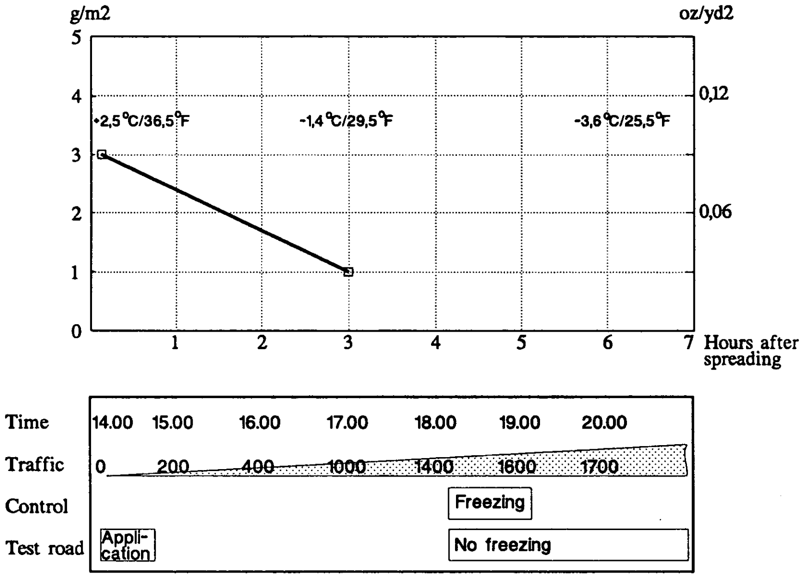


FIGURE 6 Average salt residues on November 22, 1991.

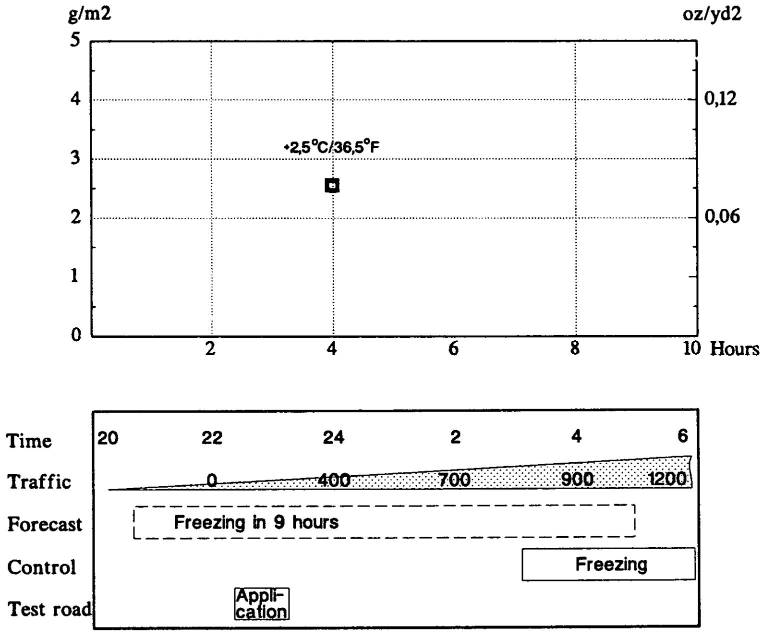


FIGURE 7 Average salt residues on November 23, 1991.

Case 4: November 11, 1991, Karstula

At 7:30 p.m. the forecast was for snowfall in 3 hr. Liquid $CaCl_2$ application took place between 8:15 and 8:30 p.m. on the test section. It was applied to a dry surface. The section length was 9 km (5.6 mi), and the application rate was 34 g/m² brine, or 11 g/m² salt, to a width of 3.1 m (10 ft) for both of the lanes. The salt measurements were done on the test road only. The bare- and wet-pavement condition on the test section was achieved earlier than on the control section, because no salting was needed because of slipperiness. The details are shown in Figure 8.

Other Anti-Icing Experiences

Prewetted NaCl was used in the Orivesi area for anti-icing purposes on some of the highway sections because the liquid spreader did not have time to cover all of the highways. The application rate used was 5 g/m², which normally worked well. In an interview about the 1990–1991 winter, the supervisors said that they used a liquid for preventive salting in 10 percent of the liquid applications. The temperature range was from 0°C (32°F) to a little below freezing. Treatments were done under dry, moist, and rainy conditions. Rates varied between 15 and 20 g/m² liquid. No failures were reported.

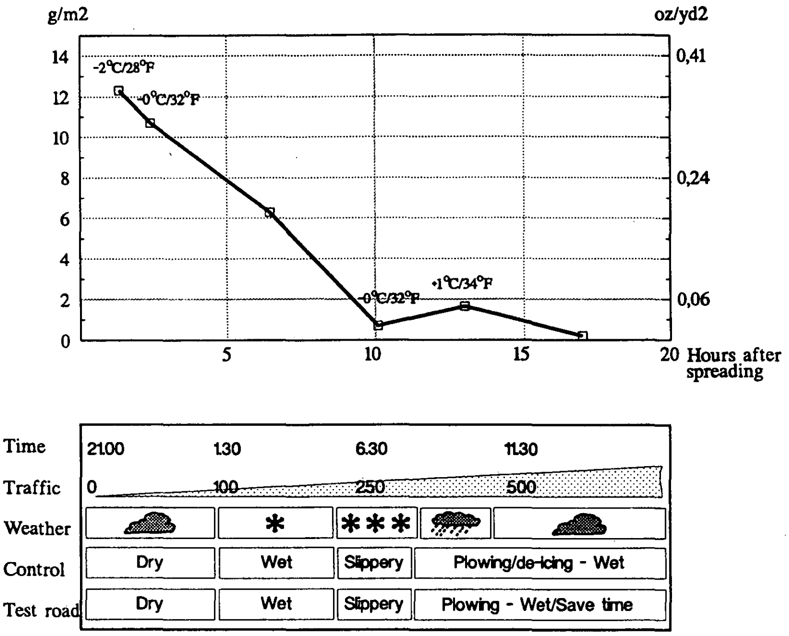


FIGURE 8 Preventive treatment with liquid $CaCl_2$ in Karstula. Reapplication was not required on test section to maintain residue; on other section prewetted salt was required to restore bare pavement.

The Raahe maintenance area used prewetted NaCl mainly as a preventive treatment for black ice. The night patrolman started the treatment at about 11:00 p.m. at 50 km/hr (30 mph). The salt had to be dripping wet. Spreading rates were 3 to 7 g/m^2. During the morning hours the operator checked the result to avoid refreezing. Salt was reapplied where needed. They were very confident and satisfied with this method.

Salt Residue Tests in Various Areas

Case 5: NaCl/$CaCl_2$ Tests in Karstula, November 11, 1991, at 3:00 p.m.

Four test sections were used to compare saline residues of small and large quantities of NaCl and $CaCl_2$. Each section was placed 200 m (220 yd) long, and two were on the right-hand lane and two on the left-hand lane:

- Section 1: 22 g/m^2 liquid NaCl or 5 g/m^2 salt
- Section 2: 15 g/m^2 liquid $CaCl_2$ or 5 g/m^2 salt
- Section 3: 51 g/m^2 liquid NaCl or 12 g/m^2 salt
- Section 4: 34 g/m^2 liquid CaCl or 11 g/m^2 salt

Case 6: Different Amounts in Hämeenlinna, November 6, 1991, at 9:30 a.m.

The application rates of 10 and 30 g/m^2 of prewetted NaCl were used to find out the spreading pattern at a width of 5 m (16.4 ft) and at a speed of 35 km/hr (22 mph). A spray bar spreader was used. Tests were carried out on Highway 57. The surface was moist all the time.

The aforementioned results are shown in Figures 9 and 10. Figure 11 describes saline residues within 3 hr. The difference in residues remained between the two applications. The measurements for the small application rate were done 10 to 15 min after the application, and those for the large rate, 30 to 35 min after application.

Case 7: Effect of Speed in Kankaanpää, April 1992

Prewetted NaCl was spread to the width of 5 m (16.4 ft) at the speeds of 30, 50, and 60 km/hr (19, 30, and 38 mph). The application rate was 20 g/m^2. The scatter patterns are shown in Figure 12. The higher the speed, the more salt was found on the shoulders. The highway was moist all the time. The residue measurements took place 5 min after the application for 30 km/hr, 15 min for 50 km/hr, and 20 min for 60 km/hr.

After about 250 vehicles—of which 25 percent were trucks—the salt residue on the road was about 30 percent of the original concentration within 3 hr. The spreading patterns show that the salt concentration was low in the middle of the truck spreading lane for the two higher speeds. The probable reason for this is a turbulence effect behind a truck and a straight current of air between the wheelpaths under the truck. The phenomenon should be examined further so as to make a sure judgment.

Other Results

The drivers and supervisors from the Finnish National Road Administration found testing useful for several reasons. They could get immediate feedback on their working methods, such as the effectiveness of adjustments to the devices, the proper spreading width, and the best possible driving line for optimum results.

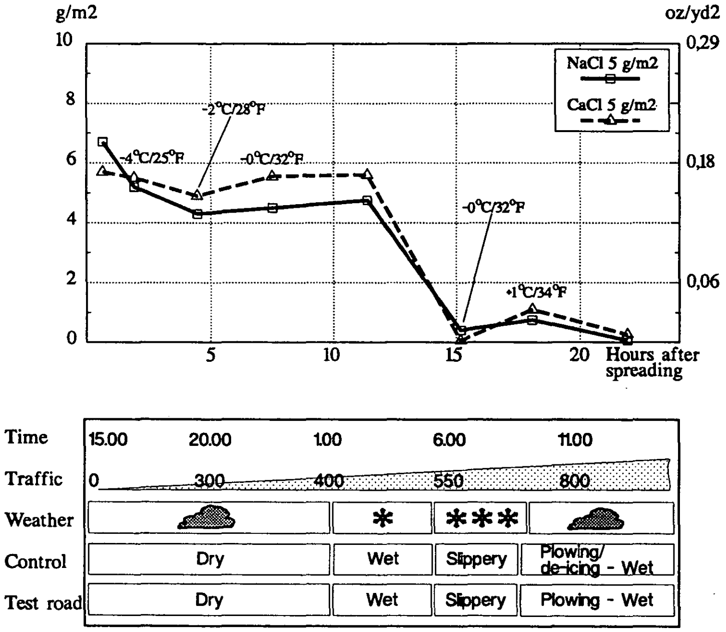


FIGURE 9 **No difference between residue of liquid NaCl and $CaCl_2$, regardless of application rate.**

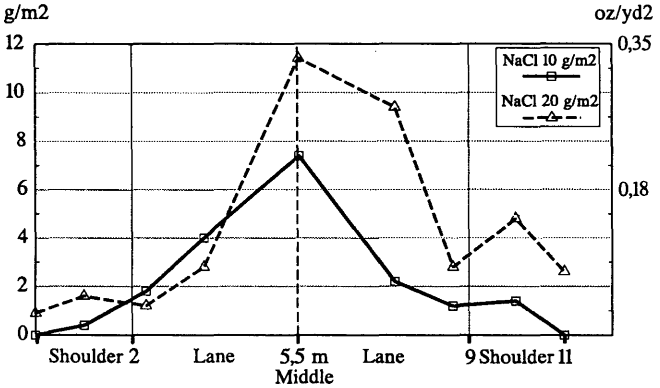


FIGURE 10 **Spreading patterns at different application rates.**

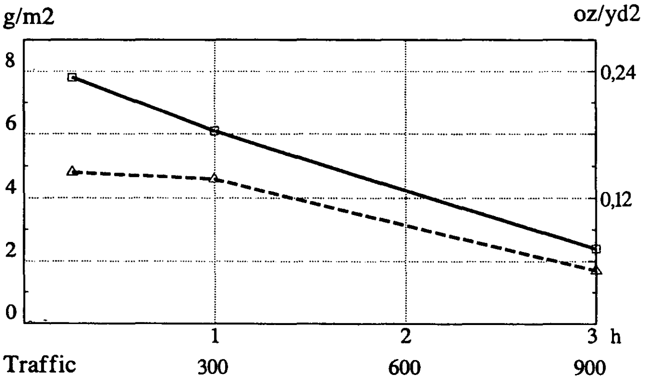


FIGURE 11 **Residues of prewetted salt at high and low application rates on roadway 7 m (23 ft) wide.**

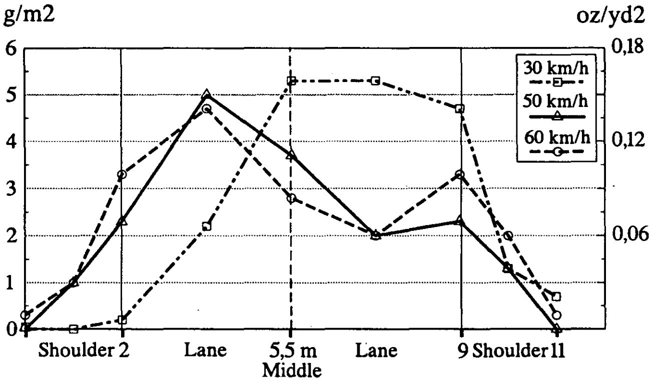


FIGURE 12 **Effect of speed with prewetted salt.**

CONCLUSIONS

Preventive chemical treatments improve safety for the motorists. If such activities are done with only minimum amounts of salt, road surfaces become moist and there is no splash phenomenon, resulting in a better image for the maintenance personnel.

Use of brines and prewetted materials decreases total salt application. Much of the dry salt flies or rolls away during spreading operations. The operations can be done in advance so that fewer emergency applications are needed.

If the temperature starts to decrease or surplus moisture occurs in a rain, snow, or hoar frost, brines dilute so much that the highways may refreeze; high amounts of preexisting moisture do the same (Tables 2 through 5). Malfunction of spreaders is possible. Frequent inspections of treated roads are necessary as well as checks of salt concentrations of brine

TABLE 2 Highway Moisture Description

Definition	Water g/m^2	Description
Little Moist	5 - 20	Detectably dark pavement
Moist	20 - 50	Clearly dark pavement
Wet	50 - 200	Spray phenomenon starts
Very Wet	200 - 400	Small drops of water in the air
Flowing	400 -	Flow according to gradient, splash

TABLE 3 Water Films and Corresponding Ice Thicknesses

Water (g/m^2)	Ice Thickness(mm)
10	0,01
30	0,03
100	0,10
300	0,30
500	0,50

A typical ice thickness of salted roads is 0,02-0,2 mm.

just before loading. A failure in these obligations can lead to unpleasant surprises.

Trying to minimize the use of salt through liquids increases costs, because of investments in equipment and a more frequent need for reapplications.

Prewetted salt flies away almost as easily as dry salt if there is much heavy traffic on the highway. However, if salt is dripping wet, it is less obvious.

High application rates disappear faster from the highways than small ones, over a period of time and traffic. Quite often a rapid decrease in salt residues can be seen very soon after the application; then the residues are decreased much more slowly (Figures 13 through 19).

Conclusions for preventive treatments drawn here are based on an insufficient number of tests because of the weather conditions during the test period. Yet all the tests were successful in preventing ice from forming or causing snow to melt right after plowing. The tests consisted of two important elements: salt residue measurements and visual checks (no friction measurements) of whether the road was icy, dry, or moist. Experiences in many Finnish road maintenance areas support the test results.

TABLE 5 Freezing Points for Liquid NaCl (23%) Spread on Road

		Freezing points by liquid (g/m^2)				
Description	Water (g/m^2)	5	10	20	40	
Little Moist	10	-5	-6	-10	-16	°C
		23	21	14	3,2	°F
Moist	30	-1	-4	-5	-9	°C
		30	25	23	16	°F
Wet	100	0	-1	-2	-4	°C
		32	30	28,4	25	°F
Very Wet	300	0	0	0	-2	°C
		32	32	32	28,4	°F
Flowing	500	0	0	0	0	°C
		32	32	32	32	°F

When there is a lot of water on the road surface, liquid salts should not be applied because of dilution.

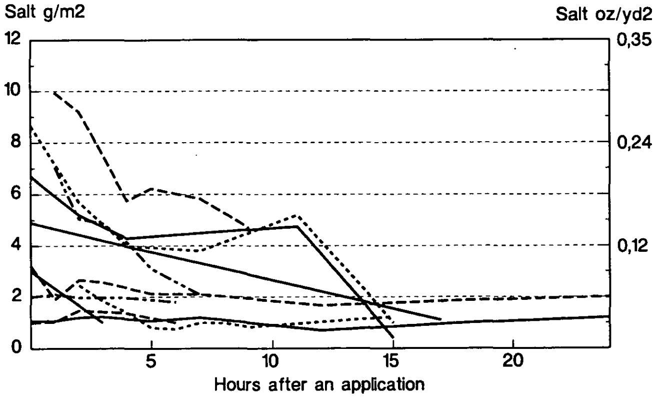


FIGURE 13 NaCl residues in relation to hours, all liquid NaCl tests.

RECOMMENDATIONS

Some preliminary recommendations can already be given. Anti-icing treatments are recommended, if weather forecasts predict black ice. The main method is liquid application. It is also obvious that good working speeds are as follows:

- Maximum of 30 km/hr (20 mph) for dry, granular salt;
- 30 to 40 km/hr (20 to 25 mph) for prewetted salt;
- 40 to 55 km/hr (25 to 35 mph) for liquids with spinner spreaders; and
- 50 to 70 km/hr (30 to 45 mph) for liquids with spray bar spreaders.

TABLE 4 Freezing Points According to Moisture and Salt Content

		Freezing points by salt (g/m^2)					
Description	Water (g/m^2)	2	5	10	20	30	
Little Moist	10	-16	-21	-21	-21	-21	°C
		3	-6	-6	-6	-6	°F
Moist	30	-3	-10	-21	-21	-21	°C
		26,6	14	-6	-6	-6	°F
Wet	100	-1,5	-2,5	-7	-11	-21	°C
		29	27,5	19,4	12	-6	°F
Very Wet	300	-0,4	-1	-2	-3,5	-5	°C
		31	30	28,4	26	23	°F
Flowing	500	-0,1	-0,4	-1,5	-2	-3	°C
		31,8	31,3	29	28,4	26,6	°F

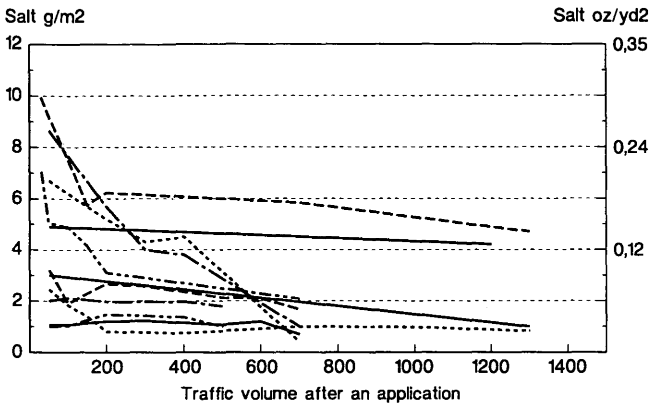


FIGURE 14 NaCl residues in relation to traffic volume, all liquid NaCl tests.

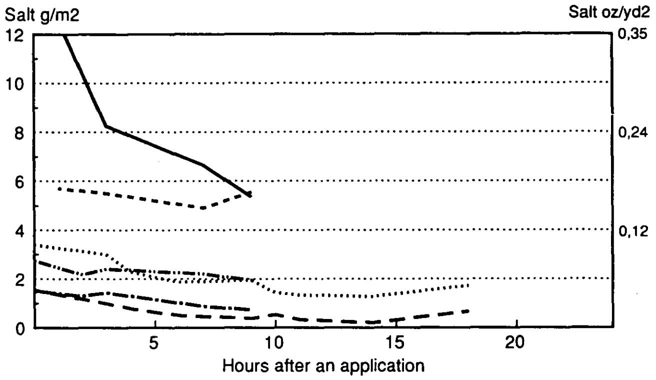
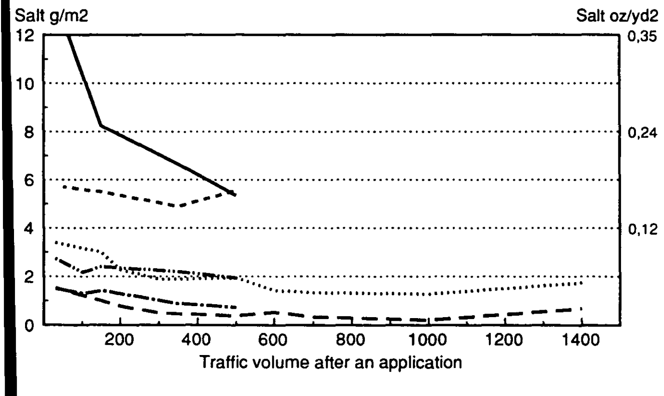


FIGURE 15 CaCl residues in relation to hours, all liquid CaCl tests.



IGURE 16 CaCl residues in relation to traffic volume, all iquid CaCl tests.

Narrow spreading patterns with dry and prewetted salts are ecommended over the use of broad ones. For black ice the eed should be directed to the middle of the highways. Acording to the test results, preventive treatment is efficient r black ice with very small application rates: about 2 to 3 /m^2 salt. These amounts can be reached accurately only in liquid form: about 10 g/m^2 NaCl liquid. Because of the efreezing risks, treatments must be carefully controlled.

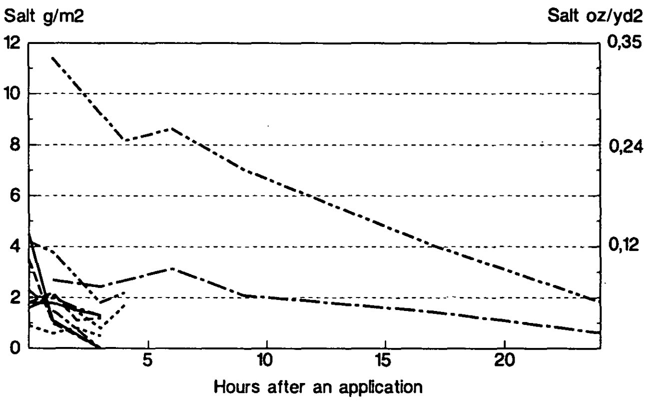


FIGURE 17 NaCl residues in relation to hours, all prewetted NaCl tests.

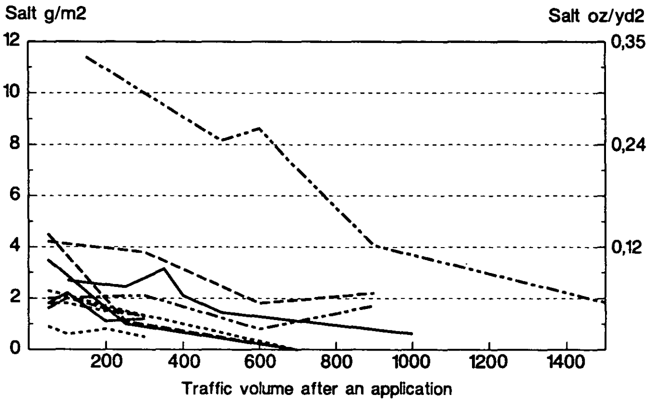


FIGURE 18 NaCl residues in relation to traffic volume, all prewetted NaCl tests.

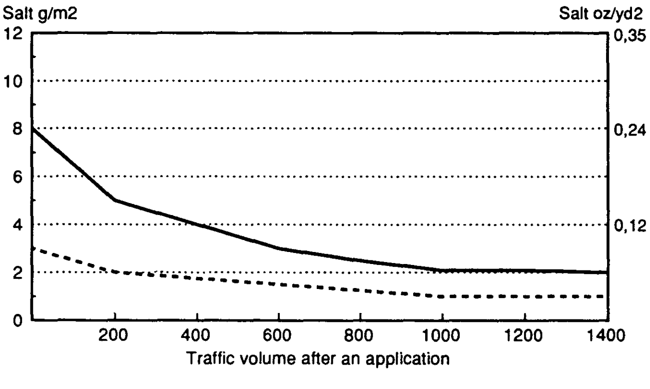


FIGURE 19 Estimated average salt residues in relation to traffic volume for moist but drying road surface.

Anti-icing can be done with brines and prewetted salts. There is practically no difference at all between liquid NaCl and $CaCl_2$ in decrease of residues. Even the small amounts of calcium chloride can keep the surfaces a little dark (moist) for 1 to 2 days.

It is not recommended to apply liquid salt during snowstorms. If done, the operations must be executed by plowing units. Second treatments follow during the next plowing cycles, when needed. According to experiences, this method creates less slush. It is useful to apply salt at the beginning of a snowfall to prevent the snow from adhering to the surface.

Preventive actions for black ice can be done at least 6 hr before forecasted freezing. Changes in weather must be taken into account, especially precipitation. Anti-icing applications can be done with both spinner and spray bar spreaders. Frequent calibration of spreading equipment is necessary.

Both a good training program and motivated personnel are required to succeed.

REFERENCE

1. T. Raukola and K. Vaani. *Field Tests for Liquid and Prewetted Salt Application* (in Finnish). Report 1/1993. Finnish National Road Administration, Tampere, 1993.

Trade-Off Analysis of Nonenvironmental Effects of Alternative Deicers: An Illinois Case Study

CHRIS D. GINGRICH, SARAHELEN R. THOMPSON, ROBERT J. HAUSER, AND J. WAYLAND EHEART

The material, storage, and application costs of salting are low. However, these direct costs understate total costs since salt also damages vehicles, highway structures, and possibly the environment. A framework for estimating the total nonenvironmental costs of deicers is presented, including costs of materials, vehicular damage, and highway structural damage. In addition to salt, the deicers considered are calcium magnesium acetate (CMA), calcium chloride, potassium chloride, urea, methanol, salt with added carboxymethylcellulose, salt mixed with potassium chloride, and salt mixed with urea. Ranking the deicers on the basis of lowest total (nonenvironmental) cost indicates that methanol may be the most attractive deicer for use in Illinois, although more study is needed of methanol's application costs, effectiveness, and dangers. After methanol, salt and salt mixtures are least expensive. CMA is more costly than all other deicers but urea. The cost of CMA and methanol is much higher than the other deicers if vehicle protection costs are not included in the evaluation criteria. In addition, the two deicers that do not harm highway structures, CMA and methanol, are found to be not cost-effective for spot application on concrete bridge decks relative to salt. This is because a significant distance extending beyond the bridge must be treated with CMA or methanol to prevent salt from splashing onto a bridge. Thus, the additional material costs of methanol or CMA are greater than the resulting savings in bridge repair costs.

An issue that is receiving much attention from highway administrators and researchers is the practice of deicing winter roads. The direct costs of salting—involving materials, storage, and application—are low. However, the direct costs understate total costs because salt also damages vehicles, highway structures, and possibly the environment. Murray and Ernst estimate that the total cost may be up to 15 times as great as the direct material costs, excluding environmental damage (*1*). Highway administrators are thus investigating other approaches to maintain winter roads that are potentially less expensive (in an overall societal sense). One such approach is the use of alternative deicers, such as calcium magnesium acetate (CMA), that presumably cause less damage to vehicles, highway structures, and the environment.

This paper presents a framework for estimating the nonenvironmental costs of deicer use, including material, vehicular, and highway structural costs. The cost estimates provide a method of ranking deicers. The framework is used to assess the economics of spot-applying alternative deicers to Illinois bridges. In addition to salt (NaCl), the deicers considered are CMA, calcium chloride ($CaCl_2$), potassium chloride (KCl), urea, methanol, salt with added carboxymethylcellulose (salt/CC), salt mixed with potassium chloride (salt/KCl), and salt mixed with urea (salt/urea). Environmental effects of alternative deicers are discussed by Eheart et al. in another paper in this Record and by Thompson et al. (*2*).

APPROACH OF STUDY

A restriction imposed throughout the analysis is that the level of deicing effectiveness is maintained at the level currently achieved with salt in Illinois. The restriction is imposed for two reasons: first, in Illinois, and in many other snow-belt states, primary roads are maintained under a bare-pavement policy whenever possible. In Illinois, the bare-pavement policy is enforced on all state roads. Thus, the requirement of deicing effectiveness ensures that the framework reflects actual road maintenance policies. Second, it is necessary to restrict one of the variables (deicing effectiveness, material costs, vehicle damage, or highway structural damage) to compare the costs of "unrestricted" variables. By holding deicing effectiveness constant, it is not necessary to estimate the traffic and safety costs of deicers at different levels of deicing effectiveness—a task beyond the scope of this study.

MATERIAL COST ESTIMATES

Material cost estimates of deicer use are based on salting practices in Illinois. To predict salting rates throughout the state, a regression model was developed. County data for total annual salt use on state roads for two winter seasons (1988–1989 and 1989–1990) were used to estimate the model. Although there are 102 counties in Illinois, data from only 85 and 96 counties are used in the model's estimations for 1988–1989 and 1989–1990, respectively. Salt data for the remaining counties were either missing or combined with another county.

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After investigating several alternatives, the following specification was chosen:

$$\mathrm{SALT}_{it} = a_1 + a_2\mathrm{SNOW}_{it} + a_3\mathrm{AVEMAX}_{it} + a_4\mathrm{AVEMIN}_{it} + a_{5\text{-}12}\mathrm{DIST}_{1\text{-}8} + e_{it} \qquad (1)$$

where

SALT_{it} = salt applied on state roads in county i per season t (ton/lane-mi);
SNOW_{it} = total seasonal snowfall (in.);
AVEMAX_{it} = seasonal average of mean monthly high temperatures (°F); included are only those months in which total snowfall is greater than or equal to 1 in.;
AVEMIN_{it} = seasonal average of mean monthly low temperatures (°F); included are only those months in which total snowfall is greater than or equal to 1 in.; and
DIST = binary variables indicating county's Illinois Department of Transportation (IDOT) district; values of district variables are set equal to 1 when in that district, otherwise 0. There are 9 districts in Illinois, with District 9 set as base district.

Estimation results are presented in Table 1 ($N = 181$). The R^2 (.816) indicates that the model has a high level of explanatory power. The signs of all the variables conform with expectations, including the temperature variables (mean values for AVEMAX and AVEMIN are 5.6 and -5.3°C, respectively).

The district binary variables are believed to capture the effect of both management practices and traffic. This was borne out by preliminary regression estimates that show traffic to be an insignificant variable when estimated along with the district variables. The traffic variable is the average daily vehicle miles for each county divided by the total number of lane miles in the county. The result is a standardized traffic variable that reduces the variation in traffic arising from multiple-lane highways. Each county's standardized traffic variable is then multiplied by the proportion of state lane miles that make up the county's total lane mileage. This yields a standardized approximation of traffic on state roads. When traffic was included without the district variables, the estimated coefficient on traffic was significant and positive, suggesting that in Illinois heavy traffic causes increased salt applications. However, this particular specification of the model had a substantially lower R^2 than the final specification in Equation 1.

To predict an average annual salting rate for a given region, average weather data may be inserted into the model. Complete historical data for each weather variable are not available for all counties in Illinois, but at least one county in each district contains a complete set of weather data. Twenty-year averages for AVEMAX, AVEMIN, and SNOW are computed from these counties and inserted into the model to obtain districtwide application rates. These rates range from 1.50 Mg/km (2.66 tons of salt per lane mile) in southern Illinois to 9.81 Mg/km (17.41 tons per lane mile) in the district containing Chicago. The weighted average annual rate for Illinois is 4.85 Mg/km (8.61 tons per lane mile).

Application rates for the alternative deicers are estimated from the annual salting rates by using substitution rates relative to salt found in the literature (Table 2). Unit prices of each deicer are also presented in Table 2.

Estimates of the storage and application costs of each deicer are based on several approaches suggested in the literature. For salt, Murray and Ernst (*1*) and Bacchus (*3*) assume that storage and application costs are equal to half the cost of purchased materials. For the alternative deicers, Dunn and Schenk (*4*) estimate storage and application costs by adjusting the multiplication factor used for salt (0.5) by each deicer's relative density—the factor most likely to affect storage and application costs. Following the approach of Murray and Ernst and Bacchus, the storage and application costs of salt are assumed to equal half the cost of purchased materials. However, for the alternative deicers, instead of following the exact approach of Dunn and Schenk, this study estimates storage and application costs by adjusting the storage and application cost for salt by the relative density of each deicer (Table 2).

The predicted salting rates and the substitution ratios, purchase prices, and storage and applications costs (Table 2) yield the estimated annual material cost per lane kilometer for each deicer in Illinois. Multiplying the costs per lane kilometer by the number of state lane kilometers yields the estimated an-

TABLE 1 Estimation of Illinois Salt Application Model

Independent Variable	Estimated Coefficient	Standard Error	t Statistic
SNOW	0.054565	0.024571	2.22
AVEMAX	-0.23751	0.066805	-3.56
AVEMIN	0.20216	0.069703	2.90
DIST1	12.831	0.95953	13.37
DIST2	5.6738	0.85711	6.62
DIST3	4.8533	0.75127	6.46
DIST4	2.3456	0.83593	2.81
DIST5	1.4857	0.64465	2.30
DIST6	1.2297	0.69525	1.77
DIST7	0.26447	0.61084	0.43
DIST8	1.7167	0.70251	2.44
CONSTANT	7.1675	1.9784	3.62

TABLE 2 Estimated Substitution Ratio, Unit Price, Density, and Storage and Application Costs of Deicers

Deicer	Substitution Ratio by Weight (relative to salt)	Price ($/Mg)	Density (kgs./m^3)	Storage and Application Costs($/Mg)
Salt	1:1	$24	1,135	$12.10
CMA	1.5:1	$682	746	$18.41
$CaCl_2$	0.77:1	$182	892	$15.40
KCl	1.41:1	$116	1,297	$10.59
Urea	2.19:1	$176	1,329	$10.30
Salt/CC	0.97:1	$58	973	$14.11
Salt/KCl	1.22:1	$68	1,167	$11.76
Salt/Urea	0.91:1	$33	1,216	$11.30
Methanol	1.19:1	$200	794	$17.25[a]

[a] Storage and application costs do not include the costs of new equipment needed to handle liquid methanol.

SOURCES:

Substitution Ratios—CMA (*19,20*), methanol (*4*), all others (*21*). Substitution rate for CMA is based on field tests, substitution rate for methanol is based on methanol's chemical composition, and substitution rates for remaining deicers are based on ice melting tests conducted at -3.89°C for 30 min.

Prices—Salt (*22*), CMA (Chevron Chemical Co., unpublished data), all others [bulk prices of chemical compounds (*23*)]. Price of mixed deicers is obtained by assuming that deicers are combined in same proportion as described by McElroy et al. (*21*).

Density—Salt and CMA (Chevron Chemical Co., unpublished data), methanol and urea (*24*), all others [information from manufacturers (*21*)].

nual material costs of each deicer on state roads in Illinois. The estimated annual material costs per lane kilometer and on state roads by district are given in Table 3. Table 3 shows that salt has the lowest average annual material costs, estimated to be $176/lane-km. CMA has the highest average annual material costs at $5,099/lane-km.

VEHICULAR COST OF SALTING

To estimate the vehicular costs of road salting, this study follows an approach developed by Menzies (*5*) and TRB (*6*). Several other studies have also estimated the costs of vehicular salt damage (*1,6,7*), but the Menzies and TRB approaches best capture recent changes by manufacturers to improve the corrosion resistance of vehicles. Following these approaches, the vehicular costs of salting may be divided into two components: protection costs and damage costs. Protection costs are the added costs of inputs that inhibit corrosion. Damage costs are equal to reductions in resale value caused by salt damage. However, since vehicles are no longer as susceptible to corrosion as they were 10 years ago (*8*), vehicle damage from salt occurs only in the form of minor cosmetic corrosion.

To estimate the costs of corrosion protection, TRB obtained estimates from manufacturers for the added cost of improved coatings, paints, panels, and other measures designed to reduce vehicle corrosion (*6*). The estimates range from $250 to $800/vehicle for typical late-model cars or, at midpoint, about $500/vehicle. However, not all of the costs of corrosion protection may be attributed to salt. Other factors such as sea spray, acid rain, and air pollution also cause vehicle corrosion. Hence, even if road salting were eliminated it is unlikely that the amount of corrosion protection added by manufacturers would significantly decrease. In light of these issues, based on discussions with motor vehicle manufacturers, TRB estimated that savings in the cost of corrosion protection would be $125 to $250/vehicle if salt (and calcium chloride) were no longer used for highway deicing. These savings would largely result from the reduced application of galvanized steel. In this study, an estimate of $200/vehicle is assumed to be the amount of protection cost per vehicle attributable to salt.

To estimate the vehicular damage costs of salt, Menzies compares rates of vehicle depreciation in three areas of the United States with different salting practices (*5*). New England is chosen as a region with high salting rates, the Mid-Atlantic as a region with moderate salting rates, and the Southeast as a region that does not use road salt. Menzies acknowledges that the approach is a simplification in that it ignores the effect of regional incomes, pollution, and the fact that vehicles may be traded between regions. Nonetheless, the average annual depreciation rates of automobiles in New England, the Mid-Atlantic, and the Southeast are estimated to be 15.9, 15.6, and 15.4 percent, respectively, which are consistent with the rates expected from the regional salting practices. Applying the depreciation rates to the average price of a new car ($15,403) and the average vehicle age in the United States (7.6 years) yields annual salt damage costs of $25/vehicle in New England and $10/vehicle in the Mid-Atlantic or, on average, about $17/vehicle.

The estimates of the costs of vehicle protection and damage from road salt may be applied to Illinois. The protection cost per vehicle ($200) is multiplied by the number of new cars

TABLE 3 Estimated Annual Material Costs of Deicers on State Roads in Illinois, by District

Deicer:	District:									Average Cost per Lane km	Illinois Total
	1	2	3	4	5	6	7	8	9		
Salt	$357 $5,535	$208 $1,671	$175 $1,471	$129 $655	$113 $855	$91 $741	$63 $324	$98 $664	$55 $234	$176	$12,150
CMA	$10,309 $160,188	$6,016 $48,368	$5,063 $42,582	$3,731 $18,966	$3,292 $24,737	$2,641 $21,449	$1,806 $9,370	$2,837 $19,218	$1,575 $6,776	$5,099	$351,653
$CaCl_2$	$1,488 $23,116	$868 $6,980	$730 $6,145	$538 $2,737	$475 $3,570	$381 $3,095	$260 $1,352	$409 $2,773	$228 $978	$736	$50,746
KCl	$1,745 $27,107	$1,018 $8,185	$857 $7,206	$631 $3,209	$557 $4,186	$447 $3,630	$306 $1,585	$480 $3,252	$267 $1,147	$863	$59,506
Urea	$4,003 $62,207	$2,336 $18,783	$1,966 $16,536	$1,449 $7,365	$1,278 $9,606	$1,025 $8,330	$701 $3,639	$1,102 $7,463	$612 $2,631	$1,980	$136,561
Salt/CC	$687 $10,674	$401 $3,223	$337 $2,838	$249 $1,264	$219 $1,648	$176 $1,429	$120 $624	$189 $1,281	$105 $452	$340	$23,433
Salt/KCl	$999 $15,521	$583 $4,686	$490 $4,126	$361 $1,838	$319 $2,397	$256 $2,078	$175 $908	$275 $1,862	$153 $657	$494	$34,072
Salt/Urea	$398 $6,188	$233 $1,869	$195 $1,645	$144 $733	$127 $956	$102 $829	$70 $362	$110 $742	$61 $262	$197	$13,585
Methanol	$2,536 $39,397	$1,480 $11,896	$1,245 $10,473	$918 $4,665	$810 $6,084	$650 $5,275	$444 $2,304	$698 $4,726	$388 $1,667	$1,254	$86,487

The first number in each cell is the cost per lane km in dollars. The second number is the cost on state roads in thousand dollars.

and trucks bought each year. Data are available for the entire state only. Vehicle sales in each district are estimated by the proportion of registered vehicles in each district. The annual damage cost per vehicle ($17) is multiplied by the number of registered cars and trucks in each district. Adding the annual vehicular protection and damage costs yields more than $266 million: $145 million for protection costs and $121 million for damage costs (Table 4).

HIGHWAY STRUCTURAL DAMAGE

Two methods are used to estimate the amount of highway structural damage caused by salt in Illinois. First, the method developed in the TRB study (*6*) is used to estimate the annual costs of salt damage to concrete bridge decks. Second, a model of bridge deck deterioration, as suggested by Vitaliano (*7*), is used to determine the impact of salt on bridge deck con-

TABLE 4 Annual Vehicular Costs of Salt in Illinois, by District

District	Protection Costs	Damage Costs	Total
1	$74,195	$59,985	$134,181
2	$14,314	$12,025	$26,339
3	$9,213	$7,785	$16,998
4	$8,343	$7,067	$15,410
5	$9,461	$8,059	$17,520
6	$9,381	$8,038	$17,420
7	$4,964	$4,324	$9,288
8	$11,125	$9,423	$20,548
9	$4,633	$4,008	$8,640
Total	$145,629	$120,714	$266,343

NOTE: Costs given in thousands of dollars.

dition, predict the life of a bridge deck, and compute the cost of salting to bridge decks in present-value terms. Finally, both approaches are used to assess the economics of spot-applying alternative deicers on bridges.

This section focuses on concrete bridge decks, since they are the highway structural component most vulnerable to salt damage (*9,10*). In particular, concrete bridge decks are vulnerable to spalling, which occurs when chloride ions penetrate reinforced concrete and cause steel reinforcing rebars to corrode and rupture the surrounding concrete. Highways and other bridge components are much less susceptible to salt damage than concrete bridge decks because they are built with less reinforcing steel and receive lesser amounts of salt.

The TRB approach separates salting costs into two components: protection costs and damage costs. Bridges constructed with inputs such as epoxy-coated rebars, concrete overlays, or interlayer membranes are highly resistant to spalling. The cost of these inputs may be attributed to salt. It would not be reasonable to attribute all of the costs of deck protection to salt in coastal areas where sea spray also causes spalling. To estimate the annual costs of protecting bridge decks against salt damage, the number of bridges built per year and their average area are multiplied by the cost per square foot of installing corrosion protection. In Illinois, epoxy-coated rebars are the primary method of bridge deck protection. With the cost of epoxy coating estimated at $18.17/m^2 ($1.69/ft^2), the annual cost of protecting bridges against salt damage in Illinois is estimated (Table 5). The cost of epoxy coating comes from Babaei and Hawkins (*11*), adjusted for inflation at an annual rate of 4 percent.

To estimate the costs of repairing salt damage on bridge decks, the TRB study focuses on bridges that are susceptible to damage from current salt applications. Such bridges are not constructed with corrosion protection, show no visible signs of salt damage, and are not contaminated with chloride ions. In this study a bridge is considered protected if it was built with either epoxy-coated rebars or a concrete protection system including low-slump, polymer-impregnated, or latex-modified concrete (*11*). It is assumed that an unprotected bridge exposed to salt for more than 10 years is already contaminated with chloride ions even if it shows no visible signs of damage. The number of bridges that will become damaged over the next 10 years is predicted by multiplying the proportion of unprotected bridges (10 to 20 years old) with deck damage by the number of bridges susceptible to current salt applications. Bridge deck condition is rated by FHWA on a scale of 0 to 9, with 9 indicating a deck in perfect condition. In this study a deck is considered damaged if it has a rating of 6 or less. Multiplying the number of bridges expected to become damaged by their average area yields the total bridge deck area that will need repair over the next 10 years. Dividing the total area by 10 yields the annual area requiring repair. Applying the approach to Illinois with an estimated repair cost of $215/m^2 ($20/ft^2) yields the estimated annual cost of bridge deck damage from salt (Table 6). The annual costs of applying salt on Illinois bridges are estimated with the TRB approach to be $4 million to protect new bridges and $5 million to repair existing salt damage.

The second method of estimating salt damage to concrete bridge decks is based on a model of bridge deck deterioration, as suggested by Vitaliano (*7*). The deck deterioration model was estimated with different specifications using a procedure for ordinally ranked, limited dependent variables as suggested by McKelvey and Zavoina (*12*). Bridges included in the model have a reinforced concrete deck, are maintained by the state, and were built or reconstructed after 1970. The following specification produced the best model in terms of explanatory power and coefficient significance:

$$C = a_1 + a_2\text{AGE} + a_3\text{ADT}^2 + a_4\text{AGESALT} + a_5\text{DPROT} + e \qquad (2)$$

where

C = present bridge deck condition rating represented by index value of integers 0 through 9;

TABLE 5 Estimated Annual Costs of Protecting Concrete Bridge Decks from Salt in Illinois, by District

District	Ave. Area of Bridges Built, 1980-1989 (m^2)	Ave Number of Bridges Built per Year, 1980-89	Annual Protection Cost Against Salt Damage ($18.17 per m^2)
1	1,432	35.4	$921,946
2	377	70.2	$481,285
3	341	70.8	$438,822
4	451	40.3	$330,543
5	232	77.3	$326,684
6	373	68.0	$461,487
7	226	53.9	$221,866
8	798	39.1	$567,673
9	199	43.5	$157,723
Total	431	498.5	$3,905,791

TABLE 6 Estimated Annual Bridge Deck Damage from Salt in Illinois, by District

District	No. of Unprotected Bridges, Built 1980-89, No Deck Damage	Ave. Area of Susceptible Bridges (m^2)	Unprotected 10-20 Year Old Bridges with Damage	Estimated Annual Damage Costs From Salt at \$215 per m^2
1	180	943	39%	$1,423,937
2	554	354	27%	$1,138,304
3	550	237	8%	$224,224
4	341	456	21%	$701,778
5	715	228	9%	$315,701
6	569	327	16%	$639,465
7	440	202	23%	$439,208
8	285	414	30%	$761,634
9	379	202	11%	$181,435
Total	4,013	320	18%	$4,969,699

AGE = current age of bridge or, if rebuilt, number of years since reconstruction;
ADT^2 = average daily traffic (ADT) on bridge, in number of cars and trucks squared;
AGESALT = AGE variable multiplied by average annual tons of salt per lane mile. Salting rates are assigned according to bridge's respective IDOT district as predicted from salt application model (Table 2);
DPROT = binary variable equal to 1 if bridge was built with epoxy-coated rebars, and equal to 0 otherwise; and
e = error term.

The estimation results are as follows (t-statistics for each coefficient are in parentheses):

$$\begin{aligned} C = \underset{(35.27)}{7.62} - \underset{(-13.91)}{.074\text{AGE}} - \underset{(-6.15)}{1.14 \times 10^{-10}\text{ADT}^2} \\ - \underset{(-6.41)}{.0029\text{AGESALT}} + \underset{(14.04)}{1.007\text{DPROT}} \end{aligned} \quad (3)$$

The signs of all the variables are consistent with the expected results and are highly significant. However, much of the variation in bridge deck condition is unexplained by the model ($R^2 = .276$, $N = 1{,}879$). The most likely explanation for this phenomenon is the omission of factors affecting deck condition that could not be quantified.

Equation 2 may be solved for the value of AGE equal to the number of years (LIFE) needed to reach a given deck condition (C).

$$\text{LIFE} = (C - a_1 - a_3\text{ADT}^2 - a_5\text{DPROT})/(a_2 + a_4\text{SALT}) \quad (4)$$

Equation 4 allows the cost of salt damage to bridge decks to be measured in terms of the present-value cost of expected deck repair. Future repair costs are discounted by a bridge's predicted life at a given salting rate and at zero salt conditions. The difference between the two costs provides a measure of the present-value cost of salt damage to bridge decks. Inserting the predicted Illinois salting rates, mean values for ADT^2 and DPROT, and a critical deck condition of 6 into Equation 4 yields present-value estimates of salt damage on bridge decks in Illinois (Table 7). The cost of deck repair is again assumed to be \$215/m^2 (\$20/ft^2, as in the TRB approach) and the discount rate is chosen at 7 percent per year. The results obtained from the deck deterioration model show that the average salt damage per square meter of bridge deck in Illinois, measured in present-value terms, is estimated to be \$21.40. The estimates range from \$6.99 to \$39.35/m^2 (\$0.65 to \$3.66/ft^2) across districts due to variations in the salting rate.

SPOT APPLICATION OF ALTERNATIVE DEICERS ON BRIDGES

A review of the literature suggests that two alternative deicers—CMA and methanol—do not damage bridges (*4,13,14*). Moreover, a comprehensive analysis of CMA damage (*15*,p.90) indicates that "asphalts, plastics, elastomers, ceramics, wood, sign sheetings and paints, rubber compounds, sealers, and adhesives appeared to be either unaffected by solutions of sodium chloride or calcium magnesium acetate, or similarly affected," and that salt causes corrosion problems whereas CMA does not. However, both of these deicers have material costs higher than that of salt. For either CMA or methanol to be cost-effective for spot application on bridges, their additional material costs must be less than the resulting savings in bridge repair costs.

The TRB approach of estimating the annual costs of salt damage on bridges does not address the question of spot-applying alternative deicers on bridges. However, the concepts underlying the TRB approach may be extended to assess spot applications by comparing the annual repair costs of salt damage with the additional material costs of using CMA and methanol on bridges susceptible to salt damage.

TABLE 7 Estimated Present Value of Salt Damage to Concrete Bridge Decks in Illinois, by District

District	Salting Rate (ann. Mgs/lane km)	Life (years)	Present Value of Deck Repairs (per m^2)	Present Value of Salt Damage (per m^2)
1	9.75	14.50	$80.63	$39.35
2	5.69	17.45	$66.01	$24.83
3	4.79	18.28	$62.46	$21.18
4	3.53	19.58	$57.19	$16.02
5	3.11	20.04	$55.36	$14.19
6	2.50	20.78	$52.68	$11.50
7	1.71	21.81	$49.13	$7.96
8	2.68	20.55	$53.54	$12.36
9	1.49	22.11	$48.16	$6.99
Illinois Average	4.82	18.25	$62.57	$21.39
Zero Salt	0.00	24.2	$41.17	$0.00

The additional material costs of CMA and methanol are obtained by subtracting the material costs of using salt on bridges susceptible to salt damage from the material costs of using CMA and methanol on those same bridges. The total bridge area susceptible to salt damage is taken from Table 6. Converting the total area from square meters to lane kilometers and applying the respective material costs per lane kilometer (Table 3) yields the annual material costs of salt, CMA, and methanol. The material costs of salt are then subtracted from the material costs of CMA and methanol. The potential savings in bridge damage from CMA and methanol use are equal to the estimated annual costs of salt damage in Table 6.

Two more costs would arise if CMA or methanol were spot-applied on bridges. First, labor and equipment costs would increase as road maintenance crews assigned spreaders and personnel to apply a single deicer selectively throughout a maintenance area. A rough estimate of these additional costs is found by increasing the application and storage costs of CMA and methanol by some factor. An arbitrary factor of 5 is used in this example. The second additional cost of spot-applying CMA or methanol on bridges stems from the distance extending from each bridge that must be treated with CMA or methanol so that salt applied on the highway does not splash onto the bridge. Evidence from actual spot application sites (Michigan Department of Transportation has spot-applied CMA on the Zilwaukee bridge near Saginaw since 1987) suggests that the minimum distance should be 1.61 km (1 mi). In this study, distances of 0, 15.25, 61, and 750 m (0, 50, 200, and 2,640 ft) are considered.

The financial assessment of CMA and methanol use on bridges using the TRB approach is presented in Table 8. The cost figures are the annual net savings of CMA and methanol use for spot applications on bridges. The assessment indicates that neither CMA nor methanol is cost-effective to apply on bridges if the minimum distance extending the bridge treated with CMA or methanol is 750 m. At a distance of 750 m, the use of CMA and methanol on bridges in Illinois results in annual net increases in expenditures of $80 million and $20 million, respectively. Only if the distance extending from a bridge requiring CMA or methanol is significantly reduced (to 15.25 and 61 m, respectively) does either CMA or methanol become cost-effective to apply on Illinois bridges.

The economics of spot-applying CMA and methanol on bridges may also be assessed with Vitaliano's deck deterioration model (*7*). Similar to the assessment using the TRB approach, the costs of salt damage are compared with the additional material costs of CMA and methanol. However, use of the deck deterioration model allows for the costs of salt damage and the additional material costs of CMA and methanol to be discounted over the expected life of a bridge to a present-value basis.

The net savings from CMA and methanol use are estimated in the following manner. The added material costs of CMA and methanol are converted to a present-value basis by discounting over the predicted bridge life under zero salt conditions a constant stream of additional annual material costs. An annual rate of 7 percent is used to discount the added material costs of CMA or methanol; this is the same rate used to discount future repair costs. The additional material costs, converted from kilometers to square meters, are then subtracted from the present value of the salt damage costs (Table 7) to obtain the present-value net savings from CMA and methanol use per square meter of bridge deck. The two additional costs of spot-applying CMA and methanol discussed for the TRB approach are also considered. The storage and application costs of CMA and methanol are multiplied by 5 to allow for added equipment and labor costs, and distances of 0, 15.25, 61, and 750 m are considered for the distance extending each bridge treated with CMA or methanol.

The assessment of spot-applying CMA and methanol on bridges using the deck deterioration model is presented in Table 9. The assessment shows that both CMA and methanol use on Illinois bridges results in increased expenditures if the distance extending the bridge treated with CMA or methanol is 750 m ($619 and $166/m^2, respectively, in present-value

TABLE 8 Estimated Annual Net Savings of Spot-Applying CMA and Methanol on Bridges in Illinois, by District

	Distance treated with CMA or methanol extending from each bridge (m)							
	0		15.25		61		750	
District	CMA	Meth	CMA	Meth	CMA	Meth	CMA	Meth
1	$911	$1,285	$685	$1,219	$9	$1,021	($10,997)	($2,207)
2	$801	$1,053	$525	$972	($302)	$729	($13,755)	($3,216)
3	$37	$178	($178)	$115	($824)	($74)	($11,338)	($3,157)
4	$542	$666	$441	$636	$138	$547	($4,787)	($897)
5	$169	$284	($11)	$231	($551)	$73	($9,342)	($2,505)
6	$509	$614	$392	$580	$42	$477	($5,652)	($1,193)
7	$399	$434	$342	$417	$170	$367	($2,623)	($453)
8	$672	$743	$607	$724	$413	$667	($2,750)	($260)
9	$152	$178	$109	$165	($23)	$127	($2,162)	($501)
Illinois	$3,115	$4,514	$1,491	$4,038	($3,378)	$2,610	($82,593)	($20,620)

NOTE: Savings given in thousands of dollars.

TABLE 9 Net Savings of Spot-Applying CMA and Methanol on Bridges in Illinois per Square Meter of Bridge Deck, by District, Using Deck Deterioration Model

	Distance treated with CMA or methanol extending from each bridge (m)							
	0		15.25		61		750	
District	CMA	Meth	CMA	Meth	CMA	Meth	CMA	Meth
1	$4.52	$30.00	($7.42)	$26.45	($43.12)	$16.02	($623.98)	($154.41)
2	$4.41	$19.25	($11.61)	$14.62	($59.89)	$.43	($844.09)	($229.57)
3	$4.09	$16.56	($10.11)	$12.47	($52.69)	($.11)	($745.05)	($203.12)
4	$3.33	$12.58	($4.84)	$10.22	($29.25)	$3.01	($426.56)	($113.55)
5	$3.01	$11.18	($9.68)	$7.42	($47.96)	($3.76)	($670.11)	($186.24)
6	$2.58	$9.14	($3.98)	$7.20	($23.76)	$1.40	($344.62)	($92.69)
7	$1.83	$6.34	($5.05)	$4.30	($25.91)	($1.83)	($364.95)	($101.29)
8	$2.69	$9.68	($1.29)	$8.60	($13.23)	$5.05	($207.53)	($51.94)
9	$1.61	$5.48	($5.16)	$3.55	($25.59)	($2.47)	($358.39)	($100.11)
Average	$4.09	$16.67	($7.74)	$13.23	($43.12)	$2.80	($619.03)	($166.02)

Figures in parentheses represent additional net costs.

terms). If the distance is decreased to 61 m, methanol becomes cost-effective. However, CMA becomes cost-effective only if the distance can be decreased to zero.

TOTAL COST OF DEICERS

Total cost estimates are obtained by adding the material, vehicular, and highway structural costs of each deicer. CMA and methanol are assumed not to harm vehicles and bridges (*4,13–15*); hence their total costs are equal to the costs of materials (purchase, storage, and application) only. The vehicle and bridge damage costs of the remaining deicers are assumed to be identical to those of salt. A review of the literature suggests that $CaCl_2$ and urea also damage vehicles and bridges, although not to the same extent as salt (*4,13,16,17*). There is no explicit mention of the effects of KCl in the literature review, but KCl is a metallic salt containing the chloride ion and thus is assumed to behave similarly to salt and $CaCl_2$. However, the amount of salt damage to vehicles and bridges varies little with changes in the salting rate once the concentration of salt reaches a certain level (*4*). Consequently, a slight reduction in salt use—as with a combination deicer containing salt—or the use of a slightly less damaging deicer would presumably not cause a significant decrease in the total amount of vehicle and bridge damage.

The material cost estimates for each deicer are based on applications on Illinois state roads only because salting rates on nonstate roads are unknown. Thus, material costs are somewhat understated. However, it should be emphasized that in order to assume zero vehicle or bridge damage costs for CMA and methanol, they must be applied on all roads and highways traveled by Illinois vehicles.

The sum of each deicer's material, vehicular, and highway structural costs is presented in Figure 1. The results suggest that for Illinois methanol is the lowest-cost deicer. The total annual cost of using methanol in place of salt is estimated to be \$90 million, although this does not include the unique application and storage costs associated with liquid methanol. However, even if the annual costs of methanol were to double as a result of higher application and storage costs, methanol would remain the lowest-cost alternative deicer. The total annual cost of current salting practices in Illinois (excluding environmental damage) is estimated at almost \$290 million. Combination deicers involving salt (salt/CC, salt/KCl, and salt/urea) are only slightly more expensive than salt alone, ranging between \$290 million and \$310 million in total annual costs. Among the remaining deicers, urea has the highest annual total cost, estimated to be more than \$410 million. CMA is the next most expensive deicer, with a total annual cost of \$351 million, which is entirely a function of its high material cost.

Further research into the use of methanol for deicing purposes should be undertaken before methanol can be considered a complete replacement for salt. Although preliminary laboratory and field testing of methanol indicates that it is an effective deicer (*4*), methanol evaporates very quickly and thus may be impractical for widespread use. Methanol is also a commonly used cleaning solvent. Therefore, its use may damage paint on vehicles. Tests by the Illinois Department of Transportation (*18*) indicate that heavy concentrations of methanol damage lacquer automobile paint but not enamel paint. Paint damage is ignored in this study but should be considered in future evaluations of methanol as a road deicer.

CONCLUSION

This paper presents a framework for estimating the total costs of deicers, including the costs of materials and damage to vehicles and highway structures. The framework is applied to Illinois. Ranking the alternative deicers on the basis of lowest total (nonenvironmental) cost indicates that methanol may be the most attractive deicer for use in Illinois, although more study is needed of methanol's application costs, effectiveness, and dangers. After methanol, salt and salt mixtures are the least costly deicers. CMA is more expensive than all deicers except urea. The cost of CMA and methanol is much higher than the other deicers if vehicle protection costs are not included in the evaluation criteria.

In addition, it was determined that the two deicers that do not harm highway structures—CMA and methanol—are not cost-effective for spot application on concrete bridge decks relative to salt. This is because a significant distance extending beyond the bridge must be treated with CMA or methanol to prevent salt from splashing onto a bridge. Thus, the additional material costs of methanol or CMA are greater than the resulting savings in bridge repair costs.

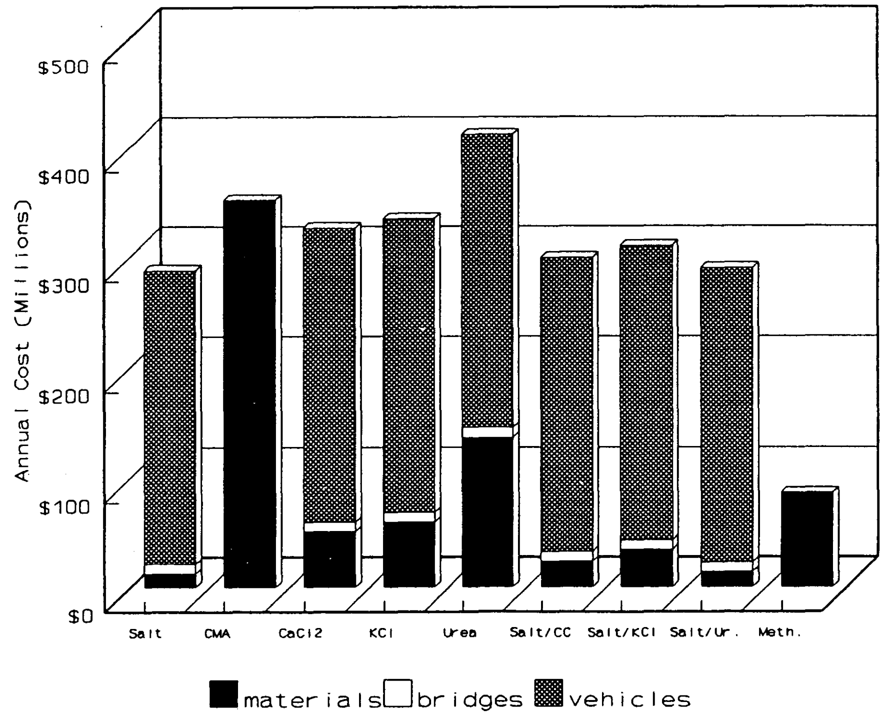

FIGURE 1 Estimated total annual cost of deicers in Illinois.

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Sodium Salts of Carboxylic Acids as Alternative Deicers

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Mixtures of the sodium salts of fatty acids with low molecular weight (acetic, formic, glycolic, and lactic) exhibit deicing properties comparable to sodium chloride. They can be manufactured from biomass by reaction with sodium carbonate or made from the acids directly by neutralization with sodium carbonate or sodium hydroxide. Preliminary data suggest that mixtures of sodium acetate with sodium formate may be effective alternative deicers. The only known drawbacks to these deicers are the presence of the sodium ion and their cost. The deicers are readily biodegradable, nontoxic, environmentally acceptable, and mildly or non-corrosive to steel. Tests indicate that the deicers will not cause concrete durability problems. Whether sodium carboxylate deicers truly represent an acceptable alternative to sodium chloride cannot be determined until actual field trials are completed.

In 1980 Dunn and Schenk presented a paper identifying calcium magnesium acetate (CMA) as a potentially effective, noncorrosive substitute for sodium chloride (NaCl) (*1*). Their paper prompted a spate of research efforts directed at making CMA economical and testing its deicing effectiveness. One of those efforts, which attempted to manufacture CMA from roasted dolomite and sawdust at elevated temperatures and pressures, was undertaken in South Dakota. After several years of work, the effort was abandoned and the research shifted to manufacturing a sodium-based deicer from the reaction of sawdust with sodium carbonate or baking soda.

The deicer produced from this process was primarily a mixture of the sodium salts of acetic, formic, glycolic, and lactic acids; the amount of each carboxylate salt was varied according to the reaction conditions used. Unfortunately, the high temperature and pressures required for its manufacture made this alternative deicer too expensive. Further research was conducted to improve production costs, resulting in a process that created the deicer and a paper pulp by-product, the market value of which was to offset the high production costs. Although tests indicate that the deicer is effective and noncorrosive, efforts to bring it into production have been unsuccessful. A patent was issued for the process in May 1987, but only laboratory quantities of the deicer have been produced.

Investigation of the deicer's properties has often raised more questions than it has answered. Freezing point depression and ice adhesion tests showed that the material could prevent freezing at temperatures as low as −40°C and, if preapplied to a concrete substrate at rates as low as 40 kg/lane-km, that it could also lower the strength of the ice-concrete bond below 100 kPa, the point at which mechanical removal of ice becomes practical.

Further investigation led to an unexpected discovery and a recently filed patent application. Analysis of freezing point depression data for variable composition deicers suggested that certain mixtures of sodium carboxylate salts formed disordered systems with ice and prevented freezing. Since sodium acetate and sodium formate were the most economical and potentially best deicing salts in the deicer mixtures from the pulping process, a series of dry crystalline solids of variable ratios was prepared and tested for freezing point depression and ice penetration. One composition did not freeze at −38°C and all but one of the sodium acetate-sodium formate (NaA-NaF) mixtures penetrated ice better than NaCl in a comparative test.

ENVIRONMENTAL

Aside from the fact that sodium carboxylate deicers contain sodium and are just as likely to introduce sodium ions into the environment as NaCl, these deicers represent a fairly innocuous environmental threat. They can be considered as generally similar to CMA with regard to toxicity, transport, fate, and effects to the environment. Tests were conducted on the mixed sodium carboxylate deicer to determine tentative values for toxicity and environmental impact (*2,3*). In comparison with NaCl and CMA (*4*), the results indicate that sodium carboxylate deicers pose a minimal environmental problem (Table 1).

Although the NaA-NaF deicers have not been tested for toxicity or environmental impact directly, they contain two of the major components in the mixture that was tested and would be used at the same pH/9 to ensure compatibility with concrete. The toxicity of sodium formate is low (LD50 = 11,200 mg/kg), and neither sodium formate nor sodium acetate should pose a serious problem, because both are used as food additives.

CORROSION

The most striking property of the original sodium carboxylate deicer made from sawdust is its inhibition of reinforcing steel corrosion both in solution and in a concrete environment. Tests conducted on No. 3 reinforcing bar tokens in 3 percent solutions of sodium carboxylate, NaCl, CMA, and distilled water showed significant corrosion occurring in all but the sodium carboxylate solution. Another test involved No. 3 reinforcement bars imbedded in ASTM C109 mortar cubes. Groups of three cubes were vacuum-saturated in a 10 percent

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TABLE 1 Comparative Toxicity and Environmental Impact

Test		CMA	NaCl	SDD
Oral LD50 (mg/kg)		3150	3750	27000
Skin Irritation		No	Slight	No
Acute Inhalation LC50 (mg/cm^3)		>300	NA	>300
Acute Dermal LD50 (mg/kg)		>5000	NA	Nontoxic
Fish Acute Toxicity LC50 (g/l)		17.5	NA	Nontoxic
Biological Oxygen Demand (rate constant mg/l/day)	20°C	0.130		0.142
	10°C	0.064		0.092
	2°C	0.020		0.053

solution of each chemical, allowed to dry for 1 week, and placed in a moisture room at 23°C for 1 week. This cycling was continued until cracks formed in some of the specimens, at which time the cubes were broken to observe the condition of the steel. Half-cell readings of each specimen were taken weekly at the end of each half of the cycle; they correlated extremely well with the corrosion of the reinforcing steel in the specimens. A summary of these half-cell readings for the first four cycles is shown graphically in Figure 1. Neither the control (H_2O) specimens nor the specimens soaked in sodium carboxylate deicer achieved active corrosion half-cell potentials or, on breaking, exhibited any rust. Both NaCl and CMA, on the other hand, had potentials in excess of −350 mV after the wet portion of the cycle, and the reinforcing steel in these specimens was severely corroded.

A major potential problem with any alternative deicer is the possibility of a synergistic enhancement of corrosion in the presence of NaCl, which already contaminates many bridge decks. To determine whether the sodium carboxylate deicer might cause such a response, mortar cubes that contained steel were first saturated with a 10 percent NaCl solution, dried, and then resaturated with the sodium carboxylate deicer or CMA. The results of corrosion testing (Figure 2) indicate that the sodium carboxylate deicer does not interact with NaCl to increase the potential for rebar corrosion. CMA, however, appeared to increase half-cell potentials above the NaCl control.

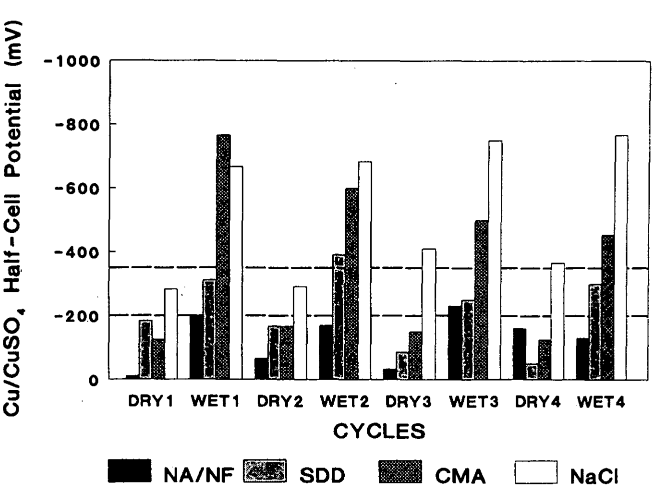

FIGURE 1 Steel corrosion in a concrete environment.

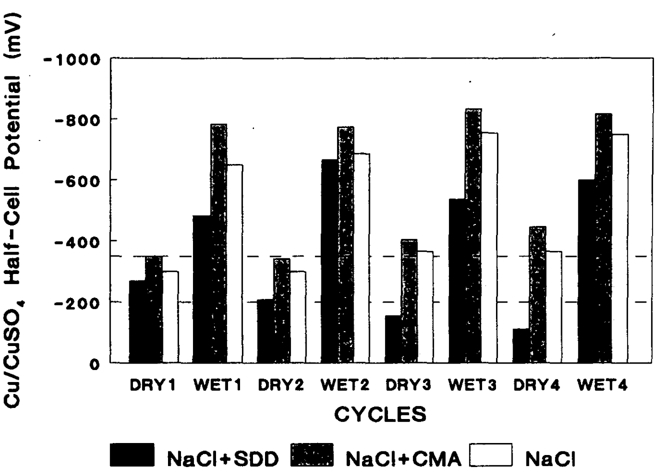

FIGURE 2 Corrosion of steel in a concrete environment with NaCl and alternative deicer mixtures.

The proposed NaA-NaF deicer has not been thoroughly tested for potential corrosion problems, but preliminary data indicate that it is mildly corrosive to reinforcing steel at a 3 percent concentration. The corrosion produced is considerably less than that produced by CMA and that produced when sodium acetate and sodium formate were tested separately without pH adjustment. More comprehensive corrosion testing is planned.

CONCRETE DURABILITY

Tests on the effects of the NaA-NaF deicer on concrete durability will be run soon. The literature on the subject is promising: Palmer reported that sodium formate does not spall cured concrete (*5*), and Grun reported that sodium acetate had no action on concrete (*6*,p.879). The sodium carboxylate deicer that contains sodium acetate and sodium formate as major constituents did not damage mortar cubes using the method of Stratful (*7*).

HANDLING

The NaA-NaF deicers are white, crystalline, relatively dense solids that do not tend to dust nearly as badly as CMA. In addition, no free acetic acid is generated from these solids as is from CMA. Solutions of the deicer do have a slight odor of acetic acid at high concentrations, but the overall handling characteristics of these materials should not present insurmountable problems.

DEICING EFFECTIVENESS

Figure 3 shows a comparison of eutectic temperatures for various deicing compounds. The original sodium carboxylate and the NaA-NaF mixture are able to prevent freezing down to −40°C, but the original sodium carboxylate deicer does not have the ice penetration characteristics of the NaA-NaF mixture. Figure 4 illustrates the results of an ice penetration test comparing NaCl with the sodium carboxylate deicer at −3.9°C. The sodium carboxylate deicer is only about 60 percent as effective as NaCl at this temperature, probably because of the presence of the higher-molecular-weight salts (lactate and glycolate).

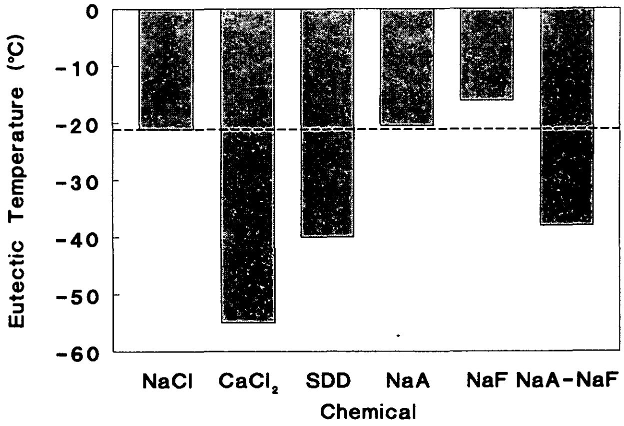

FIGURE 3 Freezing point depression of various deicers.

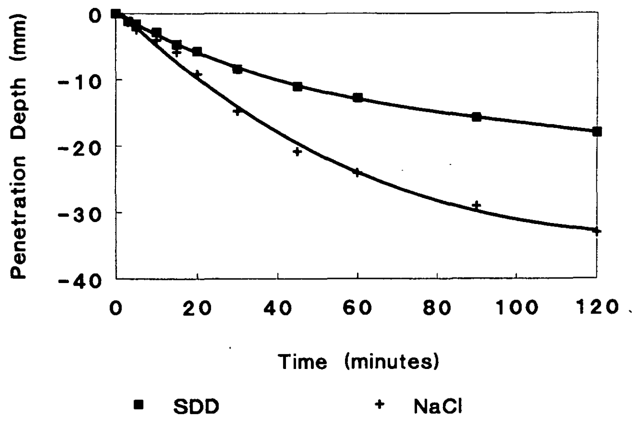

FIGURE 4 Ice penetration of NaCl and sodium carboxylate mixture deicer.

Figure 5 represents a comparative ice melting test that was not done under the rigid environmental control protocol recommended by the Strategic Highway Research Program (SHRP) deicer testing procedures but still reflects the relative ability of these deicer compositions to melt ice. The test was conducted in an upright freezer after overnight equilibration of the ice and chemicals to be tested. Three 0.25-g crystals of each deicer were introduced onto ice formed by freezing 30 mL of distilled water in a petri dish. The temperature of the freezer at the beginning of the test was −25°C; the freezer was opened and the crystals placed onto the ice as quickly as possible. The temperature inside the freezer at the beginning of the test had risen to −19.8°C. After 23 min, the temperature inside the freezer was −24°C, at which time the petri dishes were removed one at a time and the penetration of the ice measured with a micrometer. The NaCl sample was the last to be removed from the freezer. These results do not truly reflect ice penetration characteristics, because the handling procedures undoubtedly contributed to the melting action. Further tests using the SHRP protocol are planned.

Tests of ice bond strength indicate that preapplication of deicer solutions can appreciably weaken the ice-pavement bond (*8*). Figure 6 shows the typical effect of application rate on the shear strength of ice for one sodium carboxylate deicer. Another mixture actually lowered the ice-pavement shear strength below 100 kPa at an application rate of only 40 kg/lane-km. Since the NaA-NaF deicer displays similar freezing behavior and appears to form a disordered solid with ice, it should cause a similar bond reduction.

COST

The worst-case scenario for the manufacturing cost of the NaA-NaF alternative deicer using current prices from the *Chemical Marketing Reporter* approaches \$600/ton (*9*). This is based on \$0.73 to 0.75/kg for acetic acid, \$0.88 to \$0.91/kg for formic acid, and \$0.11/kg for soda ash. Direct manufacture of sodium formate from the reaction of NaOH with carbon

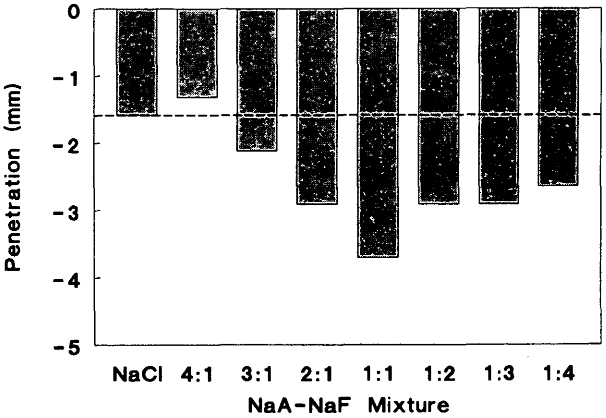

FIGURE 5 Ice penetration of NaA-NaF mixtures compared with NaCl.

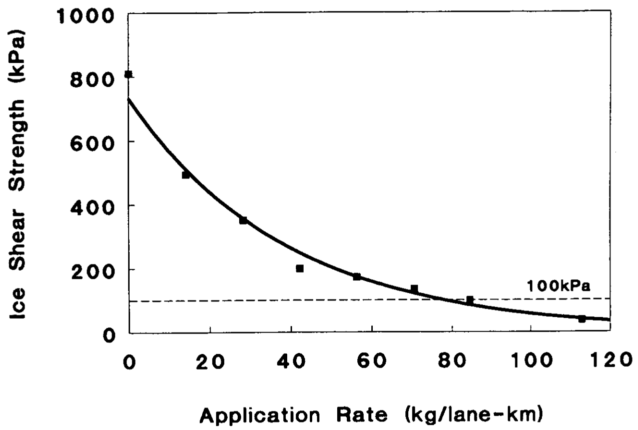

FIGURE 6 Reduction in interfacial shear strength between ice and pavement.

monoxide could lower the cost to $500/ton. Discounts based on acceptable purity, bulk quantities, and other variables could lower the actual cost of manufacturer to somewhere near $300/ton. High-purity chemicals are not required to produce acceptable deicing chemical.

CONCLUSIONS

Any alternative deicer that is proposed as a substitute for NaCl will be considerably more expensive than NaCl. Sodium carboxylate deicers, especially NaA-NaF deicers, offer a potential source for alternative deicing chemicals that combine the advantages of mild corrosivity, minimal environmental and toxicity effects, and deicing characteristics similar to NaCl with the disadvantages of high cost and the continued use of sodium salts.

Initial tests indicate that a NaA-NaF deicer can be an acceptable substitute for NaCl, especially in certain critical areas, but further testing of deicing properties, corrosivity, and concrete durability are necessary to obtain a more comprehensive idea of the potential for development.

A field test of the NaA-NaF deicer is necessary to evaluate handling and deicing effectiveness under actual winter conditions.

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Trials of Calcium Magnesium Acetate Deicer on Highways in Ontario

DAVID G. MANNING AND MAX S. PERCHANOK

Field trials of calcium magnesium acetate (CMA) have been undertaken at two locations in the province of Ontario. During the winters of 1986–1987 and 1987–1988, CMA was applied to a section of freeway and adjacent sections of service road near Beamsville. Under the prevailing conditions (which could be characterized as temperatures rarely below −5°C during periods of precipitation, relatively light snowfall, and heavy traffic volumes), CMA was found to be comparable to salt in achieving bare pavement, though more CMA was used than salt. CMA was found to be relatively more effective in longer storms. During the winters of 1989–1990 and 1990–1991, CMA, from the same commercial supplier as in the earlier tests, was applied to a section of two-lane highway near Owen Sound. The test site experienced heavy snow, frequent snow squalls, cold temperatures, and light traffic volumes. Maintenance quality standards achieved with salt were achieved only 50 percent of the time with CMA. The performance of CMA was much more sensitive to temperature, humidity, time of application, and traffic volume than was salt. Wetting the CMA or the CMA-sand mixture with a CMA solution improved performance, especially in dry, cold periods or windy conditions. It was concluded that, even if budget considerations were ignored, replacing salt with CMA in most parts of Ontario would result in a significant reduction in the level of service currently provided. A steel bin with augers for loading and unloading was found to be an effective method of storing and handling the CMA.

The Ontario Ministry of Transportation (MTO) is responsible for clearing snow and ice from highways under its jurisdiction. This is carried out by plowing, sometimes in combination with sanding or chemical deicing, in accordance with the ministry's maintenance quality standards (*1*). Rock salt (sodium chloride) is the standard deicer because it is effective under most winter weather conditions experienced in the province and is inexpensive relative to other available deicers.

The use of sodium chloride as a deicer has several harmful environmental effects; they include increasing the rate of corrosion in automobiles and highway infrastructure materials, damaging sensitive vegetation along the roadside, and contributing salt to highway runoff (*2–4*). MTO has responded by minimizing the quantities of salt used and by searching for effective and economic alternatives, with a preference for chemicals that contain neither sodium nor chloride ions (*5*).

Calcium magnesium acetate (CMA) was identified in the late 1970s as a possible alternative to salt (*6*) and has been the subject of many studies on its production, health and environmental effects, and performance (*3,4,7*). It has been evaluated under field conditions by MTO at two sites. During the winters of 1986–1987 and 1987–1988, it was tested near Beamsville, and during the winters of 1989–1990 and 1990–1991 it was applied to a section of highway near Owen Sound, Ontario.

SUMMARY OF BEAMSVILLE TRIALS

The results of the evaluation near Beamsville have been reported in detail (*8*). They are summarized here because the differences in performance at the two test sites are important to understanding the conditions under which CMA performs effectively.

At the Beamsville test site CMA was applied to a 2.4-km section of four-lane freeway [38,500 annual average daily traffic (AADT)] and adjacent two-lane service roads (less than 500 AADT). Contiguous 7-km sections of the freeway and service roads were maintained using salt and served as control sections. All the roads had a bituminous surface. The CMA was produced commercially. At the beginning of a storm, CMA and salt were applied to the appropriate sections at approximately the same time; subsequent applications were made to meet the quality standards, but it was not attempted to make the same number of applications to the CMA and salt sections because the chemicals performed differently under various storm conditions. The specified application rate for salt was 130 kg/two-lane-km (equivalent to 230 lb/lane-mi). Application rates for CMA were 182 to 221 kg/two-lane-km (1.4 to 1.7 times the standard salt application), an application ratio of 1.7 being the theoretical quantity of CMA necessary to provide equal deicing performance.

Fifteen storms were recorded during the first winter and 20 during the second. Most of the storms occurred when the temperature was between 0 and −5°C, which is typical of winter conditions in the Niagara Peninsula. The storms ranged from a few hours to 3 days long; most lasted less than 1 day.

The findings were as follows:

- The storage and handling characteristics of CMA were comparable to those of salt.
- The use of CMA did not require changes in equipment and only small changes in procedure. The tendency of CMA to stick to equipment and loading areas was a minor inconvenience. Patrol staff readily accepted the CMA.
- The times it took to achieve bare pavement in the CMA and salt sections on the freeway were similar and, with one exception, within 45 min of each other.

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- In short storms the quantity of CMA used tended to be much higher than that of salt, whereas CMA was relatively more effective in longer storms. A residual effect from one storm to the next was observed in the CMA section, particularly during the first winter.
- The ratio of the total quantities of CMA and salt used on the freeway test sections was 1.2 in 1986–1987 and 1.4 in 1987–1988.
- The application rate for CMA of 1.7 times that of salt appeared excessive and an application ratio of 1.4 appeared insufficient, but the optimum ratio was not determined.

SCOPE AND METHODOLOGY OF OWEN SOUND TRIALS

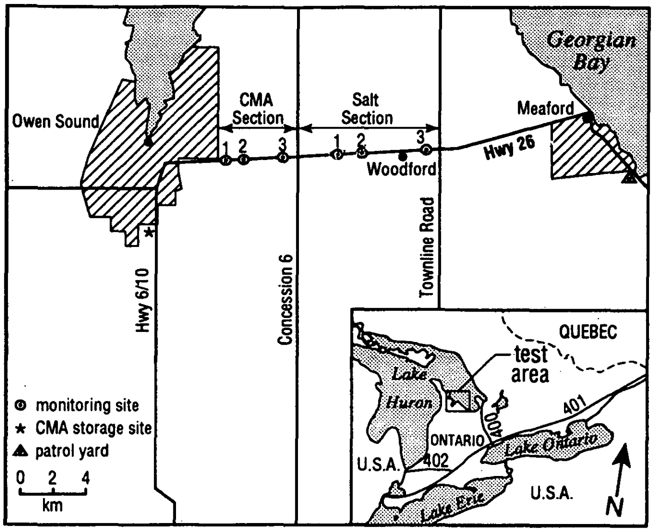
The results of the Beamsville trials were generally favorable toward the use of CMA, but it was recognized that the test conditions of relatively mild temperatures, light snow, and heavy traffic were not typical of conditions throughout most of the province. Additional testing was therefore undertaken under conditions of colder temperatures, heavier snowfall, and lower traffic volumes more representative of rural Ontario. The primary purpose of the trials was to determine whether CMA could be used as the sole deicer in the province if availability and cost were not limiting factors. A secondary objective was to improve storage and handling procedures to reduce the wastage experienced at Beamsville. Trials were undertaken during the winters of 1989–1990 and 1990–1991. CMA from the same commercial supplier used earlier was compared with salt using several criteria, including quantities used, storage, handling and spreading characteristics, time required to initiate deicing, drying and persistence effects, slipperiness, and effect on vehicles.

The trials were conducted on Highway 26 between the eastern limit of Owen Sound and the western limit of Meaford. Highway 26 is a two-lane road with a bituminous wearing surface and winter average daily traffic of 2,400 vehicles. The test area is east of Lake Huron and south of Georgian Bay and is subject to frequent snow squalls and prolonged periods of cold nighttime temperatures. The mean winter snowfall is 2.8 m, with an average of 24 days a year of blowing snow, average daily maximum temperatures in January and February of −2.4°C, and average daily minimum temperatures of −10°C (*9–11*)

In each year of the trials, two sections of Highway 26 were designated for testing: the CMA test section and the salt test section. Except for isolated incidents during the first winter, only the specified deicer, applied either neat or mixed with sand, was used in its designated section. The location of the test sections used during 1989–1990 is shown in Figure 1. For 1990–1991, both the CMA and the salt sections were extended (*12*).

Within each section, observations and measurements were made at specific test sites. The locations of the observation sites were selected to represent the range of road weather conditions experienced while still permitting a valid comparison between the sites in each test section.

Four independent sources (spreader operator, plow operator, patrol supervisor, and observers hired to collect data at the observation sites) maintained records of materials used and the time of application. In addition, in 1990–1991 plow and spreader times were checked against a time-lapse video record at one of the observation sites. Traffic volumes and weather conditions were also recorded.



CMA section
1) level, open site with moderate snowfall and heavy drifting
2) inclined, forested site with passing lane, moderate snowfall and light drifting
3) level, open site with moderate snowfall and heavy drifting

Salt section
1) level, open site with moderate snowfall and heavy drifting
2) level, open site with moderate snowfall and heavy drifting
3) inclined, forested site with moderate snowfall and light drifting

FIGURE 1 Test sections and observation sites, 1989–1990.

Storage and Handling

Storage and handling includes transferring the deicing material from the supplier's delivery truck into temporary storage at the MTO patrol yard and either transferring it from storage into a spreader truck or mixing it with winter sand to prevent stockpile freezing.

CMA was stored and handled during the Beamsville trials using the same equipment as for salt. It was dumped from delivery trucks onto a paved apron outside a salt shed and moved into and out of the shed using a front-end loader. Several problems were encountered, including dusting, spillage, and sticking to the loader tires and apron in wet conditions.

During the Owen Sound trials, CMA was stored in a 90-m^3 steel bin of the type normally used to store grain. The bin was located at a sub-yard at Owen Sound during the 1989–1990 trials and at a sub-yard near Woodford during the 1990–1991 trials. Material was transferred from highway transport trucks into the bin and from the bin into spreader trucks using electrically driven augers (Figure 2).

Method and Criteria of Application

Key measures of the effectiveness of a deicer are the quantity of the material used and the time required to effect ice melting

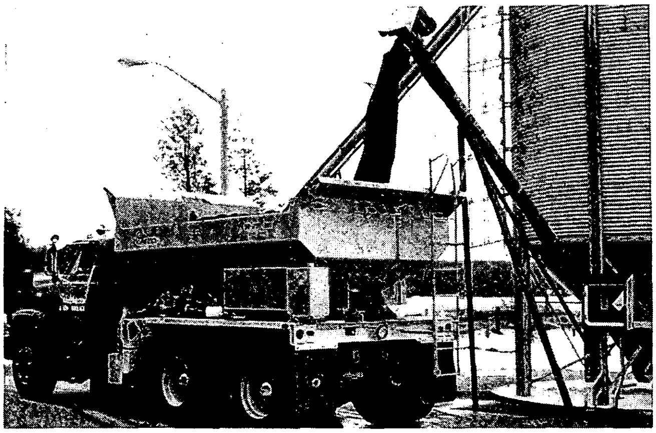


FIGURE 2 CMA storage bin and loading procedure.

or disbonding under given weather and traffic conditions. Detailed records were made of the timing, spread rate, and total quantities of CMA, salt, and sand applied at each test site during each storm.

CMA was dropped over a fixed or slowly rotating spinner to effect spreading across the road surface. This method was used instead of the conventional method of deicer application, a windrow down the centerline, because previous trials showed that CMA did not dissolve and spread as a solution. Instead, it formed a slush that remained where pellets were applied until it was removed by plowing or tire action.

The timing and rate of application differed in the 2 years of testing. In 1989–1990 the application rate for CMA was 195 kg/two-lane-km, or 1.5 times the standard salt application rate. The first applications of CMA and salt in each storm were made at the same times to permit direct comparisons of the deicing effectiveness of CMA and salt. Subsequent applications during a storm were made independently as warranted by road conditions. However, road weather conditions were not sufficiently similar in the salt and CMA test sections to warrant direct comparison, and procedures were changed after the first year of trials.

In 1990–1991, the timing of CMA applications was scheduled so as to optimize effectiveness and was not related to the timing of applications in the salt section. The application rate was also adjusted by the patrol supervisor between 195 and 247 kg/two-lane-km, depending on road and weather conditions.

Several of the 1990–1991 applications included spraying a 25 percent solution of CMA in water on the CMA pellets and winter sand immediately before spreading to determine whether blow-off could be reduced. The prewetting apparatus consisted of a commercial weed sprayer mounted on the spreader. The spray apparatus incorporated a heater and antifreeze system to prevent freezing and maintain a low viscosity of the solution during storage. The solution was applied at a pressure of 224 kPa, through a flat-tip nozzle that sprayed a fine mist on the CMA pellets or sand grains on the spinner. The resulting application rate was 1.9 L/min, or approximately 3.75 L/two-lane-km, depending on vehicle speed. The sprayer could be turned on and off by the truck operator while the vehicle was in motion.

Spread Width and Blow-Off

Blow-off occurs when deicer or sand particles are blown off the road by wind or turbulence created by passing vehicles. Blow-off is most common when particles are bouncing along the road immediately after discharge from the spinner.

Spreading characteristics were documented qualitatively as the spreader truck passed the observation sites and by videotaping the spreading operations from a trailing vehicle. Blow-off was documented at the observation sites by mapping the spread width and density under different wind and pavement wetness conditions.

Effectiveness of Ice Melting and Disbonding

Deicers act by one of two processes: one is by dissolving with a body of ice or snow and thus simply melting the mass of material from the top down; the other is by penetrating the main body of material and then dissolving a thin layer between the snow or ice and the pavement. The second process breaks the ice-pavement bond and is more efficient in terms of quantities of deicer used and vehicle safety. Less deicer is used because only a small mass of material needs to be melted, and it results in safer driving conditions because the surface is not covered with a layer of deicer solution.

Although it is difficult to measure the two processes in the field, the dominant process can be inferred by observation. If the bond-breaking process is dominant, the snow or ice will be cast from the road by vehicle tires or plowing to expose bare pavement that is wet with deicer solution. If melting at the surface occurs and enough deicer is applied, the snow or ice will gradually turn to slush and then dissolve. Providing it does not refreeze, the solution is cast aside by traffic or gradually drains or evaporates from the pavement, eventually leaving a bare and dry surface.

A standardized format was used to map the pavement conditions at the observation sites and record the weather conditions. Parameters included the type, thickness, and lateral extent of snow, ice, or deicer solution on the pavement; road surface temperature; and meteorological conditions. Road conditions were classified as icy, snowpacked, snow-covered, slushy, bare and wet, bare and damp, bare and dry, residue, or frost. The order of the conditions listed is important because a change within the range "icy" to "bare and dry" was interpreted as an improvement in road condition.

During the 1990–1991 trials, several additions were made to the procedures and an automated data collection system was installed at one observation site. At all sites in the CMA section, thermocouples were installed in the pavement to measure road-surface temperature, and thermometers were mounted on roadside posts to measure air temperature.

At the automated data collection site, road weather data were recorded at 30-min intervals and the road-surface condition was recorded on videotape at 4-sec intervals.

The pavement was marked with paint lines that, when imaged in the video system as shown in Figure 3, provided a calibrated record of the rate of deicing during every CMA application. A luminaire was installed at this site to allow nighttime videotape recording.

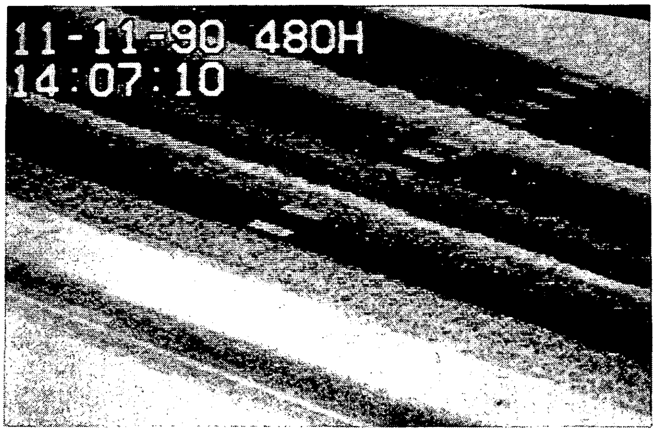


FIGURE 3 Videotape of road conditions, November 11, 1990, at 2:07 p.m.

Hourly traffic volume in each direction was measured during the first test season using a microwave detector mounted on a hydropole at the Woodford sub-yard, the midpoint of the test area (Figure 1). During 1990–1991, traffic was measured using an electromagnetic loop detector installed in the pavement surface at the same location.

RESULTS AND ANALYSIS OF OWEN SOUND TRIALS

Storage and Handling

Initially, difficulties were experienced in loading the spreader from the storage bin because of overload of the electric motor on the auger during start-up. The problem was rectified by reducing the diameter of the auger flights that extended into the storage bin, thus reducing the loading rate (to approximately 500 kg/min), and by emptying the auger before it was switched off. Excessive dusting was also observed; it was controlled by attaching a flexible nozzle to the end of the auger.

The presence of the dust raised concerns that the CMA pellets could be abraded by the augers. Samples were taken when the CMA was unloaded from the highway transport truck into the storage bin, and when it was loaded into the spreader truck, to determine whether attrition occurred in passing through the loading and unloading augers. Comparison of the size distributions of the two samples indicated that the amount of attrition was very small (*12*).

Liquid CMA, used only during 1990–1991, was delivered in 205-L steel drums and pumped into a reservoir on the spreader truck as needed. Bacterial slime was observed floating on the liquid in the steel drums upon opening, after delivery from the supplier. This was anticipated because of the metabolism of acetate by bacteria and was removed by skimming.

CMA was mixed with winter sand to prevent stockpile freezing. A rate of 5 percent by mass (which is the standard ratio for salt) was used in 1989–1990 and 2 percent by mass in 1990–1991. When 5 percent CMA was used, the pellets became soft and sticky as moisture was absorbed from the sand, leaving the dry sand susceptible to blow-off. The use of 2 percent CMA was found to be sufficient to prevent the stockpile from freezing, and it did not result in a noticeable drying of the sand.

Application Experience

During both winters, CMA was observed to stick to the sides of the spreader bin, which at times prevented it from falling onto the spreader conveyor. This problem occurred whenever CMA was loaded into a wet spreader. The problem was solved partially by parking the spreader truck in a garage or sand storage dome and by scraping and washing off any material remaining in the spreader bin immediately after use.

Slush splashing from the road caused the CMA to cake on the spinner to the extent that the spinner had to be scraped and washed between applications.

CMA pellets were observed to bounce more than salt upon hitting the pavement, unless the road was moist or snow-covered. They were also blown off the road by wind and by air currents from trucks following the spreader.

In eight tests, CMA pellets were prewetted with a 25 percent CMA solution to determine whether a liquid coating would help the CMA adhere to the road surface. The use of the spray improved the adhesion of the CMA to the road surface and reduced the spread width (*12*). In very windy conditions, sand was spread on top of the CMA to hold it onto the road. This required a second pass of the spreader truck, but, since only one vehicle was available, almost 1 hr had elapsed, which limited the effectiveness of the technique.

Quantities Applied

Statistics summarizing the deicer applications in the CMA and salt test sections are shown in Table 1. During the first test season from November 4, 1989, to April 4, 1990, CMA or CMA-sand mix was applied 181 times in the CMA test section. Data from the CMA and salt test sections in 1989–1990 exclude eight events in which salt was applied in the CMA section and 17 events in which salt-sand mix was applied in the CMA test section. Reasons for using salt in the CMA test section are as follows:

- The storage facility had run out of CMA or CMA-sand mix;
- The spreader dedicated to CMA had mechanical problems;
- Salt was deemed necessary to remove an icing condition; and
- Because of spreader availability, salt-sand application permitted a faster response during critical icing conditions.

During the 1990–1991 test season (from November 7, 1990, to April 15, 1991), CMA or CMA-sand was applied 221 times. No salt was used in the CMA section. Records for this season did not distinguish between full, spot, or multiple applications during the same spreader call-out in the salt section; therefore, they were not included in the top section of Table 1.

Information directly comparing the number of applications and quantities of CMA and salt used must be interpreted with

TABLE 1 Summary of Material Use

	1989-1990	1990-1991
Number of Material Applications[a,b]		
CMA	59	77
CMA-sand mix	122	142
Salt	65	-
Salt-sand mix	133	-
Ratio		
CMA:salt	0.91	-
CMA-sand:salt-sand	0.92	-
Mass Applied (kg/two-lane-km)[a,c,d]		
CMA	18,750	14,615
CMA-sand mix	117,329	192,308
Salt	18,048	29,771
Salt-sand mix	99,095	108,153
Ratio		
CMA:salt	1.04	0.49
CMA-sand:salt-sand	1.18	1.78
CMA-sand:CMA	6.2	13.1
Salt-sand:salt	5.5	3.6

[a] Excludes storms in which salt or salt-sand mix was applied in CMA section.
[b] Excludes spot applications.
[c] Averaged over test section.
[d] Includes spot applications.
- Data not available.

care. First, direct comparison requires that traffic and weather conditions in the CMA and salt test sections be similar, and this was not always the case. Patrol and monitor personnel observed that weather conditions frequently differed over short distances within the test areas as a result of snow squalls from Georgian Bay.

Second, no attempt was made to use neat CMA when salt was in use and a CMA-sand mixture when a salt-sand mixture was in use. A simple comparison of the number of deicer applications and total quantities applied suggests that CMA was more effective, or remained effective longer, than salt. However, the much greater quantity of sand used in the CMA section means that there were times when salt was effective but CMA was not, and sand had to be applied to provide traction only in the CMA section. In summary, the seasonal application data suggest that CMA was less effective than salt.

Effectiveness of CMA and Salt

General Characteristics

Observations were made of the comparative deicing characteristics of salt and CMA.

In the case of salt, one of two processes was observed, depending on road weather conditions. Under relatively warm temperatures and light snowfall, salt created a solution with the snow almost immediately upon application, and the solution drained off the road. Under more severe conditions when a snowpack had formed on the pavement, salt penetrated the snowpack, usually within a period of 30 min, to disbond the snowpack from the pavement and facilitate plowing. This occurred at temperatures down to approximately −12°C.

Deicing processes associated with CMA differed from those observed with salt. They were sensitive to precipitation, air temperature conditions, humidity, the type of material on the road, and traffic. Under relatively warm temperatures (above about −6°C) and light snow conditions with little traffic, CMA quickly penetrated the thin snow cover, but it did not go into a solution with the surrounding snow once it reached the pavement surface. Instead, it remained in solid form on the pavement within the original pit melted in the snow.

When CMA was applied on snow cover or snowpack with light to moderate snowfall, air temperatures above −6°C, and traffic present, pellets in the wheel tracks dissolved slowly in the snow to form a slush, but not a liquid. Tire action gradually caused the slush to accumulate between the wheel tracks, until it was removed by plowing.

Under conditions of heavy snowfall and temperatures close to the freezing point, the CMA pellets did not dissolve quickly enough to melt the accumulating snow, and they were covered by the snow. When the snow stopped falling, the CMA began to dissolve with it to form slush, which was then plowed from the road.

At temperatures below −6°C and with traffic present, CMA dissolved very slowly with snow on the road to form a slush. Slush began to form after about 30 min, depending on traffic volume, and continued to form over 2 hr or more. Again, CMA pellets remained undissolved outside the wheel tracks for hours or days after application.

After the end of a storm, and after the slush and snow were plowed from the pavement surface, a moist residue of CMA remained on the pavement for some hours or days. It gave the pavement a shiny, damp appearance although liquid was not visible. Blowing snow was observed to stick more readily to such pavements than to dry pavement in the salt section, although the snow did not become bonded to the pavement and was readily plowed off. It did necessitate more frequent plowing, however.

Prewetting the CMA pellets with a 25 percent solution of CMA in water increased the rate of reaction significantly. In several tests at temperatures above −6°C, the prewetted CMA dissolved snow in the wheel tracks at approximately the same rate as salt. At colder temperatures, prewetted CMA dissolved more quickly than dry CMA, but much more slowly than salt.

Ice Melting Effectiveness

The effectiveness of deicing was quantified in 1989–1990 by tabulating the frequency with which road surface conditions improved within 2 hr. In 1990–1991, a 30-min criterion for effectiveness was used in addition to the 2-hr criterion. The 30-min criterion corresponds approximately to standards achieved by rock salt at temperatures above −12°C and was chosen because MTO operating instructions require plowing to begin approximately 30 min after salt is applied (*1*). The effectiveness over 30 min is thus an indirect method of comparing the effectiveness of CMA with that of salt.

In both years, an effective application was defined as one in which the pavement condition improved by at least one category (as defined by the classification system used) within the prescribed time period. It should be noted that the application of the pavement condition classification was not identical in the first and second year of trials. In the first year, condition refers to the predominant condition across the driving lane at the test site. In the 1990–1991 analyses that follow, pavement condition refers to the condition of the outer wheel track zone at the test site.

Other qualifications of the analysis relate to initial condition, completeness of monitoring records, and material applied. Data were excluded if the initial condition was bare and dry, bare and damp, or bare and wet, if the frequency of monitoring was less than once in 2 hr (1989–1990) or once in 15 min (1990–1991), or if sand was applied during the monitoring period.

The duration of deicing is defined as beginning at the time of material application and ending at the observation just before plowing or the next material application.

In all cases, CMA was applied only in conditions under which rock salt would be expected to perform effectively. As shown in Table 2 using the 2-hr criterion for effectiveness, CMA was successful in 74 percent of the applications in 1989–1990 and 80 percent of the applications in 1990–1991 (excluding applications of prewet CMA). These success rates are significantly lower than the rate expected from salt, especially considering that the 2-hr criterion is much less stringent than would be considered acceptable for salt.

Table 2 shows trends of decreasing effectiveness with decreasing air temperature and increasing effectiveness with increasing traffic, and suggests that these variables act together to influence deicing. This trend would be expected for any chemical deicer.

The performance of CMA was revealed by analyzing the results from 1989–1990 of applying CMA to a snowpacked condition. All of the applications were successful in improving the road condition by at least one classification at temperatures above −6°C, some were successful between −12 and −6°C, and none was successful below −12°C. In total, 44 percent of the applications on a snowpacked surface were successful, with 12 percent resulting in slight improvement to snow-covered condition, 7 percent in moderate improvement to bare tracks, 3 percent to slushy, and 22 percent to bare and wet.

TABLE 2 Success Rate of CMA Using 2-hr Criterion

	Successful Applications (%)	
	1989-1990	1990-1991
All data	74	80
By air temperature		
-4.9°C or higher	100	100
-5 to -7.9°C	84	86
-8 to -10.9°C	44	80
-11°C or lower	20	80
By traffic count		
0 to 9 vph	61	88
40 to 79 vph	80	100
80 to 119 vph	82	91
120 or more vph	100	87

NOTE: Success is defined as improvement in pavement condition by at least one category within 2 hr after application of CMA.
vph = vehicles per hour

A more-detailed analysis of deicer effectiveness was conducted on the data from 1990–1991, which were collected on shorter intervals. These data were used to construct cumulative frequency curves of deicing effectiveness. The curves show the relationship between elapsed time since deicer application and the success rate or effectiveness of deicing.

The cumulative frequency of elapsed time between deicer application and road condition improvement is shown in Figure 4 for all CMA applications during 1990–1991. When time is not limited, the success rate was 80 percent (curve for dry CMA). When elapsed time is limited to 1 hr, the success rate was 68 percent; and when elapsed time is limited to 30 min, the success rate was 45 percent. The success rate after 30 min indicates that, if CMA were substituted for salt in the MTO winter maintenance program, successful deicing would be achieved in fewer than half of the conditions tested. Figure 4 indicates that prewetting resulted in a slight improvement in performance. However, prewetting was usually carried out under cold, snowpacked, and often windy conditions, all of which reduce the effectiveness of a deicer. If prewetted CMA had been compared with dry CMA under similar conditions, it is expected that the improvement in performance would be greater than indicated by Figure 4.

Additional information about the performance of CMA is presented in Figure 5, which shows the influence of air temperature on the effectiveness and rate of deicing. As expected, the success rate increases with the duration of deicing for all temperature ranges and with temperature for most durations. Unexpected results for elapsed times of less than 30 min suggest that other factors influence the initiation of deicing immediately after the material has been spread. Applying the 30-min elapsed time criterion resulted in a success rate of 35 to 45 percent in the temperature range above −8°C and 10 percent in the range below −8°C. The average time required for deicing (i.e., the 50th percentile of success) was 40 min at 0 to −4.9°C, 50 min at −5 to −7°C, and more than 140 min at temperatures below −8°C.

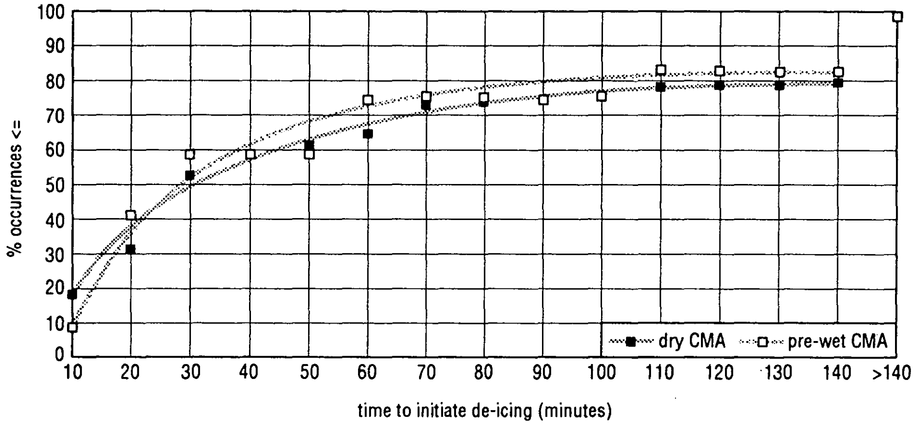


FIGURE 4 Effectiveness of dry and prewet CMA, 1990–1991.

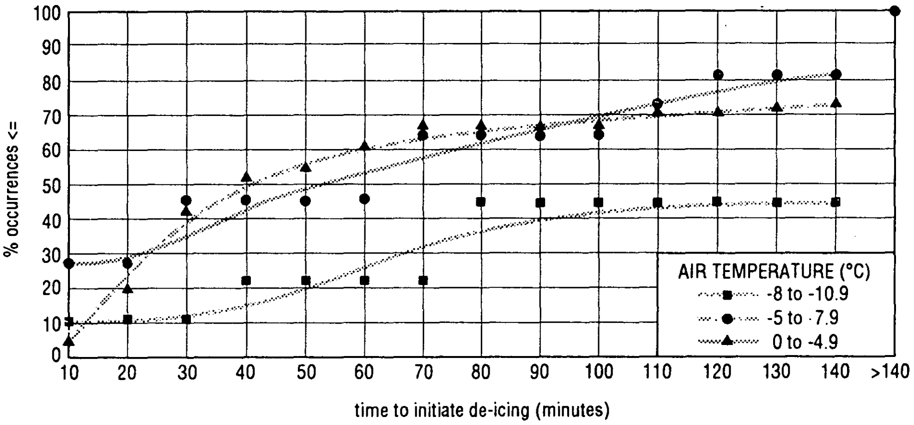


FIGURE 5 Effectiveness of dry CMA by air temperature, 1990–1991.

The influence of vehicle traffic on effectiveness and rate of deicing was similar to that of temperature. Applying the 30-min elapsed time criterion, the success rate was 30 percent for vehicle counts below 80 per hour and 55 percent for counts above 80. The average time required for deicing was 30 min at vehicle counts of 80 per hour or higher, 50 min at 40 to 79 vehicles per hour, and 60 min at 39 or fewer vehicles per hour.

ther Characteristics

rying of Pavement Previous studies suggested that CMA ries very slowly after reacting with snow or ice on the pave-ent. This could have both desirable and adverse effects on riving conditions. Desirable effects include initiation of deic-ng during subsequent storms, which might prevent bonding f packed snow or ice to the pavement and reduce the total uantity of CMA used. Adverse effects include adhesion of lowing snow to the pavement and reduction of skid resistance ue to a liquid film. Both adhesion of blowing snow and itiation of deicing (anti-icing) were observed in the present tudy. Pavement drying time in the CMA section was docu-ented from the video records taken in 1990–1991. Where rying was undisturbed by additional precipitation, the pave-ent typically took several days to dry. Comparative data were not collected in the salt section, but experience shows pavement to which salt has been applied dries within a day.

Effects on Vehicles To observe corrosion of the machinery, visual comparisons were made of the CMA and salt spreaders used during the trials. No corrosion was visible on the CMA spreaders after either season of operation, but corrosion was evident on the salt spreaders.

A transparent, sticky film was observed to accumulate on monitor vehicles that were used primarily within the CMA test section. The film was difficult to wash off with soap and water.

A few reports were received stating that vehicles that regularly traveled the CMA test section had unusually squeaky door hinges and underbody moving parts. This was also noted on the vehicle used by monitors.

CONCLUSIONS

Over four winters, MTO has studied the effectiveness of CMA as a highway deicer. Trials near Beamsville showed that it has effectiveness similar to salt under freeway traffic conditions and when temperatures are from 0 to −5°C and snow is light.

Trial near Owen Sound showed that the effectiveness of CMA decreases noticeably when traffic is light, temperatures are below −5°C, and there is moderate snowfall or drifting. Such conditions are typical of rural highways in Ontario.

In the Owen Sound trials, maintenance quality standards that are typically achieved using salt were achieved only 50 percent of the time with CMA even though a much higher application rate was used. If the standards were revised to permit a 1-hr period for a deicer to act before the road was plowed, the rate of effectiveness would have been 68 percent, and for a 2-hr period the rate would have been 74 to 80 percent. These rates could be increased by approximately 10 percent if the CMA were prewetted.

CMA can be an effective replacement for salt under a limited range of conditions. However, its widespread adoption as a replacement for salt would result in significant reductions in the level of service for snow and ice removal currently provided by MTO, even if the winter maintenance budget allowed for unlimited use of the material.

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Braking Traction on Sanded Ice

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Traction enhancement on iced pavements using abrasives was evaluated. The abrasives tested were five distinct gradations of sand built from a single host material. Four of the sands represented standard gradations as specified by the FAA, SAE, ASTM, and Transport Canada. Braking traction at a relatively fixed slip rate was measured with a full-size, self-contained instrumented vehicle. All tests were performed on an ice sheet inside a large refrigerated room. Results showed that coarse sands perform best on cold ice surfaces and that finer sands excel on warm ice. Sands with most of their grains about 1 to 2 mm in diameter performed well independent of ice temperature. The concentration of a sand on ice strongly influences the degree of traction enhancement, as does the temperature of the sand when applied to the ice. The results suggest that a mathematical expression could be generated that would relate sand type and concentration, along with several other influential parameters, to braking traction coefficient on ice.

Driving and braking traction on roads and runways in regions affected by subfreezing temperatures is often degraded by ice. Depending on the circumstances, an abrasive product may be the only way to enhance traction on iced operating surfaces. Natural sands are the most common abrasive product. Several standard gradations are identified by various agencies for specific applications. The use of abrasives at most airports is regulated by the FAA, which specifies the type of sand allowed for use on runways and the conditions and methods surrounding its use in its Airport Winter Safety and Operations Advisory Circular 150/5200-30.

This study was initiated as a result of concerns expressed by many airport operators about the lack of readily available sources of the FAA sand and its high cost relative to other sand types. At least one aircraft manufacturer has also expressed concern about the current FAA-specified sand. The manufacturer objects to the allowance of sand particles that are larger than 3.30 mm in diameter (No. 6 sieve), which the manufacturer claims can cause serious damage when ingested in turbine engines.

The goal of this study was to compare the ice braking friction coefficient of the FAA sand with that of other specified sands. The sands tested in this study were those specified by ASTM for mortar, SAE for runways, Transport Canada (TC) for runways (Table 1), and a very fine graded sand. The fine sand was included in this study because of our interest in determining the contribution of fine particles to traction enhancement. Sands containing a high fine content are generally less costly, and some aircraft personnel believe that fine particles are less likely to damage aircraft engines (*1*).

BACKGROUND

The frictional properties of sanded ice as a function of grain size has been addressed in the literature. Hegmon and Meyer tested four granular materials on ice: boiler house cinders, coke cinders, sand, and crushed stone (*2*). In their tests they used a full-size tire mounted on a pivot arm that traveled around a circular ice track in a cold room. The test temperature was held at -6°C, and the abrasives were applied to the ice to yield surface concentrations between 160 and 650 g/m^2. Their study concluded that size fractions between 1.18 and 4.76 mm in diameter (falling between sieves No. 16 and No. 4) contribute most to the friction coefficient; they recommended that finer and coarser fractions be eliminated or minimized.

Hayhoe tested crushed and uncrushed materials of three distinct size gradations at a surface concentration of 980 g/m^2 (*3*). Hayhoe was primarily interested in the effect of varying sand and air temperatures on the friction coefficient. The uncrushed material consisted of a mixture of roofing gravel and concrete sand. The crushed material used was Pennsylvania Department of Transportation and mortar sand. Hayhoe also used a full-size tire on an indoor circular ice track. Test results for an ice temperature of -24°C indicated that the friction coefficient improved with coarsening of a sand; for ice temperatures near melting (-1°C), the friction coefficient improved with greater fine grain content. At intermediate temperatures (about -12°C), Hayhoe's results agreed with those of Hegmon and Meyer, that a sand consisting of grains between 1.18 and 4.76 mm in size (No. 16 and No. 4 sieves) gave the highest friction coefficient.

Connor tested four materials using both laboratory and field test methods: the British pendulum test, Tapley deceleration meter, and stopping distance measurement using a full-size automobile (*4*). The abrasives used in Connor's study included crushed stone, "pit-run" stone (source aggregate for the crushed stone), concrete aggregate with a high fine sand content, and coal cinders. All abrasives were applied in surface concentrations between 100 and 2000 g/m^2 on ice at temperatures of -23, -18, -9, and -1°C for the laboratory tests and at -20°C in the field. Connor found that coal ash—by far the finest of the four materials with 44 percent of the grains finer (by weight) than 0.297 mm in diameter (No. 50 sieve) and 20 percent finer than 0.074 mm (No. 200 sieve)—outperformed the other materials in most cases. Connor also concluded that angular material provided higher friction coefficients than rounded particles. The results were presented as a function of sand concentration on the ice.

The Airports Authority Group of Canada also studied the effect of grain size on ice friction at ice temperatures of -9 and -3°C (*5*). Their tests were designed to determine the

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TABLE 1 Allowable Gradations for Several Specified Sands

Sand Type	Sieve Number	Percent Finer by Weight
FAA	4	100
	8	97-100
	16	30-60
	50	0-10
TC	4	100
	8	30-50
	16	0-20
	50	0-2
SAE	6	100
	8	60-100
	25	0-20
	40	0-5
ASTM	4	100
	8	95-100
	16	40-75
	50	10-35
	100	2-15

relative surface concentrations of two sands that would give the same coefficient of friction. One sand had grain sizes no larger than 2.36 mm (No. 8 sieve), and the other allowed grains up to 4.76 mm in diameter (No. 4 sieve). Measurements were made on an actual iced runway with a Tapley deceleration meter and a Saab friction tester. They concluded that the finer material must be applied at a surface concentration of 85 to 95 g/m^2 to match the braking performance that was measured on ice treated with the coarser sand at a surface concentration of 50 g/m^2. For concentrations greater than 120 g/m^2 on cold ice or 240 g/m^2 on warm ice, however, the finer sand provided a higher coefficient of friction.

In a precursor to the study reported here, the authors performed an initial assessment of frictional qualities of four sand types on ice (*6*). They compared the FAA sand with three other popular sand types: from SAE (SAE AMS 1448), International Civil Aviation Organization (ICAO), and ASTM (ASTM C144). Using a small-scale sliding friction table, the sliding friction of a rubber-faced slider on sanded ice at −10°C was measured. Tests were done on bare ice, loosely sanded ice, and ice with sand frozen on at a single concentration of 1750 g/cm^2. The friction coefficients for the slider on bare ice were found to be higher than those measured on loosely sanded ice and, in some cases, on ice with sand frozen on. Test results were presented as a performance ratio (friction coefficients for sanded ice to bare ice), which allowed the sands to be ranked distinctly—in order of decreasing effectiveness—as ASTM, FAA, SAE, and ICAO. The performance ratio showed a strong, linearly increasing trend as the percentage of a given fine grain size in the sand was increased. Greater increases in traction with increases in fines were found for frozen-on sand than for loosely sanded ice.

EQUIPMENT AND FACILITIES

To ensure environmental control for our tests, the entire test program was conducted inside the Frost Effects Research Facility (FERF) at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. The FERF is a large building capable of holding a constant ambient air temperature ranging between −12 and 15°C. For a test surface, we constructed a temporary ice rink 30 m long and 3.6 m wide inside the building. Controlling the temperature of glycol that was passed through cooling coils in the ice enabled the temperature of the ice to be controlled. Thermocouple strings frozen into the ice sheet at three locations were used as feedback to the glycol source to attain the desired ice-surface temperature.

Traction was measured using a versatile instrumented vehicle that can operate in a variety of measurement modes. The CRREL instrumented vehicle (CIV) is based on a 1972 Jeep Cherokee and measures three mutually perpendicular forces at the contact patch for each of the four tires, the speed of each tire, and the speed of the vehicle itself. A computer-based data acquisition system collects data at a rate of 10 samples per second and stores the data in a spreadsheet format for later analysis. Further details on the CIV are given elsewhere (*7*).

To match the measurements taken by the usual FAA-endorsed devices (skidometer, Saab and K.J. Law friction testers, Tapley meter), the CIV was configured to operate at a constant rate of negative slip (braking) of between 10 and 20 percent. To accomplish this, all four tires were driven at a common rate of rotation, but they were installed with a 15 percent difference in circumference on the front and rear axles. Thus, the tires with the least vertical load (normal force) were forced to slip to take up the difference in rotation. For the CIV, the rear wheels have the least normal load. With smaller-diameter tires installed on the rear axles, all the slip took place there.

Data were collected with the vehicle operating at a constant ground speed of 5 km/hr over a 17-m segment of the ice surface. This yielded at least 10 sec of data collected at steady-state conditions (at least 100 data points for each tire).

During a braking traction test, the CIV measured the total tire-dragging force of the slipping tires, which included both the interfacial force at the tire-ice contact patch and the internal resistance to rolling naturally present in a tire (caused by flexing of the tire belts and carcass). To isolate the interfacial (friction) force, the internal resistance was determined in separate tests in which the CIV measured the tire-dragging force of the tires in a nonslip condition. This resistance force was subtracted from the total tire-dragging force to obtain the desired friction force.

New tires (P185/75R14 Goodyear Invicta) were installed on the rear axles where braking traction was measured; they were inflated to 240 kPa for all tests. Average dynamic vertical load on the rear axles was 5575 N/tire, and the average static contact patch measured 190 cm^2 in area.

TEST VARIABLES

The primary test variable in this study was sand gradation. A single source material from a local sand pit was used to produce all five of the test sands, which are given in Table 2. This material was a naturally occurring sand (glacial stream deposited) with semirounded particles.

TABLE 2 Grain Size Gradations for Study Sands and Source Material (percentage finer by weight)

Sieve							
Number	Opening (mm)	TC	FAA	SAE	ASTM	Fine	Source[a]
4	4.75	100	100	100	100	100	100
8	2.36	42.8	97.7	99.0	97.7	100	87.8
16	1.18	20.3	57.2	71.1	95.1	100	58.3
30	0.59	7.9	19.3	11.9	68.8	83.9	26.1
50	0.30	1.3	3.5	1.4	28.2	38.1	11.5
80	0.18	0.5	1.1	0.5	11.0	18.7	6.4
100	0.15	0.4	0.7	0.4	7.6	15.0	5.2

[a]Material taken from sand pit and selectively sieved to produce all study sands.

Tests were performed at two air and ice temperatures. To represent a "cold" condition, the ice was kept at −10°C and the air at −12°C. A "warm" ice condition was represented by ice at −3°C and air at −1°C.

Since abrasive performance is related to the quantity of material applied to the ice, two and sometimes three distinct concentrations of each sand type were tested for each set of conditions. Currently, the FAA recommends a sand application rate (concentration) of 49 to 98 g/m². We chose a concentration of 73 g/m² to fit the FAA specification and concentrations of 34 and 142 g/m² to represent half and double this.

All the test sands were heated to 70°C before application to ensure adherence of the sand particles to the ice surface. To determine the effect of sand temperature on abrasive "bonding" to the ice, a test series was performed in which the sand temperature was varied before application. A local sand pit product that had been run through a 9.5-mm slotted screen (3/8-in. sieve) was applied at 3, 20, and 70°C to simulate a sand kept in an unheated building, sand kept in a building with conventional heating, and sand that was super-heated just before distribution, respectively.

TEST PROCEDURE

Each test series began with traction and resistance tests run on a clean, smooth ice sheet immediately before application of a test sand. This provided a baseline reference of friction coefficient and was used to monitor the comparability of prepared ice surfaces. The ice sheet used for testing was much more slippery than would ever be allowed to exist on an operational runway, but the surface maximized our chances of detecting any differences in the frictional characteristics of various sand types.

After the bare-ice friction tests, sand heated to 70°C was applied to the ice surface with a conventional lawn broadcast spreader. Five minutes after sand application, four resistance tests followed by six traction tests were performed. Since measurements were being taken on both rear tires, 12 separate measures of traction were obtained. Each test was run in a fresh track on the sanded ice to avoid any areas disturbed by the slipping tires from a prior test.

After the completion of a test series, the test sand was removed from the ice sheet and the ice surface was restored to a clean, smooth surface for the next set of tests. A total of 560 tests were performed between March 18 and April 13, 1992.

RESULTS AND ANALYSIS

Measurements of friction force and normal load on each tire were taken during steady state conditions of speed, slip, and direction, allowing average values to be calculated for each test. Friction coefficient, often referred to as μ, was calculated for each test as the ratio of friction force to normal force. Within the FAA, and at most airports, it is customary to refer to a friction number, which is a whole number obtained by multiplying μ by 100. Friction numbers for our tests are shown graphically in Figure 1.

Our initial analysis considered the FAA sand at its recommended concentration of 73 g/m² to be the standard for comparison. At this concentration, the FAA, fine, and ASTM sands provided about the same amount of traction enhancement on cold (−10°C) ice, as shown in Figure 1 (*top*). These sands provide a friction number of about 15, an 83 percent increase over the bare-ice friction of 8.2. The SAE and TC sands gave higher friction numbers, roughly equal at close to 20, a 140 percent improvement in traction on bare ice.

On the warm (−3°C) ice [Figure 1 (*top*)], the FAA sand had the lowest friction number (15.2). The TC, SAE, and ASTM sands showed better performance, respectively, averaging a friction number of 17.2. This was a 53 percent increase over the bare ice and 13 percent better than the FAA sand. The fine sand gave the highest friction number (18.4), giving a 64 percent improvement over bare ice and a 21 percent better friction number than the FAA sand.

For the two ice temperatures tested, the FAA sand is the least effective of most of the test sands at the 73 g/m² concentration. The fine sand gives the best performance on the warm ice, but the poorest on the cold ice. The best all-temperature sand would appear to be the SAE sand, although the TC sand shows nearly equal effectiveness.

The trends noted are not readily explained by the gradations of the sands. Plots of performance against percentage passing any given sieve size (example shown in Figure 2) looks similar for all the size fractions identified in Table 2. A slightly increasing (for −3°C ice) or slightly decreasing (for −10°C ice) friction number is seen with increasing percentages of fine material in these plots.

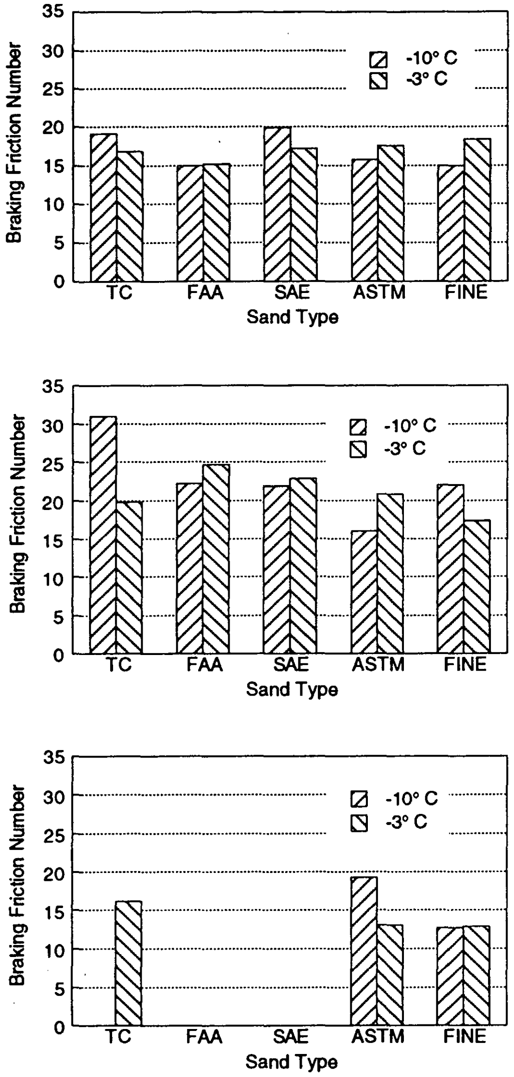

FIGURE 1 Braking friction performance at FAA-recommended sand concentration (73 g/m²) (*top*), twice the FAA-recommended sand concentration (142 g/m²) (*middle*), and half the FAA-recommended sand concentration (34 g/m²) (*bottom*).

Comparing the rankings of the sands at the two ice temperatures, the ASTM and fine sands had improved friction numbers at the higher temperature, the TC and SAE sands had diminished performance, and the FAA sand remained unchanged. This may be related to the relative percentage of fines contained in each sand type. To check for this trend, each sand's warm-to-cold ice tractive performance was plotted against the percentage of material less than 0.595 mm in diameter (No. 30 sieve) (Figure 3). A performance ratio greater than 1 indicates a sand that works better at higher temperatures, and a ratio less than 1 indicates a sand that works better at lower temperatures.

Freehand curves highlight the trends indicated by the data in Figure 3. The data for the 73-g/m² concentration indicate that when an abrasive contains at least 20 percent material passing the No. 30 sieve, the performance of the sands is independent of temperature. As the percentage of fines becomes less than about 20 percent, a very strong decrease in friction number occurs for warm ice compared with cold ice. For sands with high fines content (greater than 20 percent), only a slight increase in performance is seen for warm ice as compared with cold ice. Because the sand types used in this study leave a large gap between those containing large and small amounts of fines, a regression analysis could not legitimately be performed on the data in Figure 3.

With higher concentrations of sand applied to the ice, higher friction numbers were expected. This was found for all but one case; the fine sand showed a drop in performance when the sands were applied at a concentration of 142 g/m² on the warm ice sheet. [Relative performances of the sands at this concentration are shown in Figure 1 (*middle*).] On cold ice, the FAA, SAE, and fine sands had equal performance, giving a friction number of about 22. This was nearly 170 percent better traction than the bare ice. By comparison, the ASTM sand provided 27 percent less friction (16), and the TC sand 41 percent better performance (31), than the FAA, SAE, and fine sands.

At the high sand concentration on warm ice, the FAA sand showed the highest friction number (24.7). This represented a 120 percent increase in traction over the untreated ice. The

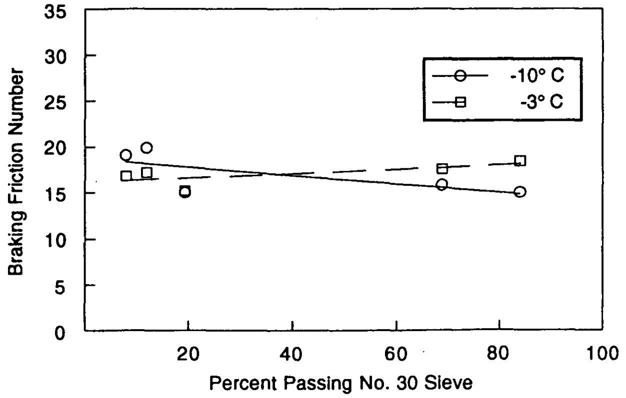

FIGURE 2 Variation in braking friction performance with fraction of sand smaller than a No. 30 sieve (0.595 mm) for the FAA-recommended sand concentration (73 g/m² at 70°C).

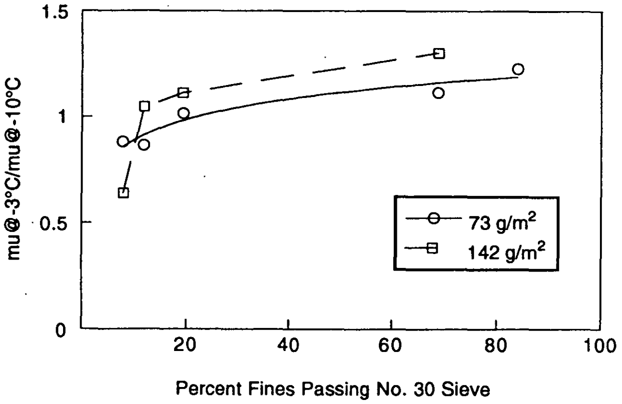

FIGURE 3 Relative improvement in tractive performance with ice temperature increase as a function of fraction of sand smaller than a No. 30 sieve (0.595 mm) for two sand concentrations.

other sand types provided 7 percent (SAE), 20 percent (TC), 25 percent (ASTM), and 30 percent (fine) less traction than the FAA sand. The friction number obtained for the fine sand in this case is suspect, since it did not follow the trend of improved performance with increased concentration that was seen for all the other sands.

Although the TC sand showed clearly superior traction on the cold ice, it displayed only mediocre performance on the warm ice. However, the SAE sand provided high friction numbers relative to the other sands and its relative ranking was not significantly affected by ice temperature.

The percentage improvement in traction with increasing ice temperature at the 142-g/m^2 concentration was also plotted (Figure 3). The fine sand was not included in this plot since, as noted, its behavior was anomalous. At this concentration, it is also clear that sand performance changes with ice temperature as a function of the amount of fines the sand contains. At the high sand concentration, this trend seems to be somewhat stronger than was observed at the recommended concentration. It also appears that the transition (performance ratio of 1) occurs at about 20 percent material passing the No. 30 sieve.

For the higher sand concentration, the results shown in Figure 1 (*middle*) do not correspond with the behavior displayed at the recommended concentration [Figure 1 (*top*)]. In fact, it can roughly be said that the rankings for the recommended concentration are the inverse of those found at twice this concentration (this is more true for the warm ice than the cold ice). This implies that traction is a strong function of concentration of abrasives on ice. By themselves, the physical characteristics of sand grains and the size distribution of the grains cannot be used to determine traction enhancement potential; application concentration must be included to make a determination.

Several tests were also performed at a sand concentration (34 g/m^2) below that recommended by the FAA. The ASTM and fine sands were tested on the cold ice. Results showed a surprisingly high friction number for ASTM sand (19.3) and a value of 12.7 for the fine sand [Figure 1 (*bottom*)]. On the warmer ice, the two sands showed essentially equal performance with friction numbers of 13. The TC sand was also tested on the warm ice, on which it yielded a friction number of 16.2.

The results of the low sand concentration tests show that, even with minimal abrasive application, at least a 50 percent improvement over bare-ice traction is possible.

Braking friction number was plotted against concentration for each sand type at both temperatures (Figure 4). Linear regression analyses were performed for each sand type by itself, and in nearly all cases a strong correlation resulted. The bare-ice friction number was included in the regression, corresponding with a sand concentration of zero.

Table 3 lists the regression coefficients and R^2, a measure of variability. The ASTM sand at low temperature showed a poor linear correlation because of the high performance recorded at the low concentration. The fine sand at the warm temperature also had a low regression correlation owing to the lower performance recorded at the highest concentration. A second-order regression on each of these data sets would yield a much better fit. However, confirmation of the trends shown by these two sands would be prudent before attempting o move to higher-order regression analyses.

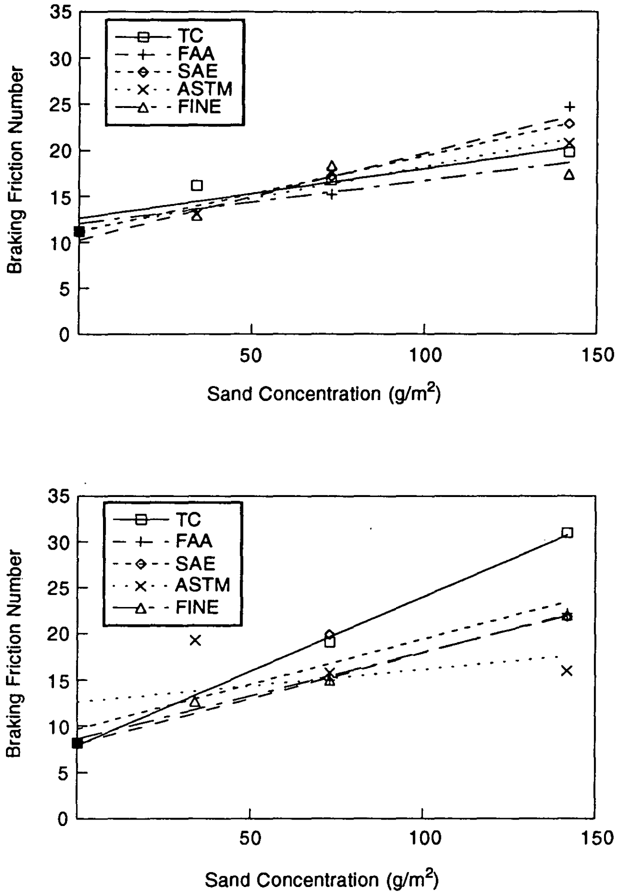

FIGURE 4 Braking friction number variation with application rate for test sands at −3°C (*top*) and −10°C (*bottom*).

On the basis of the regression analyses, increasing the concentration of any of the study sands on the ice caused an increase in traction coefficient. The expected increase in friction number ranges from 6 to 16 for each 100-g/m^2 increase in sand concentration, ignoring the two cases with poor correlation.

Comparing the slopes of the regression lines for the warm and cold ice for a given sand type supports the trend depicted in Figure 3. The TC sand, with very few fines, has a much stronger performance increase with concentration on the cold ice. The FAA and SAE sands show a nearly identical slope for the cold and warm ice. The ASTM sand has a stronger concentration dependence on the warm ice, as would the fine sand if the anomalous data point for 142 g/m^2 were not considered.

The test series designed to look at the effect of sand temperature was performed with the source material used for the study sands. This sand had a more evenly distributed range of grain sizes (Table 2) than the study sands. Tests were performed only on the warm ice (−3°C), with a concentration of 73 g/m^2. The sand was applied at a low temperature (3°C), a typical room temperature (20°C), and a super-heated temperature (70°C); braking friction numbers of 12.8, 14.7, and 19.7, respectively, were measured. Regression analysis on these data showed an excellent fit (Figure 5) to a linear equation, with increasing performance achieved for higher sand

TABLE 3 Regression Coefficients for Braking Traction as a Function of Sand Concentration for Each Study Sand

Regression coefficients: (Y= mX + b)[a]	TC	FAA	SAE	ASTM	FINE
			Ice temperature: -10° C		
b	7.9	8.1	9.7	12.6	8.6
m	0.161	0.099	0.098	0.035	0.094
R^2	0.999	0.999	0.933	0.456	0.994
			Ice temperature: -3° C		
b	12.6	10.2	11.2	11.3	12.0
m	0.055	0.095	0.083	0.070	0.047
R^2	0.861	0.938	0.999	0.966	0.683

[a] Where Y is the friction number, X is the sand concentration in g/m^2, b is the y-intercept of the equation, m is the slope of the best-fit line, and R^2 is the coefficient of determination.

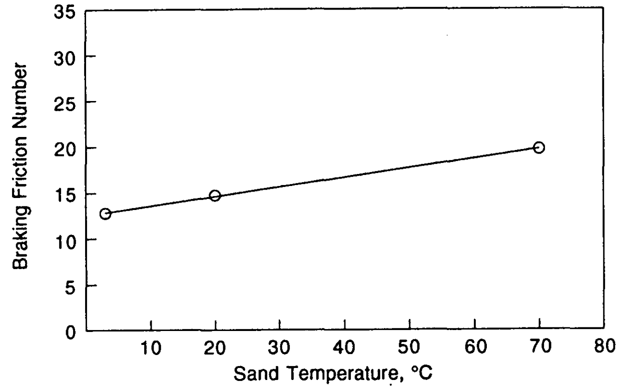

FIGURE 5 Braking friction number variation with sand temperature for source material applied at concentration of 73 g/m² at −3°C ($y = 12.6 + 0.102x$).

temperature. From this equation, every 10°C increase in sand temperature over ice temperature increases the friction number by 1.

DISCUSSION OF RESULTS

When comparing the results with those of past research, strong agreement was found. On cold ice with a high concentration of sand, the TC sand was found to provide significantly better performance than any of the other sands. This corresponds exactly with Hegmon and Meyer's conclusions that a coarse sand (primarily containing grain sizes between the No. 4 and 16 sieves) worked best in cold ice (−6°C temperature) tests (*2*). Hayhoe confirmed this result but concluded that, on warm ice (−1°C), traction was improved by increasing the percentage of fines contained in a sand (*3*). We also found this to be true, as shown in Figures 2 and 3.

Our results confirmed the importance of sand concentration on traction enhancement with abrasives, as pointed out by the Airports Authority Group (*5*). Both of the sands that they studied were coarse by comparison with some of those included in our study, but the group found that equal performance with two different sands could be obtained by applying each sand at a different concentration. Given a particular ice temperature, Figure 4 could be used to determine an application rate for each sand that would result in equal performance for all the sands used in this study.

In our previous study, friction on a cold ice sheet was found to strongly increase with increasing fines (*6*). This seems generally to disagree with the study reported here. However, the nature of the friction measurement in the two studies was significantly different. In our prior study, a small slider was used to generate a friction force, which resulted in a 100 percent slip rate (i.e., corresponding to a locked-wheel skid). In the current study, a low rate of slip that duplicates the slip present at the tires of large braking aircraft was used.

The difference in the two slip rates is significant in that, with a 100 percent slip condition, the tire is not rolling. This means that abrasives on the ice surface can only enter the tire-ice contact patch by being forced under the locked tire. The potential for dislodging, tumbling, and tossing the abrasive particles out of the path of the tire is great. In fact, it is greatest for the larger sand particles since they have a higher relief above the ice surface and would be more difficult to force under the leading edge of the tire. It follows then that sands with a high percentage of fines would stand a better chance of allowing more abrasive product to be drawn under the tire where they can contribute to traction enhancement.

A tire operating at a moderate to low rate of slip is rotating at a rate that is only somewhat less than a nonslipping tire. By rotating, the tire is able to roll onto and over sand particles on the ice surface, no matter what their size.

Our results also showed that heating a sand before it is applied to an iced surface can increase the friction number significantly. This behavior is clearly the result of the sand grains bonding more fully to the ice when applied at a high temperature. A greater percentage of the sand grains were partially imbedded in the ice as the application temperature increased. Heated particles of sand melt into the ice and refreeze to create a surface texture similar to sandpaper. The greater the difference between sand and ice temperature upon application, the stronger the mineral-ice bond and the higher the level of friction enhancement generated. Larger grains of sand held their heat longer and thus did a better job of bonding with the ice than did fine sand particles. More sand grains remained in the tire tracks for the hot sand than for the cold sand.

CONCLUSIONS AND RECOMMENDATIONS

Generally, coarse sands such as the TC sand provide the highest level of friction enhancement on cold (−10°C) ice surfaces. On ice at temperatures just below melting, sands with a large percentage of fines yield the highest friction coefficients. Sands composed mostly of grains from 1 to 2 mm in diameter (approximately No. 8 to No. 16 sieves), such as the SAE sand, showed good performance at both test temperatures.

The abrasive concentration on an ice surface is a more controlling factor than sand gradation in friction enhancement on ice surfaces. However, cost, environmental consequences, and logistics problems with storage, handling, and cleanup most likely will dictate practical limits on concentration.

The effect of sand application temperature can also easily overshadow sand type. A sand with a large percentage of 1- to 2-mm-diameter grains (approximately No. 8 to No. 16 sieves) heated to 70°C will hold its heat long enough during application to ensure a good bond to the ice. However, like sand concentration, logistical matters will govern what level of sand temperature is reasonable.

If the FAA were to endorse a single sand type, of the five sands included in this study, we would recommend that the SAE sand be specified for airport use. However, this would do little to alleviate the concerns of airport operators, because the SAE sand is no more likely to be available at sand pits than the current FAA-specified sand. Thus, a much more flexible specification must be generated to be of any practical value and to represent a step forward from current practice.

This study suggests that any sand is capable of matching the performance of another sand by the calculated selection of its application rate and the temperature at which it is applied to the ice. The effect of variable sand friction performance with ice temperature was also found to be linked to the amount of fines in the sand. Combining these factors, it appears entirely feasible to generate a mathematical expression that would describe the general relationship between sand type (degree of fines), ice temperature, sand application rate, sand application temperature, and braking friction performance. Using this approach, an airport operator would be free to explore various options for producing a desired level of friction enhancement on iced runways.

ACKNOWLEDGMENTS

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PART 3

Environmental Considerations

Methods and Reasons for Cutting Use of Salt in Finland

RAUNO KUUSELA, TAPIO RAUKOLA, HEIKKI LAPPALAINEN, AND ANTTI PIIRAINEN

Current standards in Finland require that all roads with average daily traffic above 6,000 be treated with salt through the winter. Sodium chloride is used in solid, prewetted, and liquid form, typically 120 000 t/winter. Calcium chloride is used as prewetter or in liquid form; annual quantities are less than 200 t. The application rates of salt vary from 5 to 40 g/m^2. The main argument against road salt has been the proven or suspected effects on groundwater resources, partly because of the glacial origin of Finland's soil. Thus, the pressure to minimize or even stop the use of salt has increased. One example shows that after an area of groundwater was contaminated, it took about 30 years for the soil to return to normal. The new strategy for reducing salt use is to use only prewetted salt and liquid salt whenever sensible. Low-volume roads are no longer treated. Accurate and fast snow clearing is one of the basic issues: dual-blade plows and hydraulically extendable plows have been developed for better snow and slush removal.

Finland is situated in Europe near Sweden, Norway, and the former Soviet Union (Figure 1). In terms of size, only a few European countries are larger than Finland. The distance between Helsinki and North Lapland is 1200 km. Of 5 million inhabitants, 60 percent live in urban areas, primarily in the south. The Finnish National Road Administration (FinnRA) is responsible for a road system of 76 000 km. The country is divided into 13 road districts, each of which is divided into 152 subareas (or road master areas).

CLIMATE

The average annual temperature is about 5.2°C in the southern region (the maritime climate of Helsinki) and about -1.0°C in the north. The thermal winter lasts between 125 and 200 days, and annual precipitation is 400 to 600 mm. The average annual snowfall is about 35 percent of the total precipitation. The greatest snow depth of the winter in forests is 450 mm in Helsinki and 800 mm in Lapland.

The last three winters have been very mild. In Helsinki the long-term average temperature in February is -5.5°C, but this year it was nearly 0°C. This type of weather necessitates much deicing and snowplowing (Figure 2).

TERMS

Some terms to be used in the paper are defined:

- Esker: an elongated ridge of rounded stratified fluvioglacial deposits consisting primarily of sands and gravel with some finer and coarser materials. Some are only tens of meters long, but others extend for hundreds of kilometers.
- Aquifer: water-saturated horizon that has sufficient porosity and permeability to yield economic supplies of groundwater; consistent groundwater area.
- Curative: a treatment before ice formation or snow accumulation.
- Preventive: a treatment after ice formation or snow buildup.
- Prewetting spreader: a type of a spreader that facilitates the wetting of granular salt.

DEICING METHODS IN FINLAND

In Finland the roads are classified for winter maintenance operations. Classes I and I Super are chemically treated throughout the winter (*1*) (Table 1). Sodium chloride (NaCl rock salt) is used in solid, prewetted, and liquid form, typically 120 000 t/winter (7 to 10 t/two-lane-km) (Figure 3). Calcium chloride ($CaCl_2$) is used as prewetter or in liquid form (32 percent); annual quantities are less than 200 t. The application rates vary from a preventive 5 g/m^2 to a curative 40 g/m^2.

The roads in Maintenance Class II or lower are treated with a sand-salt mixture of 25 kg for one cubic meter of sand (approximately 1:50). The sand application rate is about 300 g/m^2.

RISK LEVELS OF CHLORIDES

Different organizations have set up limits for chloride content in drinking water (*2*). The waterworks' standard maximum level of chloride content in drinking water in Finland is 100 mg/L if the works provide water for more than 200 consumers. The optimum level is below 25 mg/L. No recommendations for sodium content in water have been set.

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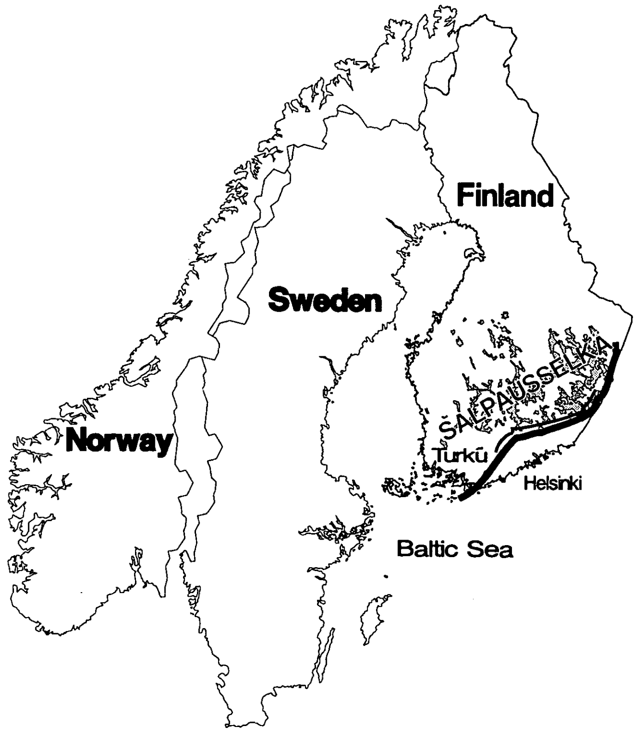

FIGURE 1 Finland and its Scandinavian neighbors.

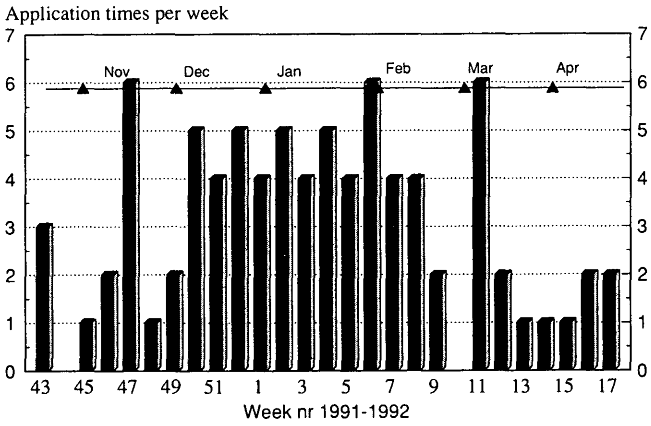

FIGURE 2 Deicing application on Highway 8 (Raisio district near Turku seacoast, 15 km from Gulf of Bothnia.)

TABLE 1 Winter Maintenance Classification

Category	Traffic Volume
I Super Divided	Freeways
I Super	ADT > 6000
I	ADT 1500 - 6000
II	ADT 200 - 1500
III	ADT < 200
IV	Pedestrian and Bicycle Paths

ADT = average daily traffic

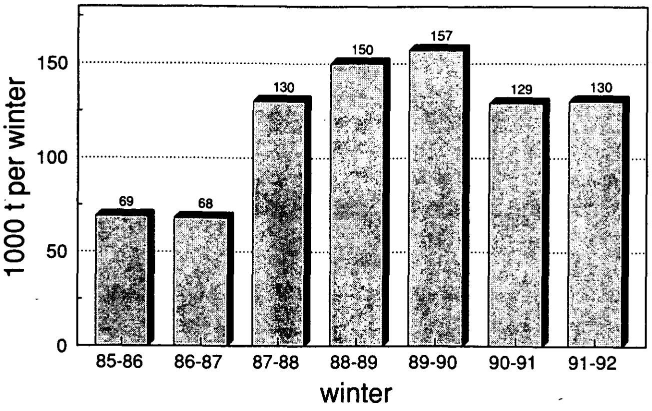

FIGURE 3 Usage of deicing salts in Finland, 1985–1992, for about 10,200 two-lane-km at application rate of 10 to 15 t/two-lane-km.

ENVIRONMENTAL EFFECTS OF SALTING

Effects on Plants

In Finland the results of the analyses show only a limited effect to plants from road salting. The sensitivity of trees is highly dependent on the species. The main problem is the salt spray from melted snow or ice. The most common trees—such as pine, spruce, and birch—are relatively resistant to the effects of road salt. However, local discoloration problems with young pine trees growing very close to the road have been found. The salt spray seems to decrease their tolerance to cold and disease (*3*).

Effects on Groundwater Resources

In the mass media the main argument against road salt has been the proven or suspected effects on the groundwater resources. Part of the problem is the glacial origin of Finland's soil. The Salpausselkä Ridge comprises nearly 400 km of virtually continuous esker (Figure 1). Building roads on the top of a gravel-filled ridge used to be cheap and easy; for this reason old highways have been built over the ridge. The huge banks of gravel and sand are also a very important groundwater formation area. Unfortunately, the contamination sources—in this case, traffic and maintenance—are in the worst possible place.

A recent study for FinnRA examined road salting on the Salpausselkä Ridge because it contains Finland's most important groundwater reserves (*4*). There are more than 80 municipal waterworks (each waterworks serves more than 200 inhabitants) as well as many private wells and small waterworks along the ridge. Nearly 1 million Finns (a fifth of all inhabitants) receive their drinking and domestic water from the Salpausselkä aquifers.

The study examined the salt concentration variations at 27 waterworks. In most cases it could be shown that the salt concentration in the groundwater had clearly increased because of the use of road salt. The Salpausselkä Ridge comprises many small aquifers, the geohydrological conditions of which differ. Thus, the salt content in the groundwater can vary regionally as well as locally.

The chloride concentrations vary significantly in the aquifers along the Salpausselkä, although the road salt loading had been consistent on the highway. As the risk of the future groundwater contamination caused by salting is estimated, the subjects should be examined separately. No single recommendation for road salt use can be supplied on the basis of this paper.

Most waterworks are located in large aquifers. In such cases, salt dilutes effectively. Because of this dilution, the changes in the quality of the aquifer water caused by salting are delayed, or they cannot be observed at all in areas where long-term sampling or a sufficient yearly sampling schedule for chloride analysis has not been arranged.

If the aquifer becomes salinated slowly, the purification is even slower. Measurements have been carried out since 1933 for the Kaaringo waterworks near the town of Turku (Figure 4). It became salinated from 1960 to 1966; the amount of chloride rose from 20 to 65 mg/L. Here, road salt may not be the only cause, because extensive deicing did not start until 1966.

There are two other possible sources of contamination: industrial waste waters and "natural" salt soil layers of sea origin, which make the determination of a normal chloride level difficult. In the northern part of Finland are groundwaters with chloride levels of only 2 to 5 mg/L. Some esker origin waters have values of 15 to 20 mg/L, and near the west coast of Finland, groundwaters contain a natural chloride level of up to 200 mg/L.

A protective silt-clay layer was built in 1969 mainly to prevent oil damage. It also stopped saltwater penetration. However, it will take about 30 years for the soil to return to normal. In the large aquifers of the Salpausselkä, it would take notably longer for salinated groundwater to become pure again.

There are 4100 km of public roads in the Kymi district, near the Salpausselkä. The total winter maintenance costs are $6.3 million. Ice control costs in the main network (720 two-lane-km, salt deicing) are $1.6 million. Substantial payments were first made in 1991 for the contamination of wells. Most of the wells supply water to only one or two houses. The costs for new wells or for providing an alternative water supply were $500,000, and these costs were probably at about the same level in 1992. Compared with ice control costs, this bill is high. Figure 5 shows the salt content in relation to the distance from the road; the numbers come from 72 waterworks in the Häme district. Correlation between the distance of the road and chloride concentration is not very strong.

STRATEGY FOR REDUCING SALT USE

Today it is impossible to do without the application of salt on the high-capacity roads. No other deicer can be used on a larger scale for road maintenance. However, there are several possibilities for reducing the problems caused by salt. FinnRA's present strategy is as follows:

1. Because traffic flow improves the effect of salt, less salt will be applied to high-volume roads and none to roads under ADT 2,000 (except in fall and spring).
2. Large quantities of salt are needed for melting snow and ice, so rapid and efficient snowplowing is needed and routine

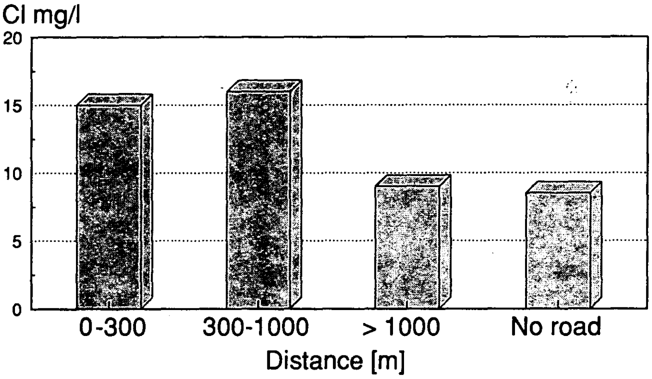

FIGURE 5 **Average chloride concentration by distance of Class I highway; "no road" means nearest road is more than 10 km from waterworks.**

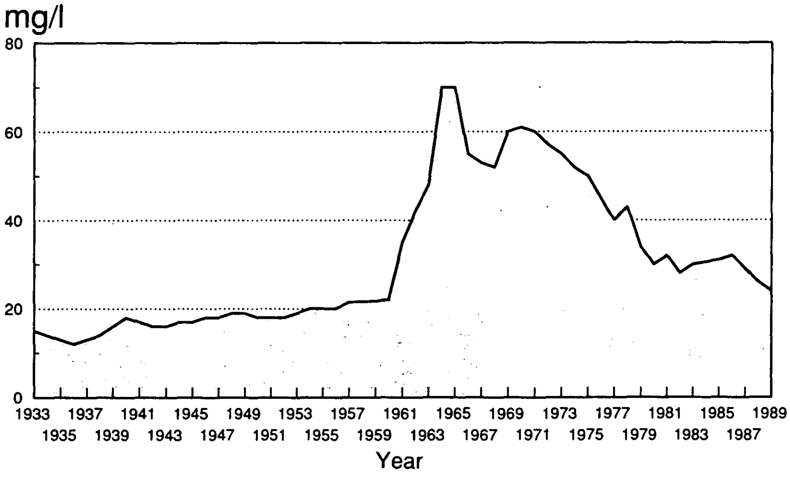

FIGURE 4 **Chloride concentration in groundwater at Kaaringo waterworks.**

salting is not necessary during snowfalls if the snow does not pack onto the road surface (temperatures under −3°C).

3. To minimize the loss of salt, prewetting salt will be the standard method, and for temperatures down to −3°C and for anti-icing, the liquid salt method will be used.
4. As for equipment, road speed-related control and frequent calibration are needed; the same equipment should not be used for salt and sand because calibration is almost impossible.
5. A standardized method of reporting is needed, and differences between districts must be followed and analyzed.
6. Motivation and training: human activities are important.

The winter maintenance policy for the coming years permits chemical deicing but only in certain cases: to prevent the formation of black ice, to keep snow from becoming compacted, and to maintain a slushy consistency to make snowplowing easier. Roads are cleared and dried by salting away a thin layer of snow and slush.

In Finland effective techniques have been introduced that make it possible to improve greatly the speed and quality of work. A greater removal speed will reduce the possibility of snow's becoming compacted. A typical investment period is 1 to 2 years.

The road-weather information systems give more time and opportunities to optimize the procedures. In temperatures below −6°C, no salting is carried out because the quantities of chemicals needed are not in line with the safety code. Drivers should also take care and pay attention to their own safety.

A relatively good safety benefit is gained by new slush plows. The amount of salt needed to convert snow to dry slush is about half of that required to make snow totally wet.

The use of wet or brine salt as a standard method supported by plants that produce a heavy volume of brine (30 to 40 m^3/H) reduces by up to 30 to 50 percent the amount of salt per treatment compared with dry salt. Yet rapid snow and slush removal helps to cut down the amount of deicers even more as there will not be so much snow to be melted away. During the last 3 years the number of prewetting spreaders has grown from 50 to 125 and liquid spreaders, from 2 to 125.

Liquid salt is one of the keywords when reducing salt use in Finland. From FinnRA's experiences, the advantages of liquid salt are

- Very rapid reaction time (only minutes),
- Greater spreading speed (up to 70 km/hr),
- First good method for preventive treatment during fall and spring,
- Possibility of operating over longer distances because of even distribution when using very small quantities, and
- Application rates are 75 to 50 percent less than with granular salt, because of accuracy.

But there are drawbacks:

- Because of refreezing, the temperature of the road surface may not be below −3°C;
- The critical snow depth is 10 to 20 mm at −1°C;
- If the total amount of water is low, temperatures under −3°C are possible, but the correlation between these must be thoroughly understood;
- Two types of equipment, brine mixing plant and storage facilities, may double deicing costs; and
- Total saving in tons is less than 20 percent if most snowfalls occur in temperatures below −1 to −5°C, in which granular salt is needed.

In southern Finland during the 1990–1991 and 1991–1992 winters, nearly 75 percent of all application times were in the possible liquid salt operational temperature from the Raisio district (Figure 2).

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Environmental Effects of Alternative Deicers: Review and Assessment Method for Calcium Magnesium Acetate Biochemical Oxygen Demand Applied to Illinois Example Case

J. WAYLAND EHEART, WING-HO HO, CHRIS D. GINGRICH,
ROBERT J. HAUSER, AND SARAHELEN R. THOMPSON

A modeling-based method for assessing the potential impact of calcium magnesium acetate (CMA) on the dissolved oxygen in streams through biodegradation is presented. The method was applied to two example Illinois streams—the Kaskaskia River and the Boneyard-Saline Branch-Salt Fork-Vermilion river system, both of which receive urban and rural runoff. These two examples were chosen as pessimistic, involving small streams potentially receiving relatively large amounts of CMA biochemical oxygen demand. The method predicts that the oxygen degradation in the stream may be severe under the worst conditions, which involve the largest number of small successive snowfalls since records have been kept, after each of which CMA is assumed to have been applied, as well as stream ice cover, which prevents reaeration. Both example streams are predicted to go anaerobic over part of their length. However, if only the stream ice cover is assumed not to exist, thus allowing aeration, the dissolved oxygen impact is, although significant, insufficient to violate the prevailing stream standard of 5 mg/L. The results suggest that in Illinois streams the oxygen-depletion impact of CMA may be severe but that such instances will be relatively uncommon; more often the impact will be well within that which can be assimilated by the stream.

Highway administrators currently face a dilemma in choosing a method to deice winter roads. Direct costs of salting, usually with rock salt (sodium chloride), are relatively low, but these costs exclude damage to vehicles, highways, bridges, and the environment. If external costs are included, the total cost of salting increases considerably. In 1976, for example, this larger cost for the United States was estimated at nearly $3 billion—15 times the costs for materials, storage, and application (*1*). On the other hand, the public demands safe roads throughout the year, requiring that a deicing agent be used to clear winter roads. Past attempts to lower the total costs of deicing have focused on reducing the amount of salt applied on roads; these strategies often either failed to reduce significantly total salt applications or resulted in an inferior level of winter road safety.

Some alternative deicers are less corrosive than salt, but they have higher initial costs. In another paper in this Record, Gingrich et al. address whether the increase in the initial cost of alternatives is less than the savings in vehicle, highway, and bridge damage that would result from their widespread use. The environmental effects of these alternatives may be qualitatively different, rendering comparison difficult. The most popular of such deicers is calcium magnesium acetate (CMA). Although it is a salt, its potential environmental effects are generally different from those of salt. It damages vegetation and soil to a much lesser extent than salt (*2*), causes less ion mobility (*3*), but may have a somewhat greater impact on phytoplankton, invertebrates, and fish (*2,4,5*). Additionally, it will deplete oxygen from streams and lakes by aerobic biochemical degradation of the acetate ion, which is readily and rapidly used by aerobic bacteria (*6*). Reviews of environmental effects of alternative deicers are presented by D'Itri (*7*), TRB (*8*), and Goldman and Malyj (*9*). A number of papers assess the biological degradation and potential oxygen-depleting effects of CMA-laden runoff in sewage treatment works (*10,11*), ponds and lakes in which complete mixing is assumed (*2,6*), and soil (*3,12*). However, the authors are unaware of any studies of these problems in natural streams.

This paper reports on a quantitative modeling study focusing on the oxygen-depleting effect of CMA in two Illinois streams: the Kaskaskia River and several tributaries and a stretch of the (southeastern) Vermilion River. The next section presents a modeling-based method for assessing the potential impact of CMA on the dissolved oxygen (DO) in streams through biodegradation.

OXYGEN-DEPLETION EFFECTS OF CMA FOR ILLINOIS EXAMPLE CASES

In this section, we describe a modified Streeter-Phelps (*13*) model that is used to predict the DO in a stream. The model

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uses the standard method of characterizing aerobically biodegradable waste in terms of its biochemical oxygen demand (BOD), the amount of oxygen it would consume under microbial action in a sealed container. The model is applied to two example cases in Illinois. The Streeter-Phelps model is quite venerable and simple, although the modifications to accommodate other effects besides point sources of BOD are more recent and add to its sophistication. Nevertheless, it remains one of the most useful tools available to estimate the impact on water quality of BOD discharges, because it requires the evaluation of so few parameters. More sophisticated models were available to the authors, but calibrating such models was beyond the scope of the research project.

Modeling Method

The model, which accounts for tributary flow and multiple point sources of BOD along the length of the stream, is given by the following recursive equations. Let D_j be the DO deficit, that is, the difference between the DO and the saturation DO, at the downstream end of any segment of the stream (referred to as a reach) j. Then

$$D_j = \frac{L_{j-1}Q_{j-1} + \ell_j(Q_j - Q_{j-1})}{Q_j} h_j + \frac{D_{j-1}Q_{j-1} + d_j(Q_j - Q_{j-1})}{Q_j} g_j$$

where

$$L_j = \frac{L_{j-1}\, Q_{j-1} + \ell_j\, (Q_j - Q_{j-1})}{Q_j} f_j$$

$$f_j = e^{-k_{rj}t_j}$$

$$g_j = e^{-k_{aj}t_j}$$

$$h_j = \left(\frac{k_{dj}}{k_{aj} - k_{rj}}\right) (e^{-k_{rj}t_j} - e^{-k_{aj}t_j})$$

k_{dj}, k_{rj} = BOD decay and removal coefficients in reach j, respectively;
t_j = travel time;
k_{aj} = reaeration coefficient in reach j (the four previous parameters are assumed uniform within reach j);
Q_{j-1} = streamflow at downstream end of reach j, so that $(Q_j - Q_{j-1})$ is the combined flow of all tributaries entering reach j;
L_j = BOD concentration at downstream end of reach j; and
ℓ_j, d_j = BOD and DO deficit concentrations in combined tributaries to reach j, respectively.

The model assumes that the BOD decay is a first-order reaction and, combining that assumption with the principle of superposition, allows multiple point sources of BOD along the length of the stream. Longitudinal mixing in the receiving stream is assumed negligible, which allows the use of this steady-state model for what is an inherently unsteady process. This assumption, though not entirely justified for a slug input such as is modeled here, is chosen because it is pessimistic. Furthermore, data on longitudinal dispersion coefficients were unavailable for the streams modeled.

The principal mechanisms for the effect of CMA on DO are (a) the rate of biodegradation by microorganisms in the stream, (b) the rate of replenishment of oxygen from atmospheric reaeration, and (c) the amount of CMA entering the stream. These mechanisms are represented by the model, and parameters are associated with each.

Selecting Model Parameters

Connolly et al. (*6*) report on a laboratory batch reactor experiment showing that the decay coefficient, k_d, of CMA in water (and presumably microorganisms) from a small stream tributary of the Scituate Reservoir in Rhode Island is 0.0326 per day at 2°C. However, Wright and McDonnell (*14*) report a streamflow-dependent formula for the decay coefficient that yields decay coefficients of the same order of magnitude or slightly larger than those reported by Connolly et al. (*6*). The Wright and McDonnell estimate was adopted as pessimistic (*14*).

The rate of atmospheric reaeration is characterized by the reaeration coefficient, k_a. The model estimates the reaeration coefficients by the O'Connor and Dobbins formula (*15*). The model adjusts both the decay and the reaeration coefficients for variations in water temperature according to the exponential formula (*16*). The temperature correction factors are taken as 1.047 for the decay coefficient and 1.024 for the reaeration coefficient.

Estimating Delivery Rate of CMA

The quantity of CMA entering the stream depends on (a) the area of treated roadway that drains to the stream, (b) the rate and frequency of application of the deicer, (c) the route and the rate of transport from the roadway to the stream, and (d) the extent of biodegradation along the route of transport.

When CMA is transported from the treated roadway to the stream, some CMA may be biodegraded in soil between the road and the stream. To be pessimistic, however, the model assumes no degradation to occur between the road and the stream. This assumption, admittedly pessimistic, might be accurate during rapid snowmelt events during which the CMA-laden runoff predominately travels rapidly over land and through ditches rather than slowly through soil.

The model uses a factor of 0.72 to convert initial CMA concentration to ultimate BOD (*2*). The streamflow data are extracted from the records of streamflow compiled by the U.S. Geological Survey. Ungauged flow rates are estimated from flow rates at nearby gauging stations in proportion to the drainage area. The model also requires a description of the hydraulic geometry along the length of the stream. The hydraulic parameters are adopted from Stall and Fok (*17*).

The would-be CMA concentration after a snowmelt event is estimated as follows: It is assumed that the mass of CMA on the road just before the snowmelt event is known. Because the streamflow upstream of the uppermost stream gauge is unknown, minimal biodegradation of CMA between its point of origin and that point is assumed. Hence, it is assumed that biodegradation commences at the uppermost stream gauge. From topographic maps, the amount of CMA in each stream catchment can be determined. A snowmelt event is identified from the record as a period in which the air temperature increased above freezing, the snowpack decreased, and the streamflow of the receiving stream increased.

The snowmelt hydrograph (Figure 1) is decomposed as follows: The streamflow before the snowmelt event is attributed to groundwater accretion and is called the base flow, B. The excess streamflow during that period is attributed to snowmelt and is assumed to carry a constant concentration of CMA. Therefore, the concentration of CMA in the CMA-laden water flowing into the stream during the entire snowmelt event is calculated as the mass of CMA on the roads in the basin, M, divided by the volume of water in the hydrograph above the base flow. This volume, V, is mathematically the integral of the streamflow Q minus the base flow B over time. The actual concentration of CMA in the stream, then, varies over time, depending what fraction of its flow is from the snowmelt containing CMA and what fraction is from groundwater, which is assumed not to contain CMA. Thus, the concentration of CMA in the stream at any time is given by

$$C = (Q - B)M/[Q \int (Q - B)dt]$$

To be pessimistic, the maximum value of this concentration, which occurs at the peak of the hydrograph, is used in determining the headwater BOD in the modified Streeter-Phelps equation. Under the assumption of zero longitudinal dispersion, the minimum DO would occur as this slug of water passed through the stream system.

Occasionally, the streamflow in the hydrograph does not return to its antecedent (pre-snowmelt event) value. (It is likely that some of the water is being held up in shallow groundwater.) In such cases, the base flow is taken as the antecedent flow and the streamflow is artificially returned to this value at the time of the first occurrence of a zero-depth snowpack. This is a pessimistic approach in that it assumes the CMA to be delivered to the stream more rapidly than it actually is.

This method assumes that the snow containing CMA melts at the same rate as other snow, which may not be an accurate assumption. The roadside snowpack contains a melting agent that lowers its melting point and might cause it to melt more quickly. It is assumed, however, that this will not occur to any significant degree, since in any such melting the CMA solution would mix with more unmelted snow, thus preventing its progress toward the stream until the air temperature is high enough to melt all the snow. Instead, the roadside snowpack, because it has a much lower surface-to-volume ratio, may actually melt more slowly than a uniform snowpack covering the land, despite containing a melting agent. Thus the assumption of a uniform rate of melting for all snow is seen as pessimistic in that it overestimates the rate at which CMA is delivered to the stream. If the peak CMA concentration occurs either before or after the peak streamflow, the concentration throughout the snowmelt event will be less than estimated by this method.

Example Cases

Both example cases are chosen to represent worst-case scenarios for the oxygen depletion effects of CMA and are characterized by small streams being polluted by relatively large amounts of BOD associated with CMA use in an urban area. Figure 2 shows the locations of the two cases. The first is an upper reach of the Kaskaskia River in Illinois. Within this example, two scenarios were simulated; the first includes CMA BOD from urban sources in west Champaign, Illinois; rural sources in the Kaskaskia basin; and sewage BOD from the southwest treatment plant of the Urbana-Champaign Sanitary District. The second includes only the sewage plant and rural portions, excluding the urban runoff.

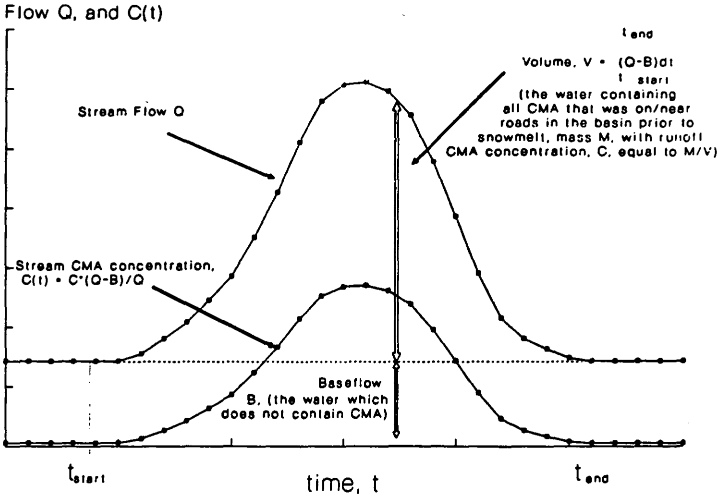

FIGURE 1 CMA delivery determined from decomposition of snowmelt hydrograph.

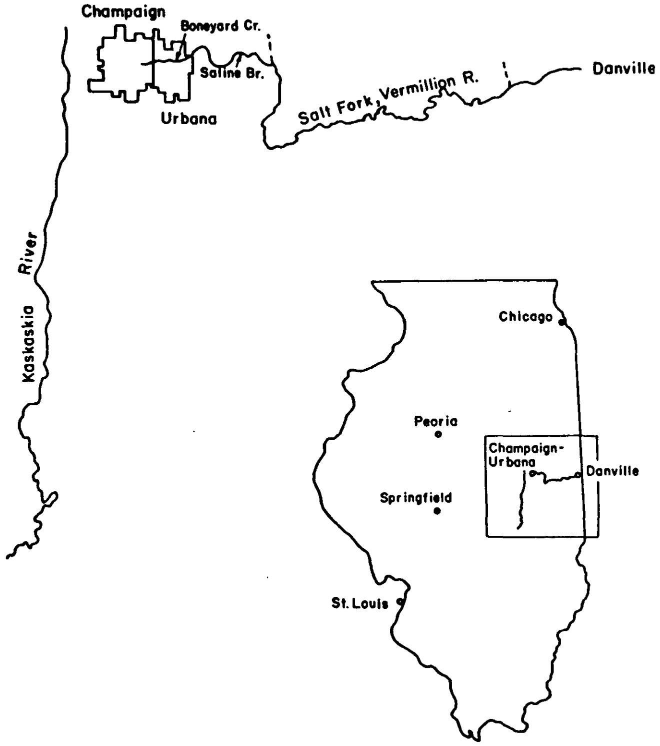

FIGURE 2 Locator map of example cases.

The second case is the Vermilion River in the Wabash River Basin in Illinois. It includes Boneyard Creek, Saline Branch, Salt Fork, and Middle Fork Vermilion River. Boneyard Creek, which is a small stream passing through Champaign-Urbana, Illinois, receives a large portion of the street runoff from those cities. For this example, only one scenario was simulated, which included the urban, rural, and sewage portions of runoff for this basin.

For both cases, the worst period of snowmelt from the historical record was December 1, 1983, through January 5, 1984. During this time, there were five relatively light snowfalls, interspersed with and followed by closely spaced melting events, resulting in what would have been a high concentration of deicer in the melt runoff. Each snowfall was assumed to have been followed by the application of deicer at the equivalent salt rate of 250 lb/lane-mi (71 kg/lane-km). This is the rate used by most counties in Illinois and most Illinois Department of Transportation districts. On the basis of the substitution rates discussed earlier, a CMA application rate of 1.5 times that of road salt, or 375 lb/lane-mi (107 kg/lane-km), is assumed.

Results

During a thawing period, it is possible to have both delivery of water from snowmelt and an ice-covered stream. This is considered the worst case; there is no atmospheric reaeration, and replenishment of oxygen is entirely due to DO in the tributaries. Thus, for both the Kaskaskia and Vermilion cases, two conditions of atmospheric reaeration were analyzed in the BOD modeling: aerated and ice-covered.

Kaskaskia River

Figure 3 illustrates the modeling results as DO profiles for the Kaskaskia River. Because of the high spatial density of deicer-treated highways and the low flow in the river, the BOD in the stream due to CMA is highest near the head of the river (near Bondville and Ficklin). The maximum CMA BOD entering the river occurs near Bondville; it is about 20 mg/L, depending on the scenario. The DO in the river is completely depleted under the most pessimistic conditions of full urban runoff and ice cover. The DO profile of the river when it is aerated is higher than that when it is ice-covered, and it is particularly significant near Bondville and Ficklin. This shows that the potential oxygen depletion of CMA in the river may be substantially reduced by atmospheric reaeration. The figure also shows that the urban portion of CMA runoff contributes substantially to the BOD load. The effect of the sewage discharge was included, but it was not substantial.

Boneyard–Saline Branch–Salt Fork–Vermilion Basin

Figure 4 illustrates the results of the BOD modeling for streams in the Boneyard–Saline Branch–Salt Fork–Vermilion basin.

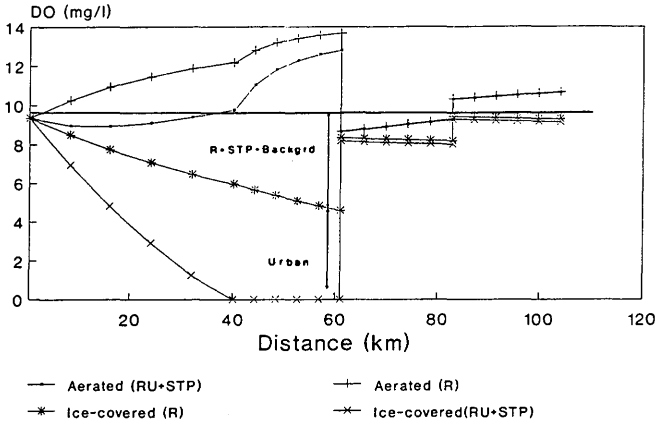

FIGURE 3 DO profiles for Kaskaskia River.

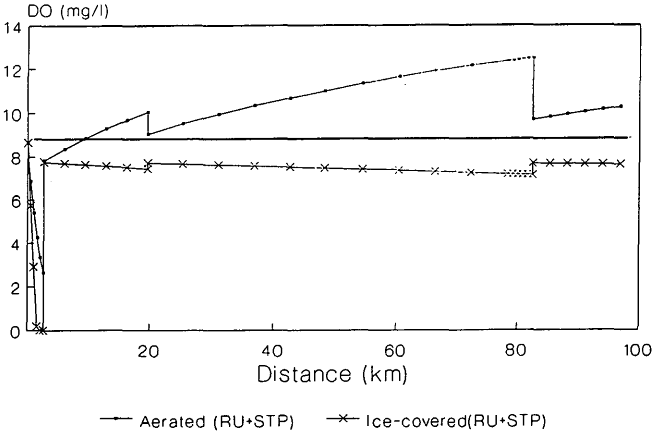

FIGURE 4 DO profiles for Boneyard–Saline Branch–Salt Fork–Vermilion system.

Because of the high density of roadways from which Boneyard Creek receives CMA, the CMA BOD entering the Boneyard Creek at Champaign-Urbana is as high as 124 mg/L. This high BOD has the potential of complete oxygen depletion at certain locations when the streams are ice-covered. When they are aerated, there is substantial DO depletion in Boneyard Creek (DO falls from 8.6 to 1.4 mg/L), but the DO increases to above 7.8 after Boneyard Creek enters the Saline Branch.

FINAL REMARKS

The modeling results presented in this paper suggest that under certain circumstances, CMA may deplete oxygen in streams substantially. The scenarios evaluated were deliberately crafted to be quite pessimistic. The examples were thought to be the most pessimistic in Illinois. Both involved the same urban area, Champaign-Urbana, discharging street runoff to a small stream. Such a case—that is, a relatively large city located on a small stream—is generally the most critical for deicer impact on the water quality of the stream.

The pessimistic assumption of ice cover during a snowmelt event is somewhat unlikely, since snowmelt is often accompanied by ice breakup. Nevertheless, after particularly severe winters with thick stream ice cover, snowmelt runoff can increase streamflows while the ice remains intact. Moreover, even when stream ice is gone, ice cover on lakes may remain.

The assumption of no degradation of acetate between the road and the nearest gauged stream is somewhat pessimistic in a rural setting. Soil microbial activity may significantly reduce the amount of CMA that will actually reach the streams. However, this effect is less pronounced in urban areas where a large portion of the flow is on streets and in storm sewers, where little such rectification occurs.

The assumption of zero longitudinal dispersion is pessimistic, but it is more accurate for the smaller upstream reaches of streams in which the greatest DO loss was predicted. The model did not include sediment oxygen demand, parameter values for which were unavailable for the two Illinois streams modeled. Accounting for this effect would decrease the amount of CMA-laden runoff that the stream can accommodate without violating the DO standard. An analytical mathematical model for DO that accommodates longitudinal dispersion is readily available but the dispersion parameter is not, and evaluating it was beyond the scope of this project.

Although a definitive verdict on the effect of CMA on DO in streams will have to await further, and probably empirical, study, the results presented here suggest that the oxygen-depletion effects of CMA in natural streams may be of concern, but primarily in cases of urban areas on small streams.

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This paper has not undergone the peer review process of the Illinois Department of Energy and Natural Resources; the findings are those of the authors and do not necessarily reflect the views of the department.

PART 4

Drift Control

An Approach to the Design of Treatments To Prevent Snowdrifting on Highways

MAX S. PERCHANOK, DAN G. MCGILLIVRAY, AND JAMES D. SMITH

Drifting snow causes hazardous driving conditions at many locations in Ontario. Drifting can be reduced by a variety of changes to the natural landscape, but selecting the best solution for each problem situation can be difficult, and the consequences of an inadequate treatment can be extremely costly. A standard design treatment and a computer modeling system have been developed to help reduce snowdrifting hazards on highways. The standard treatment involves a cross-sectional design and a vegetation scheme. Components of the treatment include a steep backslope, a wide storage ditch, a shallow sideslope, and a snow hedge that reduces the amount of snow reaching the highway. The snow storage requirement of the standard treatment is 31.5 m^3/m of hedge length. It was developed empirically from five seasons of snow accumulation measurements. The computer modeling system simulates the snowdrifting process over gridded areas of complex terrain, in time steps of 1 hr. The system can be used with real or design storm meteorological data to compare the effectiveness of landscape or geometric treatments proposed by the highway designer. Tests on highway sites in southern Ontario's snow belt have demonstrated the viability of the model, and it is now being incorporated into computer-aided systems for designing highways and planning roadside landscaping.

The Ministry of Transportation of Ontario (MTO) has a winter maintenance program to keep provincial highways clear of snow and ice that accumulate on the driving surface during winter (*1*). The program is carried out through active measures such as plowing and applying deicing chemicals and abrasives.

At certain highway locations, snow and ice problems are exacerbated by local topographic effects that cause fallen snow to drift onto the road. Drifting can result in several types of driving hazard. In the simple case, drifting snow sticks to the driving surface and accumulates in deep drifts. More plowing is required at the drifting sites than in the rest of the patrol area.

When a thin layer of snow accumulates, vehicle tire action causes the snow to melt and refreeze, forming a film of ice that requires additional applications of salt or sand. In other cases the drifting snow crosses the highway at windshield level or higher, obstructing drivers' visibility (a whiteout). Whiteouts create a particularly hazardous situation that can be remedied only by closing the road.

In addition to the safety hazard, localized snowdrifting reduces the efficiency of the maintenance program because extra equipment callouts are required to service very localized areas.

MTO has developed a range of passive control measures to minimize the winter driving hazards caused by localized drifting snow. They are not used on all highways, only where localized drifting causes inconsistent driving conditions, safety hazards, or increased maintenance expense due to extra equipment callouts to service localized areas (*2*).

Passive measures of the winter maintenance program include the installation of temporary snow fences or permanent snow hedges, each of which reduces the quantity of drifting snow that reaches the road surface (*1*). Over a 25-year life cycle, passive treatments may cost up to 100 times less than active measures, depending on the relative occurrence of snow accumulation due to precipitation versus drifting (*2*).

Passive treatments are also incorporated in the geometric and landscape design of Ontario highways on a site-specific basis. In the past, the design of passive treatments required specialized expertise available only through the Research and Development Branch or private consultants. The design process was therefore expensive and time-consuming in comparison with the design process for the rest of the highway.

This paper describes an approach to the design of passive snowdrift treatments. It incorporates a standard design that is applicable in many highway situations, and a computer modeling system that can help highway designers with minimal expertise in snowdrifting to develop site-specific treatments where the standard treatment is not applicable.

MTO STANDARD TREATMENT

Description

A single treatment was developed at MTO that can be used to prevent localized snowdrifting in topographic situations common on Ontario highways: highways that are on shallow fill or in a shallow cut, have standard highway drainage ditches, and are exposed to snowdrifting from adjacent farm fields.

The standard treatment incorporates a right-of-way cross-sectional design and roadside vegetation scheme that prevent drifting snow from reaching the highway and provide off-road storage for plowed snow. The essential elements of the treatment are a snow hedge and a snow storage ditch. Other important features are a steep backslope, a wide storage ditch, a shallow inslope, and a vegetation scheme (Figure 1).

The purpose of the snow hedge is to interrupt low-level wind flow and cause snow carried by saltation and suspension to be deposited in a drift on the ground. Snowdrifts thus formed have a characteristic shape and length that are related to the height and porosity of the hedge and determine the

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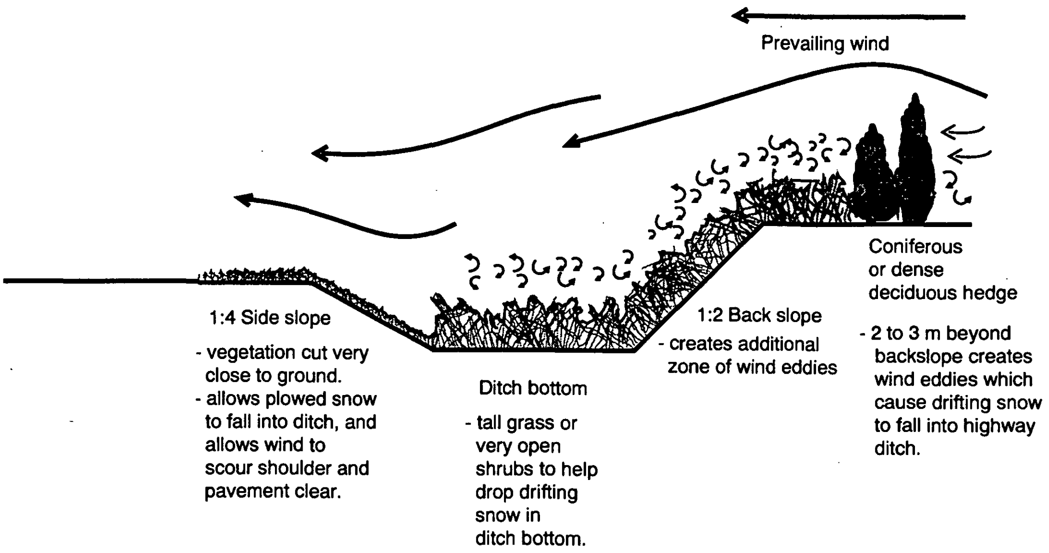

FIGURE 1 Right-of-way treatment for snow control.

required setback from the road (*2,3*). A setback of 15 times the mature height of the hedge is specified on level ground to ensure that the drift does not encroach on the highway (*1*), although shorter multiples are possible under certain conditions. The most effective hedges in Ontario are three-row spruce or two- to three-row cedar hedges. Very dense spacing and additional rows are required to achieve an adequate density where deciduous shrubs are used for snow protection.

The snow storage ditch, located between the hedge and the road, stores the drifting snow captured by the hedge as well as the fallen snow that is plowed from the road. The steep backslope causes a separation in the wind flow at the brow of the slope, to slow the wind further and ensure that any snow that remains entrained is deposited in the ditch. It reduces the setback requirement for the snow hedge as compared with the setback required on level ground.

The width of the ditch provides sufficient volume to accommodate the maximum winter accumulation of drifting plowed snow. Methods for calculating the required volume are described later. A minimum 5-m width is specified as a safety feature for errant vehicles.

The sideslope design has two purposes. A slope of 1:4 or shallower promotes a smooth wind flow from the ditch bottom over the road surface, so that any snow that has not been deposited in the ditch will be carried across the road. Physical model tests have shown that the brow of a slope steeper than 1:3 causes wind eddies at the shoulder rounding and results in the deposit of entrained snow on the windward edge of the pavement (*4*). The second purpose of the shallow sideslope is to obviate the guide rails on a fill section. Guide rails, which are required on a steep fill, interrupt the wind flow up the sideslope and frequently cause the deposit of snow on the pavement.

The vegetation scheme is coordinated with the geometric treatment. Tall grass or shrubs on the backslope and in the ditch bottom serve a similar function to the snow hedge and the steep slope in slowing the wind to ensure that all entrained snow is deposited before it reaches the inslope. Vegetation on the inslope should be cut as close to the ground as possible to minimize aerodynamic drag. Drag on the inslope would prevent acceleration of the wind up the slope and across the road.

Dimensions

Any treatment that acts on the principle of preventing drifting snow from reaching the highway must have the capacity to store the maximum winter accumulation of falling snow plowed from the road into the ditch and drifting snow deposited on the ground upwind of the road. Several methods are available for estimating the appropriate storage volumes.

Falling Snow

The falling snow storage is the annual maximum volume of snow that accumulates in the ditch. It is a function of snowfall onto the road and the ditch, minus melt and evaporation, adjusted to account for compaction by natural processes and plowing.

An estimate of the accumulated maximum snow depth for southern Ontario is provided by the Canada Department of Transport (*5*) (Figure 2). A suitable value for Ontario is 0.8 m (30 in.); this value accounts for losses due to drifting and compaction due to the metamorphosis of a natural snowpack, but it does not account for compaction by plowing. A factor of 0.5 can be used to account for plowing, and this results in a snow storage requirement for plowed snow in Ontario of about 0.4 m. This is approximately 20 percent of the mean annual snowfall for the same region (*6*). A typical, 4.5-m-wide highway lane and shoulder therefore requires $4.5 \times 0.4 = 1.8\ \text{m}^2$ of storage for plowed snow times the length of highway affected.

Drifting Snow

The drifting snow storage requirement can be estimated either analytically or empirically. The empirical method was used

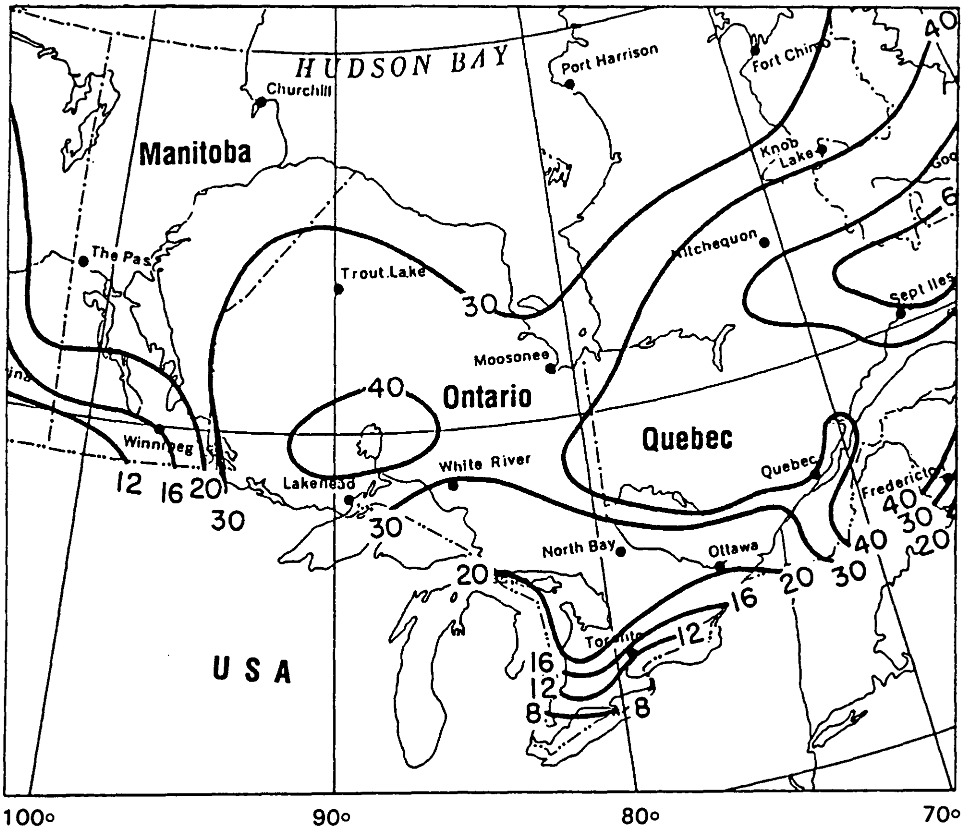

FIGURE 2 Median depth of maximum winter snow cover for 20 winters (1 in. = 2.54 cm) (*5*).

to develop a drifting snow storage volume for the MTO standard snowdrifting treatment.

Snow accumulation measurements are available from a variety of snow fence and snow hedge tests at six sites in the snow belt of southern Ontario over 5 years. All of the sites experienced severe localized snowdrifting. The maximum measured seasonal accumulation of drifting snow during these tests was 31.5 m^3/m of barrier length. This value occurred at a 4-m-tall snow hedge exhibiting an early stage of drift development throughout the season (*3*).

Numerical methods are also available for estimating the volume of drifting snow that should be accommodated by a drift treatment. Pomeroy developed physically based models of snow transport and sublimation (*7*) that were adapted by Tabler to estimate the flux of blowing snow at any site as a function of wind speed and height (*8*). The results are presented as a nomogram that estimates the total seasonal requirement for storage of drifting snow (in tonnes), as a function of wind fetch (*2*) (Figure 3). The nomogram makes assumptions about wind speed and frequency, relative humidity, snow density, and the proportion of total snowfall available for drifting. It also assumes a uniform ground surface.

The nomogram requires as input the relocated part of the annual snowfall in terms of mass. The relocated part of the annual snowfall is defined as the proportion of the annual snowfall that is available for drifting, should there be sufficient wind. This includes snow that is not trapped on the ground by gullies, vegetation, compaction, or crusting (*2*). The mean annual snowfall for the subject region is 2.84 m, as stated (*5*). It is converted to mass through multiplication by the snow water equivalent; Tabler recommends a water equivalent conversion of 0.1 g/cm^3, or 10 percent. The relocation factor is the proportion of the snow mass that is susceptible, over the winter, to drifting; Tabler recommends a snow relocation factor of 70 percent. Therefore, the mean annual depth of snow available for drifting is

$$2.84 \text{ m} \times 0.10 \times 0.70 = 0.2 \text{ m} \tag{1}$$

For a 1000-m wind fetch, the nomogram estimates a seasonal snow transport of 130 t/m of highway length. Assuming a snow density of 400 kg/m^3 (*9*), this converts to a snow volume of 325 m^3/m.

The model was adapted for use in southern Canada by an adjustment to the method of calculating the proportion of snowfall available for drifting (*10*). Using this adjustment and assumptions similar to those just mentioned, the model estimates a drifting snow volume between 112 and 175 m^3/m.

The calculated values differ from the storage requirement of 31.5 m^3 as derived from field measurements, by an order of magnitude, and suggest that additional investigation into this variable is needed. A value of about 30 m^3/m of highway affected is used in planning snowdrift treatments for provincial highways in Ontario.

The standard treatment is incorporated in sections of Highway 401, a four-lane freeway in southern Ontario. It provides protection from drifting snow under most conditions. In the

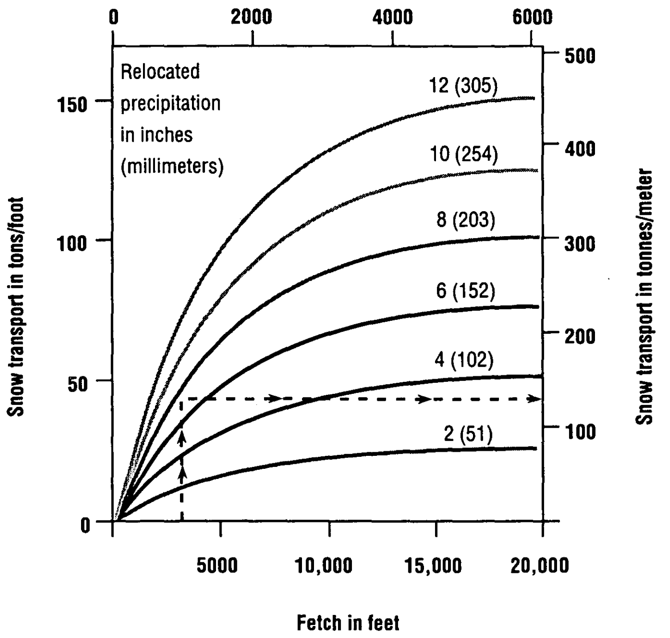

FIGURE 3 Variation of seasonal snow transport with fetch and relocated precipitation (*2*).

past 3 years the treatment has also been incorporated in plans for several two-lane rural highways in the same region that are being reconstructed. The treatment areas will be monitored after construction is completed to document changes in the severity of snowdrifting problems and assess the effectiveness of the standard treatment.

OTHER TREATMENTS

The standard treatment cannot be used in every situation. Among the conditions that preclude its use are these:

1. Sufficient right-of-way is not available or affordable;
2. Highway drainage requirements prevent excavation of a snow storage ditch;
3. Soil conditions are not compatible with snow hedge growth;
4. Snow problems are caused by drifting or by lack of storage but not both; and
5. Site problems are not addressed by the treatment.

In such cases, treatments must be individually designed. Two processes can be used to design individual treatments: analogues of previously used treatments, and computer or physical simulation of alternative treatments.

Previously Used Treatments

Treatments can be adapted that have been used in similar situations. Many of these were recently compiled in a catalogue of treatment designs for particular drifting problems (*10*). This catalogue provides a useful starting point, but most of the solutions are presented conceptually and it is up to the user to supply dimensions and other important details. Even if dimensions were provided, they would have to be adapted to fit specific field situations, and small changes to a treatment may reduce its effectiveness. Therefore, a risk of failure is inherent in analogues of previously used treatments.

On low-speed, low-volume roads or where the installed treatment may be changed with little expense, a moderate risk of failure may be acceptable. An example is a temporary snow fence that can be monitored by highway crews and adjusted or moved if necessary. On high-speed, high-volume roads, where a significant safety hazard could result from an unsuccessful treatment, or where budgetary considerations preclude adjustment, uncertainty must be reduced to a minimum before the treatment is installed. In such cases, an iterative process of design and preconstruction testing is recommended. This can be carried out by computer simulation.

SNOWDRIFT Model

A computer modeling system called SNOWDRIFT has been developed at MTO to assist highway designers who have no specialized expertise in snowdrifting to design landscape and highway cross-section treatments for drift prevention. The model simulates snow erosion and deposition due to drifting at any highway site and with any snowdrift prevention treatment specified by the user. It provides quantitative output that allows the user to compare objectively the effectiveness of different treatments.

The SNOWDRIFT model offers several advantages to the highway designer that are not offered by physical modeling, full-scale monitoring, or other numerical models.

1. Treatments can be changed or new sites input quickly and at no cost, using topographic maps;
2. Changes in snow properties that affect the propensity of the snow to drift can be accommodated;
3. Hypothetical or actual meteorological conditions—including snowfall, drifting, and melt periods—can be simulated without physical adjustments to the model;
4. Snow transport is simulated over complex terrain; and
5. Changes in surface roughness due to snow accumulation or erosion are automatically accommodated.

The modeling concept developed at the Centre d'Applications et de Recherches en Télédétection (CARTEL), University of Sherbrooke, recognizes that snowdrifting is affected by surface topography and roughness and by the changes in the terrain due to snow accumulation and melt through winter.

The initial condition of the terrain may be a snow-free surface of specified roughness, or a snow-covered surface. Snowfall is added according to data provided in hourly meteorological files. Erosion and deposition are then computed on an hourly basis, at grid locations within the modeling domain. This process results in a new topography grid and a new roughness grid that become the initial condition for the next hour (Figure 4).

The model assumes that the dominant transport mechanisms are creep and saltation within the height of influence of the surface roughness.

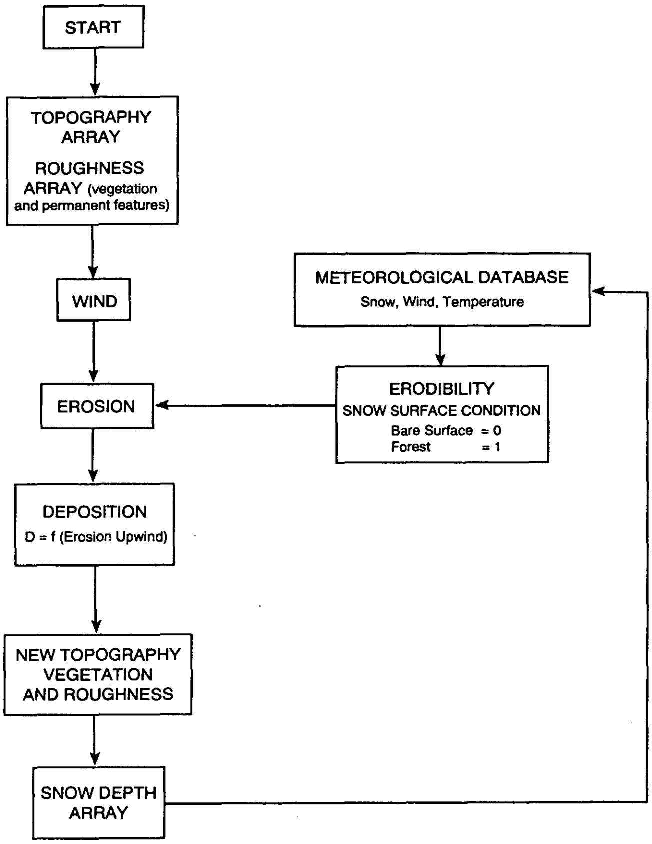

FIGURE 4 Simplified flow chart for SNOWDRIFT model.

Snow erosion is computed by

$$E(I,J) = (C_1\, W_s + C_2\, T_L + R_v/12)E_r \qquad (2)$$

where

C_1, C_2 = empirical coefficients,
W_s = function of wind speed and elevation of surrounding grid points,
T_L = parameter that accounts for local changes in topography,
R_v = local changes in surface roughness upwind of grid point, and
E_r = snow erodibility through empirical factors for snow age and air temperature.

Snow deposition is computed by

$$D(I,J) = A(I,J) - E(I,J) + S_f + S_p \qquad (3)$$

where

A = function of sum of depth of snow eroded from upwind three grid cells plus fallen snow and initial snow depth,
S_f = snowfall, and
S_p = initial depth of snow at that time step.

The model is designed to operate with input data that are eadily available:

- Hourly wind speed and direction, air temperature, and precipitation type and amount (from the closest meteorological station);
- Topography within a domain of approximately 1 × 1 km, at horizontal resolution of 4 m or better (from highway surveys);
- Surface roughness expressed as vegetation or land use classes (Table 1); and
- Location of subresolution-calibrated snow control devices such as fences, hedges, and ditches (specified by the user).

Meteorological data are read from a spreadsheet file, topographic data are input from a digitizing tablet, and calibrated snow control devices are input from either a digitizing tablet or an interactive, on-screen system.

Results for each hourly period include contour maps of snow depth, profiles of snow depth at user-selected locations, and numerical summaries of snow accumulation on the pavement.

Figures 5 and 6 illustrate the on-screen display and results from a calibration run for a snowdrifting problem site on

TABLE 1 Surface Roughness Categories

Number Used on Map	Land-Use Categories	Snowdrift Model Roughness Values
1	Crop land	0.9
2	Tilled field	0.8
3	Natural grassland/pasture	1.0
4	Asphalt road	0.95
5	Gravel road	0.2
6	Deciduous trees	0.05
7	Coniferous trees	0.4
8	Deciduous shrubs	0.3
9	Coniferous shrubs	0.95
10	Buildings	1.0
11	Tower	1.0

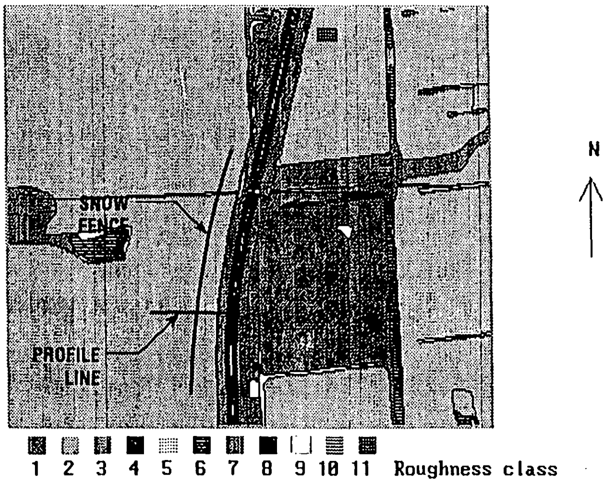

FIGURE 5 Land use/roughness map; Cochrane's Curve (Highway 400), 1.02- × 1.02-km plot.

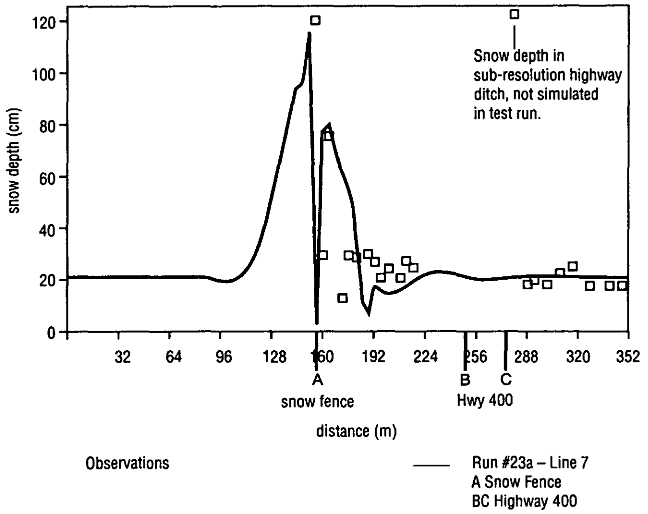

FIGURE 6 Observed and predicted snow depths along Profile Lane 7; based on Calibration Run 23.

Highway 400, a six-lane freeway north of Toronto. Figure 5 illustrates a terrain roughness classification map (see Table 1 for roughness classes), including the location of the highway and other roads, crop and forest areas, and cultural features. A user-input snow fence and a user-selected snow-depth profile line are also shown.

The model was run for 2 weeks beginning on December 1, 1989. This period began before the first lasting snowfall of the season and includes three snowfall events, three drifting events, and a short period of above-freezing temperatures. Winds were predominantly from the west.

Figure 6 compares measured and modeled snow depths at the end of the test period, at a profile line that crosses a snow fence and the highway. Major characteristics of drift shape, depth and location, and level snow depth are accurately represented by the model. An anomalous point at distance 280 m (snow depth 122 cm) is the snow depth measured in a highway ditch that was not simulated in the test run because it is below the grid resolution of the model. SNOWDRIFT is currently being calibrated for subresolution landforms such as highway ditches, as well as a variety of snow fences and hedges. Once the calibrations are complete, verifications will be performed using field measurements from locations and storms different from those used for calibration. Additional studies are planned to investigate the feasibility of reducing the model grid resolution from 4 to 1 m.

The model runs on a personal computer and is being incorporated into a mainframe, computer-aided drafting system that is used at MTO to design new highways, which will allow highway design staff with little or no expertise in snow science to develop and then test snowdrift treatments for any location in the province. SNOWDRIFT will provide three benefits to MTO: it will reduce the need for outside expertise or laboratory facilities, it will shorten the lead time required for designing and testing snowdrift treatments, and it will allow designers to identify areas that may be susceptible to snowdrifting on future highways before they are constructed.

The system also provides a useful tool for economic assessments of highway construction. It can be coupled with probabilistic weather data to establish the risk of different depths of snow accumulation, visibility reduction, or other driving hazards associated with treatments to prevent snowdrifts.

CONCLUSIONS

A rational approach has been developed for the design of passive treatments for prevention of snowdrifting problems on highways. It includes a specific design that is widely applicable at problem sites in Ontario, a source of conceptual designs for sites at which the problem is not addressed by the standard design, and a means of testing any treatment during the design process.

The standard treatment is designed to trap all of the winter's drifting snow and store it along with plowed snow in a ditch upwind of the highway. Dimensions of the standard treatment were developed from estimates of the required storage volumes. Field data suggest that treatments should accommodate 1.8 m^2 of drifting snow and 30 m^2 of drifting snow per meter length of treatment in southern Ontario.

Conceptual designs are provided in the literature for treatments in situations that are not addressed by the standard treatment. However, expertise is required to provide dimensions and other design details required for incorporation of the alternative treatments into a highway design.

A computer modeling system has been developed that can be used by personnel who do not have special proficiency in snowdrifting to test the effectiveness of any treatment designed to prevent drifts. This approach will reduce the risk inherent in the use of untested treatments.

The model can also be used to develop a risk-based approach to cost-benefit analysis of treatments for snowdrifting.

ACKNOWLEDGMENTS

The authors acknowledge H. Granberg of CARTEL for his description and discussion of the original modeling concept that was used in the development of SNOWDRIFT. The authors are also grateful for the support and editorial review of D. G. Manning of the Materials Research Office and the encouragement of T. Klement of the Surveys and Design Office and H. K. Kirchner of the Maintenance Office, MTO.

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Trapping Efficiency of Snow Fences and Implications for System Design

R. D. TABLER AND R. L. JAIRELL

The trapping efficiency of a snow fence is the quantity of wind-transported snow retained in proportion to the incoming snow transport over the height of the fence. Trapping efficiency declines as a fence fills with snow, and this relationship determines the efficacy of a snow fence system in reducing snow removal costs and improving visibility. A numerical simulation illustrating how initial trapping efficiency varies with wind speed is described, including field measurements indicating how trapping efficiency changes with time. Engineering equations developed from these results show how savings in snow removal costs vary with the design capacity of snow fence systems. A snow storage capacity just equal to the mean annual snow transport will reduce costs by about 80 percent over the long term. The ratio of benefits to costs is maximized with a storage capacity equal to 90 percent of the mean annual snow transport.

Trapping efficiency of a snow fence is defined here as the proportion of snow blown over the height of the barrier that is permanently retained by the fence. Trapping efficiency changes as a fence fills with snow, and this relationship determines the effectiveness of a snow fence system in reducing snow removal costs and improving visibility throughout a winter.

To be effective, snow fences must have adequate capacity for storing snow. Methods are available for estimating snow transport at a site and for determining the height or number of rows of fencing needed to provide the required storage (*1–3*). However, a design year must first be specified, and it is not intuitively evident that the average winter would be the optimum choice. Knowing how trapping efficiency varies with snow accumulation allows a benefit-cost analysis to determine the optimum design year.

This paper describes some of the factors affecting trapping efficiency and uses field measurements to develop engineering approximations describing how trapping efficiency changes with time.

SNOW TRANSPORT

Blowing snow particles range in size from infinitesimally small to as large as 0.5 mm (0.02 in.) in diameter. Particle size decreases with height above the surface, with mean diameter ranging from about 0.2 mm (0.008 in.) at 5 cm (2 in.) to less than half this size at 100 cm (3.3 ft). Snow particles derived from freshly fallen snow are smaller than those originating from a snow cover that has remained undisturbed for a few days. As snow particles are carried by the wind, they become progressively smaller and more rounded from fragmentation, abrasion, and evaporation.

Snow trapping efficiency varies with the mode of particle movement. Particles too large to be lifted by the wind roll or creep along the surface. Creeping particles are easily trapped by a fence, but only a small proportion of blowing snow (less than 20 percent) is transported in this manner, except at low wind speeds.

Most saltating particles (those that appear to jump along the surface) are contained in the first 5 cm (2 in.) or so above the surface. Although trajectories vary with particle size, wind speed, and surface conditions, a typical jump is a parabolic arc 1 cm (0.4 in.) high and 25 cm (10 in.) long (*4*). Saltating particles are also readily trapped by a snow fence, and because their impact is an important mechanism for dislodging other particles, removing saltating particles from the airstream can disrupt erosion of the snow surface and reduce transport for great distances downwind. This is one reason for the effectiveness of snow fences.

"Turbulent diffusion" refers to the mechanism by which particles are transported in suspension without the periodic surface contact that typifies saltation. A saltating snow particle becomes entrained in the airflow when the gravitational force on the particle is less than the drag force imposed by upward-moving air currents. The diffusion process favors smaller particles, and suspended particles are therefore smaller than those moving by saltation. As suspended particles become smaller through evaporation, they tend to be carried higher above the surface. This sorting process causes particle size to decrease with increasing height above the surface. The numerical model developed by Pomeroy (*5*) indicates that most blowing snow is transported in the turbulent diffusion mode but that the greatest portion of the total suspended particle mass is contained in the first meter or so above the surface. Suspended particles can be caught by a snow fence if they settle to the surface in a region sufficiently sheltered to prevent subsequent dislodgement.

The erosion and transport of snow particles is driven by the shear stress, τ_o, exerted on the snow surface by the wind. For the turbulent flow conditions associated with blowing snow,

$$\tau_o = \rho |du/dz|^2 \, \iota^2 \qquad (1)$$

where

ρ = air density,
du/dz = vertical gradient of wind speed, and
ι = mixing length.

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"Snow transport" refers to the mass of blowing snow transported by the wind over some specified period of time, expressed per unit of width across the wind. An engineering approximation for total snow transport in the first 5 m (16 ft) above the snow surface, Q_{0-5}, is

$$Q_{0-5} = u_{10}^{3.80}/233{,}847 \qquad (2)$$

where u_{10} is wind speed in meters per second at 10 m above the surface and Q_{0-5} is transport in kilograms per second per meter of width across the wind (*3*).

SNOW DEPOSITION PROCESSES AT SNOW FENCE

A fence exerts a restraining force on the wind, reducing wind speeds and changing the shape of the wind profile. These effects reduce the surface shear stress, allowing creeping and saltating particles to come to rest. Some of these particles are deposited on the windward side of the fence as surface winds decelerate approaching the barrier. According to Takeuchi, saltating particles are deposited on the windward side of barriers and suspended particles settle out on the leeward side (*6*). However, many of the suspended particles passing through a snow fence do not reach the ground before they are carried beyond the sheltered area.

At the start of the snow accumulation season, the aerodynamic effect of the fence controls the deposit of snow entering the sheltered region. But as the snowdrift develops, it exerts an additional influence on the flow field that progressively changes as the shape and dimensions of the drift change. The complexity of the problem become apparent when one considers how drifts grow.

In the initial stages of drift growth, particles passing through a porous barrier encounter a zone of greatly diminished winds and decreasing surface shear stress, extending downwind for a distance of about 12 times the height (*H*) of the fence, or 12*H*. Most particles reaching the ground within this region come to rest, forming a lens-shaped drift that becomes progressively thicker in the middle as deposition continues.

This initial lens-shaped deposit thickens until the airflow can no longer adjust rapidly enough to follow its curvature, and at this stage the flow separates from the surface in the same way as it does over an airplane wing when the stall angle is reached. This results in the formation of the slip-face and recirculation zone (Figure 1) that characterize the second stage of drift growth. The recirculation zone extends downwind from the slip-face for a distance equal to about six times its height. During this stage of development, the drift itself adds significant resistance to the approaching wind. The added resistance slows the airflow passing over the drift, allowing snow to be deposited on the nose of the drift and reducing surface winds within the recirculation zone to a minimum. As a result, with light to moderate winds, trapping efficiency can be greater than the initial trapping efficiency at the onset of accumulation, but stronger winds can cause particles to be carried beyond the recirculation region before reaching the ground. If the snow cover contains newly fallen snow, the electrostatic charge on the particles causes them to adhere to the surface, forming a snow cornice at the top of the slip-face and enhancing the trapping efficiency. The second stage is characterized by an increase in drift depth, with little elongation, and is represented by Measurements 1 through 3 in Figure 2.

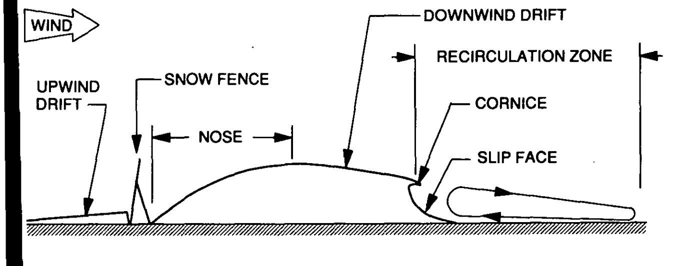


FIGURE 1 Slip-face and recirculation region formed by 50 percent–porous snow fences during intermediate stages of drift growth.

As the lee drift depth approaches its maximum, which for 50 percent–porous fences is 1*H* to 1.2*H*, the third stage of growth begins, characterized by a filling in of the recirculation zone as the drift lengthens downwind and represented by Measurements 4 through 6 in Figure 2. As long as a slip face is present, however, trapping efficiency remains relatively high.

The fourth stage of growth begins when the drift first assumes a smooth profile without the slip-face, marking the disappearance of the recirculation zone. At this point the drift is about 20*H* in length, as indicated by Measurement 6 in Figure 2. This stage should be marked by rapidly declining trapping efficiency, and only creeping and saltating particles are deposited. Subsequent growth is therefore relatively slow as the drift elongates to its ultimate length of 30*H* to 35*H*, as represented by Measurement 7 in Figure 2.

The fourth stage ends when the drift ceases to grow—that is, when it reaches equilibrium for the existing wind conditions. Typical dimensions of equilibrium drifts formed by 50 percent–porous fences are shown in Figure 3. After equilibrium is achieved, trapping efficiency remains at zero.

FACTORS AFFECTING TRAPPING EFFICIENCY

Trapping efficiency varies with length, height, and porosity of a snow fence. The presentation in this paper is restricted to very long fences (more than 30*H*) having 50 percent open area and a bottom gap equal to *H*/10. But so many other factors affect trapping efficiency, either directly or indirectly, that a meaningful quantitative evaluation is difficult at best. If the angle of attack between wind and fence is not exactly

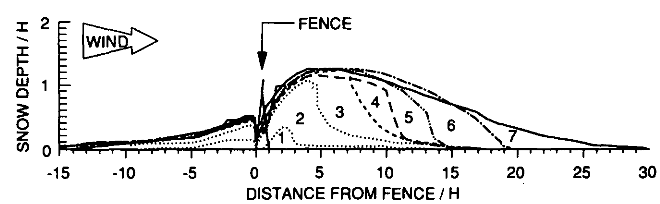


FIGURE 2 Profiles of snowdrift formed by a 3.8-m-tall Wyoming-type snow fence, on seven measurement dates (*2*).

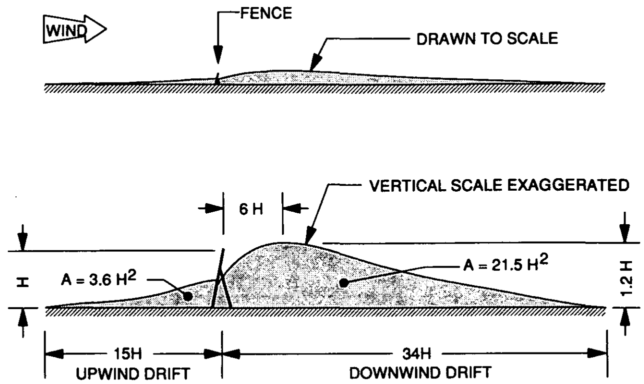


FIGURE 3 Shape of equilibrium drift formed by a 50 percent-porous snow fence on flat terrain (*2*).

90 degrees, for example, a crosswind component on the leeward side can transport some of the particles along the length of the fence until they are swept away in the slipstream around the end of the fence. Trapping efficiency also varies with the chronology of changes in wind speed or direction. Susceptibility to erosion depends on the strength of the ice bonds between deposited particles, and the strength of such bonds changes rapidly with time, doubling in 2 days and trebling in 3 days (*7*). But the dominant factors affecting trapping efficiency are ambient wind speed and the influence of the developing drift; these considerations are the focus of this paper.

Wind Speed

The initial trapping efficiency (E_o), at the time of the first drifting event when there is no appreciable accumulation of snow, is amenable to numerical simulation to determine how ambient wind speed affects trapping efficiency. Knowing the vertical size distribution and fall velocity of snow particles, and the general characteristics of the flow field behind a fence, it is possible to trace the trajectories of particles to determine the distance at which they reach the ground. If this distance exceeds the region of decreasing surface shear stress behind the barrier, it can be assumed that the particles will not be trapped.

The wind field behind 50 percent-porous snow fences was assumed to be that shown in Figure 4, as determined from intensive wind profile measurements behind 1.2- and 4-m-tall snow fences, using the equipment described elsewhere (*8*). These studies indicated that, to a reasonable approximation, the representation in Figure 4 is valid for all heights and ambient wind speeds.

For various fence heights and ambient wind speeds, a computer simulation was used to determine a critical interception height, defined here as the maximum height at which the average-sized particle would reach the ground within a distance equal to 15*H*. Trapping efficiency was then calculated as the mass flux contained below the interception height in proportion to the total transport summed over the height of the fence, as given by the vertical distribution of mass flux proposed by Tabler (*3*).

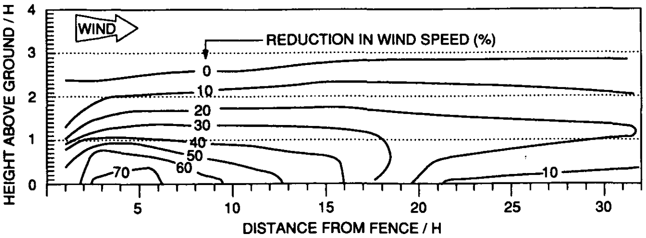


FIGURE 4 Curves of equal wind speed reduction, in percent, behind a snow fence 4 m tall (13 ft) having 50 percent open area and 15-cm (6-in.) bottom gap.

The simulation was made at 5-cm height increments, starting at the ground and ending when the interception height was reached. For each height, the simplifying assumption was made that particle size was uniform and equal to the mean of the distribution at that height:

$$\overline{D} = 303\, z^{-0.27} \tag{3}$$

where $\overline{D}$ is the average particle diameter in microns at height z in centimeters above the surface (*9*).

The fall velocity, V, for each particle size was calculated from the following relationships:

$$F_D = mg = 0.5 \rho C_D v^2 A \tag{4}$$

$$C_D = (24/R_e)\,(1 + 0.0806 R_e) \tag{5}$$

$$R_e = DV/\nu \tag{6}$$

where

F_D = drag force on the particle,
m = particle mass,
g = gravitational constant,
C_D = drag coefficient,
A = particle cross-sectional area,
R_e = Reynolds number, and
ν = kinematic viscosity (*10,11*).

The calculations reported here used air characteristics at −10°C (14°F).

It was assumed that the particle follows the mean flow field behind the barrier (*11,12*) so that the particle's horizontal speed ($u_{p,z}$) can be taken as the ambient wind speed ($u_{z,\mathrm{up}}$) at the height of the particle, adjusted for the wind speed reduction, R (%), shown in Figure 4:

$$u_{p,z} = u_{z,\mathrm{lee}} = u_{z,\mathrm{up}}\,[1 - (R/100)] \tag{7}$$

The wind reduction field in Figure 4 was approximated by multiple regression equations relating wind speed reduction to height above surface and distance from barrier, with different equations being developed for different regions. The ambient wind profile was assumed to be

$$u_{z,\mathrm{up}} = 2.5\, u_* \ln(z/z_0) \tag{8}$$

where u_* is shear velocity and z_0 is the height at which u = 0. For blowing snow conditions on snow-covered flat terrain, $u_* \approx u_{10}^{1.18}/98.3$ and $z_0 \approx u_*^2/31{,}250$, where velocities are in centimeters per second and heights are in centimeters (*8,13*).

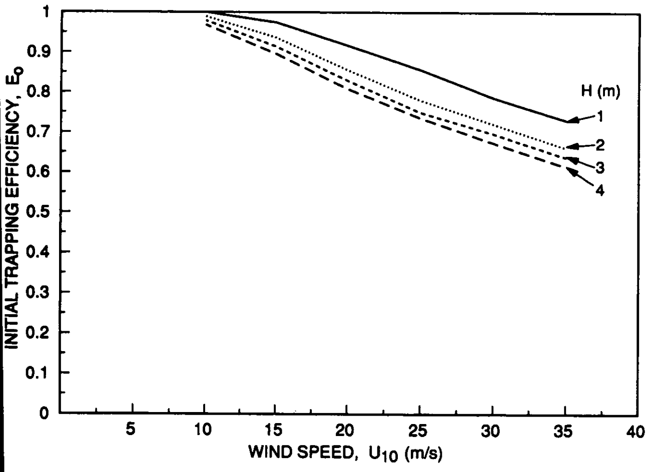
With this information, it was possible to determine the location at which the particle reached the ground by routing the particle through the flow field, using time increments of 0.01 second to recalculate particle positions. If the fallout distance was less than $15H$ from the barrier, the particle was assumed to be permanently trapped. This procedure was repeated for incremental increases of initial particle height until the critical interception height was reached.

As shown in Figure 5, this analysis indicates that initial trapping efficiency decreases somewhat as fence height increases, attributable to the decreasing particle size (and hence fall velocity) with increasing height. However, the 10-m ambient wind speed has a much more pronounced effect on efficiency. For a 2-m-tall fence, for example, E_o varies from 0.99 at u_{10} = 10 m/sec to 0.68 at u_{10} = 30 m/sec.

Although the preceding analysis could be refined by taking into account the nonuniform distribution of particle sizes at each height, as Schmidt and Randolph did in their analysis of snow deposition at a downwind-facing step (*11*), it is not expected that such a refinement would significantly change the results obtained here. The question of how trapping efficiency changes as a fence fills with snow is of far greater importance for designing snow fence systems, and the rest of this paper is devoted to this subject.

Developing Snowdrift

The effects of a snowdrift on trapping efficiency are indicated by a similar simulation analysis of snow deposition behind downwind-facing step-like terrain breaks (*11*). As reproduced in Figure 6, results from that study suggest that trapping efficiency is reduced by an uphill approach to the step but increases rapidly as the downhill angle increases. From the previous description of how snow is deposited behind a fence, it is apparent that the angle of approach to the crest of the slip-face changes as the drift grows, being positive (uphill) as the drift deepens during the second stage and negative (downhill) as the drift lengthens during the third stage of growth. Through much of the third stage the approach angle remains relatively constant, averaging about 3 degrees, consistent with a relatively high efficiency. Another significant observation from Figure 6 is that step height has little effect on trapping efficiency. These results suggest that trapping efficiency changes in a complex way as a drift grows, and there may be intervals when trapping efficiency increases with time.



IGURE 5 E_o versus fence height and 10-m wind speed, as etermined by numerical simulation.

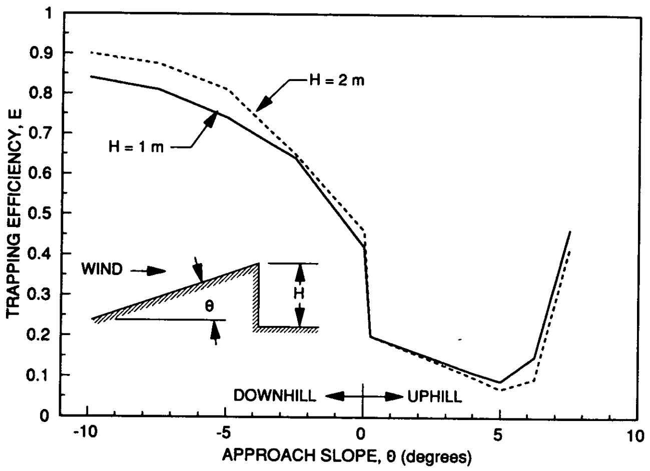


FIGURE 6 Initial trapping efficiency of downwind-facing steps in relation to approach slope and step height (*11*).

FIELD MEASUREMENTS OF TRAPPING EFFICIENCY

This paper combines results from three types of field measurements to develop engineering equations to describe how trapping efficiency changes as a fence fills with snow. In a "three-fence study," trapping efficiency was estimated by measuring changes in snow accumulation in a tandem series of three tall snow fences. Results from this study were published previously (*14*) but have been recalculated using improved estimates for the storage capacity of the fences involved. In the second study—the "snow removal study"—the progression of snow deposition behind a fence 2.4 m tall (7.9 ft) with an undisturbed drift was compared with that behind an adjacent section of the fence where the snow was removed after each measurement. These results have not been reported previously. The results from these formal studies of trapping efficiency are supplemented with measurements of snow accumulation changes behind two tandem rows of 3.8-m-tall fences. Although providing less-precise estimates of trapping efficiency, these "two-fence study" measurements help to define the general functional form of the relationships between trapping efficiency and residual storage capacity.

Study Area and Experimental Methods

All measurements used Wyoming-type snow fences (*14*) on Interstate 80 about 55 km (34 mi) northwest of Laramie, Wyoming. The sites are on relatively flat terrain covered with low-growing herbaceous vegetation, at an elevation of about 2370 m (7,776 ft). Snowfall averages about 250 cm (98 in.), and snow transport over the past 20 years has averaged about

90 t/m of width (31 tons per foot) across the wind. The fences used for these studies are perpendicular to the prevailing winds.

Snow depth and water equivalent were sampled behind the study fences after each major drifting event. Snow depths and water equivalent were measured at intervals of 3 m (10 ft) along permanent transects oriented perpendicularly to the fences. An aluminum probe was used to measure snow depths, and water equivalent was sampled with a Mount Rose snow tube. Snow sampler densities were multiplied by 0.91 to correct for the overmeasurement known to be characteristic of this type of sampler (*15*).

Three-Fence Study

This experiment used measurements from three tandem fences having a combined snow storage capacity of 300 t/m (112 tons per foot), about four times greater than the average annual snow transport. This fence system is 490 m (1,608 ft) long and consists of a 2.4-m-tall (7.9-ft) lead fence, followed by a 3.8-m (12.5-ft) fence spaced 61 m (200 ft) downwind, followed by a second 3.8-m fence 91 m (299 ft) farther downwind. After each major drifting event over two winters, snow depth was measured on four permanent transects passing through all three fences, and water equivalent was sampled along one transect selected at random.

It was assumed that the second and third fences were perfectly efficient in trapping snow (i.e., $E = 1$). Although this assumption cannot be strictly true, the fact that the second fence was less than 15 percent full the first year, and 25 percent the second, suggests that the trapping efficiency would be comparable with that of an empty fence. The assumption of 100 percent trapping efficiency for the second fence is supported by the fact that the snow caught by the third fence was approximately equal to the precipitation relocated between the second and third fences. In addition, the close spacing of the fences results in a cumulative shelter effect, with wind speeds approaching the second fence being 10 to 20 percent less than those upwind of the lead fence (Figure 4). Trapping efficiency, E, was therefore calculated as

$$E \approx \Delta Q_1/[\Delta Q_1 + \Delta Q_2 - (2/3)\Delta Q_3] \quad (9)$$

where ΔQ_1, ΔQ_2, and ΔQ_3 are the changes in mass storage over a measurement period, and the (2/3) factor accounts for the different spacing between the last two fences (61 and 91 m, respectively). The resultant trapping efficiencies are plotted against the average cross-sectional area, $\overline{A}$, of the drift over the measurement interval, expressed in proportion to the cross-sectional area A_e of the equilibrium drift:

$$\overline{A}/A_e = \overline{A}/(25H^2) \quad (10)$$

where areas are in square meters (*2*).

Snow Removal Study

The fence used for this study is a single row of fences 2.44 m (8 ft) tall and 146 m (479 ft) long, located about 3 km (1.9 mi) from the fence system used for the three-fence study. Over one winter, snow on the downwind side of half of this fence was removed with a dozer after each major drifting event. On the other half of the fence, the snow was left to accumulate naturally. Before removing the snow, snow depth and water equivalent were measured along two permanent transects in each half. Both pairs of transects were spaced 12.2 m (40 ft) apart and bracketed the middle of the two fence sections. The ratio of the changes in the water equivalent of snow storage between these two treatments provided a measure of the trapping efficiency of the nonremoval section relative to the initial trapping efficiency, E_o, as represented by the snow removal section:

$$E/E_o \approx \Delta Q_n/\Delta Q_r \quad (11)$$

where ΔQ_n is the change in snow storage in tonnes per meter behind the nonremoval section and ΔQ_r is the change behind the section of fence where the drift was removed after each measurement. The relative cross-sectional area of the nonremoval section was computed from Equation 10.

Although the trapping efficiencies calculated from the snow removal study are not exactly the same as those derived from the three-fence study, this experiment provides an independent measure of how trapping efficiency changes as a fence fills with snow.

Two-Fence Study

The observation that the trapping efficiency of the second fence in the three-fence study was approximately 100 percent suggests that two rows of fences having comparable height and spacing can also be used to estimate trapping efficiency. Unlike the three-fence measurements, this calculation does not account for the portion of the second fence drift contributed by snowfall that fell between the two fences, but this error is relatively small for major drifting events and would tend to compensate for the overestimated efficiency of the second fence.

Trapping efficiency was therefore calculated from snow measurements at two rows of 3.8-m-tall fence, spaced 91 m apart, using the equation

$$E \approx \Delta Q_1/(\Delta Q_1 + \Delta Q_2) \quad (12)$$

These measurements were made over 15 years for other studies at several locations on Wyoming I-80.

ENGINEERING APPROXIMATIONS

As might be expected from the complex interactions of the various factors affecting trapping efficiency, the data from these studies show considerable variability (Figure 7). The general trend, however, is consistent with the intuition for how trapping efficiency might change as a drift grows, as previously described. The relationship can be approximated by

$$E \approx E_o[1 - (A/A_e)^2]^{0.5} \quad (13)$$

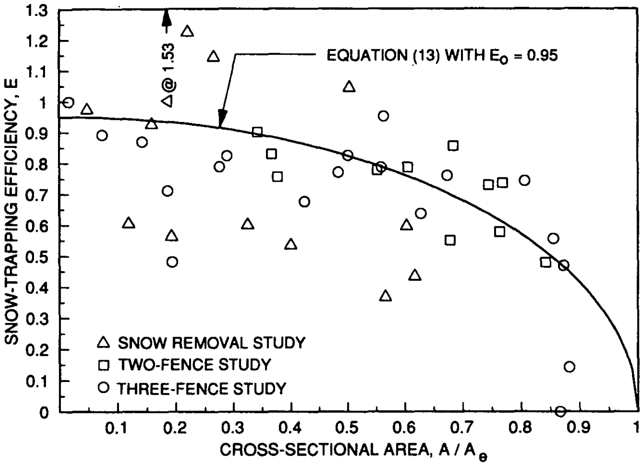


FIGURE 7 Trapping efficiency versus cross-sectional area of snowdrift, as determined from field measurements.

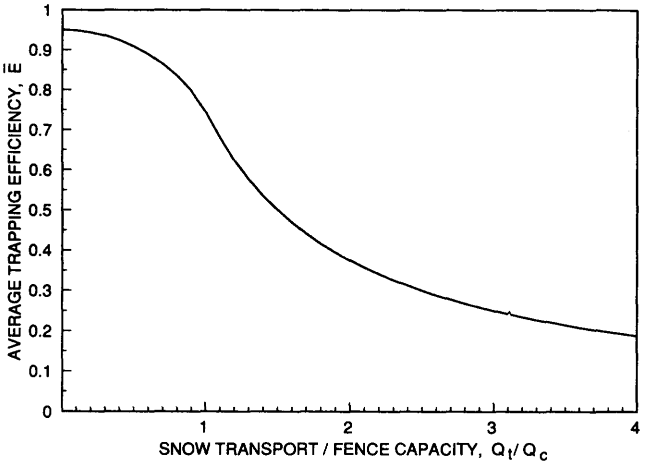


FIGURE 8 Average trapping efficiency over a season as a function of A_f relative to A_e (Equation 14), taking E_o = 0.95.

where E is trapping efficiency expressed as a fraction and A is the cross-sectional area of the drift, and A_e is the cross-sectional area of the equilibrium drift when the fence is filled to capacity. For the field data reported here, E_o appears to average about 0.95, which is consistent with the results of the numerical simulation.

The average efficiency, $\overline{E}$, over a winter having snow transport, Q_t, equal to or less than the capacity of the fence, Q_c, is estimated by integrating the area under the curve represented by Equation 13 from $A = 0$ to A_f, the value at the end of the season:

$$\overline{E} = [1/(A_f/A_e)]\,(E_o)\,\{0.5(A_f/A_e)[1 - (A_f/A_e)^2]^{0.5} + 0.5\sin^{-1}(A_f/A_e)\} \qquad Q_t \le Q_c \qquad (14)$$

For the case in which transport was just sufficient to fill the fence, the average trapping efficiency given by Equation 14 is $0.79E_o$. For years in which snow transport is greater than the capacity of the fence,

$$\overline{E} = E_o\,(0.79)\,(Q_c/Q_t) \qquad Q_t > Q_c \qquad (15)$$

The plot of average efficiency as given by Equations 14 and 15 (Figure 8) indicates that fences provide considerable benefits even in years in which snow transport exceeds the design storage capacity of the fence.

IMPLICATIONS FOR SYSTEM DESIGN

If the probability distribution for snow transport is known, Equations 14 and 15 can be used to estimate the reduction in snow removal costs, averaged over the physical life of the snow fences, in relation to the design storage capacity of the system. For any particular storage capacity design modulus, $K = Q_c/\overline{Q}_t$, the expected long-term average trapping efficiency, $\overline{E}_k$, is given by

$$\overline{E}_k = \int_0^k F(M)\overline{E}_{K,M}M\,dM \Big/ \int_0^k F(M)M\,dM \qquad (16)$$

where $M = Q_t/\overline{Q}_t$. The frequency, $F(M)$, is given by the snow transport distribution. Although the frequency distribution of snow transport has received little attention in the past, inference is possible from the distribution reported for winter precipitation (*16*) and from potential snow transport as calculated from wind records using Equation 2 (*3*). For illustrative purposes, it is assumed here that the frequency distribution for the modular coefficients of seasonal snow transport is the same as that for winter precipitation, that is, mean 1.0 and variance $\sigma^2 = 0.1$:

$$F(M) = (2\pi s^2)^{-0.5}\int_{-\infty}^{k}\exp\{-(M - 1)^2/(2s^2)\}dM \qquad (17)$$

This assumption is supported by one study of the potential snow transport estimated from wind speed records at Prudhoe Bay, Alaska (*3*). For locations having persistent snow cover throughout the winter, the assumption is probably close enough to reality that there would be no appreciable effect on the outcome of this analysis. Equations 14 through 17 were used to calculate average trapping efficiencies as a function of design modulus K. Assuming that reduction in snow removal costs would equal trapping efficiency, these results are plotted in Figure 9. A value of 1 for K, for example, indicates that the storage capacity of the system is exactly equal to the average annual snow transport. For $K = 0.5$, the storage capacity would be half of the mean annual snow transport. From Figure 9 it can be seen that using the average winter as the design year reduces snow removal costs by about 80 percent. Doubling the storage capacity reduces costs only by another 11 percent.

Even underdesigned systems reduce snow removal costs appreciably. A system having storage capacity to contain only half of the average annual snow transport, for example, reduces snow removal costs by more than 50 percent because significant savings accrue in all years, even those when the snow transport greatly exceeds the capacity of the fence (Equation 15).

Expected annual benefits, B, from a snow fence system are given by

$$B = P_{sr}\overline{E}_k\overline{Q}_t \qquad (18)$$

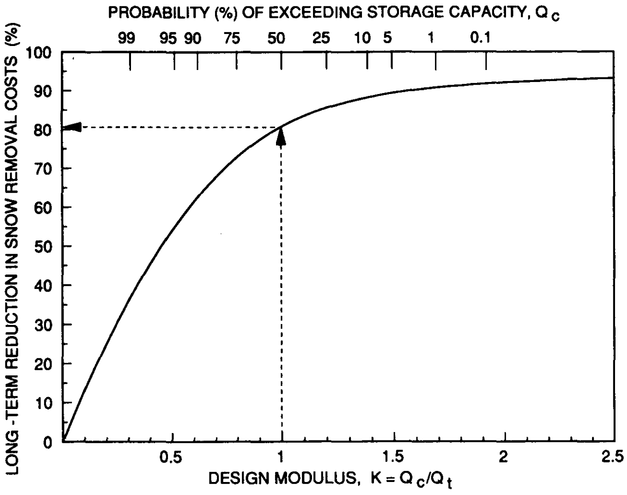


FIGURE 9 Long-term reduction in snow removal costs as a function of snow fence design year, for a road where all snow would be deposited without fences (Equations 14 and 15); model assumes no cost for snow falling directly on road surface.

where P_{sr} is the unit cost for mechanical snow removal. The storage capacity of a snow fence varies with fence height according to

$$Q_c = 8.5\,H^{2.2} \tag{19}$$

where Q_c is in tonnes per meter of fence length (*17*). Because the cost of snow fence construction increases linearly with height (*2*), average annual cost, C, of a snow fence system is related to design modulus K according to

$$C = O + a_{iT}F = O + a_{iT}P_f(K\overline{Q}_c/8.5)^{1/2.2} \tag{20}$$

where

O = annual maintenance expense,
a_{iT} = annual capital charge per dollar of fixed investment for interest rate i and amortization period T, and
P_f = capital investment cost per meter of fence height.

If maintenance cost is taken to be directly proportional to capital investment, then it can be shown by example that for all values of Q_t, Q_c, O, a, i, and T, the benefit-cost ratio (B/C) reaches a maximum at $K = 0.90$, that is, when storage capacity equals 90 percent of mean annual snow transport. Considering the uncertain frequency distribution of snow transport, designing snow fence capacity equal to mean annual snow transport is consistent with economic optimization.

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PART 5

Snow and Ice Removal Equipment

Abrasive Air Blast System for Disbonding Ice and Snow from Pavement

MARK D. OSBORNE

An abrasive air blast system is being developed and tested at the Keweenaw Research Center for disbonding strongly bonded compacted snow and ice from roadways. An investigation was first conducted to determine if abrasive air blasting could be a practicable way to remove ice and compacted snow from paved roads. The study included the use of available off-the-shelf equipment that could be installed on a highway department type of truck. Laboratory experiments were carried out in a cold room using a scaled-down system to remove ice and compacted snow that was bonded to asphalt and concrete road sections. Parametric studies were conducted to determine optimum nozzle height, angle, air pressure, abrasive type, and depth and width of material removal as a function of speed. Maximum speed obtainable in the laboratory was 1.93 km/hr (1.2 mph). A computer model was correlated with experimental data and then extrapolated to the desired speed of 32.2 km/hr (20 mph). Preliminary field tests at up to 32.2 km/hr (20 mph) showed good correlation to the model predictions. The results show that the concept is feasible but requires further development. A new source of funding has been obtained. The new study will use a one-nozzle system mounted on a truck and field-tested under realistic conditions. The main objectives of the new study are to develop a control system for the nozzles to limit road damage and to conduct further parametric field tests to verify earlier laboratory and computer model predictions.

Winter conditions of ice and snow cause serious disruptions in the economies of most states and produce hazardous conditions for the public. For example, typically during a snowstorm the road commission snowplow vehicles plow the main body of snow off of the roadways in a relatively short time. In many instances, traffic on the roads causes some of the snow to pack on the roadways, forming a bond between the compacted snow and the road surface. In other cases, ice storms cover roads with a thin layer of ice. Roads over bridges that may have some water on them tend to form ice faster than main roads. In the northern half of the United States and other northern countries, melt-freeze cycles cause some of the snow to partly melt and refreeze several times, which only strengthens the bond to the road. Scraper blades have been unsuccessful in removing all of the compacted snow and ice.

In these cases it has been the procedure to apply road salt or sand to melt the snow or ice and break the bond to the road surface. There are several problems with this technique. Salt is corrosive, causing deterioration to bridge structures, roadways, and automobiles. Salt is blamed for groundwater contamination in the heavily populated eastern part of the United States. Salt and sand also require time to become effective, and they do not usually work below −12°C (10°F). Currently, calcium magnesium acetate (CMA) is being tested; it appears, thus far, to be environmentally safe and noncorrosive. CMA still requires time to work and does not appear to work at temperatures lower than −12°C (10°F). A system needs to be developed that will effectively remove ice and compacted snow, as soon as possible and without harming the environment, to make the public road system safer and reduce road maintenance costs.

A new system for removing ice and compacted snow from roadways without the use of salt or other chemicals is being developed at the Keweenaw Research Center (KRC). KRC is a research agency of Michigan Technological University with a full-time staff of research scientists and engineers. Results of an early study proved that the system might be feasible but that it would require further development. This paper provides an overview of the early study and a follow-on study, and it presents plans for developing a full-scale abrasive air blast system.

DEVELOPMENT OF ABRASIVE AIR BLAST SYSTEM

Initially, KRC proposed to study the possibility of using high-pressure, high-volume flow rate air for removing ice and compacted snow from roadways. A literature search revealed that several studies had been conducted with air-pressure or air-assisted-displacement snowplows (*1–4*). Most studies, such as that by Posey (*1*), used low air pressures [34.5 kPa (5 psi)] and high-volume flow rates of air through a slot, but the air was unable to remove the strongly bonded compacted snow or ice. In some of these studies, low-pressure air was forced through a narrow slot, over the width of a road lane and directly behind a plow blade, in an attempt to loosen the ice and snow on the road as the truck was plowing. To the author's knowledge, using high-pressure, high-volume flow rate air through a nozzle had not been attempted before. Later in the study, when investigating a patent for the idea, it was discovered that one person had conceived the idea of scraping the ice to make ice chips, collecting the chips, and then blasting the ice chips to remove the remaining ice off of the roadway. No specific pressures or air flows were mentioned. No papers could be found on this idea, and it is not known how far the ice chip concept has been developed.

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Preliminary Tests

A preliminary test was run using a small air compressor and sandblaster to examine the potential of using air alone, CMA as an abrasive, and a common abrasive (Black Beauty, a ground slag that is a by-product of coke furnaces). The tests were conducted in late spring. The high-pressure air did remove some compacted snow, but it also left some snow and removed no ice. The CMA, which comes in a light, round pellet form, removed more compacted snow than air alone, but it appeared to bounce off the ice or break as it hit the ice. Black Beauty, which has sharp edges and is somewhat more massive than CMA, removed the compacted snow and some of the ice. This led to the conclusion that air alone and CMA would not work but that the hard, coarse Black Beauty or a similar abrasive could be successful.

Information Study

A literature study was conducted to gather information about current types of air compressors, abrasive air blasters, abrasives, and nozzles available on the market. At the same time, a small-scale laboratory study was initiated to determine the optimum parameters required for removing ice and compacted snow.

From the results of the literature study it was determined that a compressor producing 689 to 1206 kPa (100 to 175 psi) of pressure with a very high volume air flow rate (depending on the nozzle used) would be best for the abrasive air blast system. Compressors of this size are generally powered by diesel engines and have an operating life of 10 years or longer, if properly maintained.

Several sandblasting companies were contacted. The pressures used for most sandblasters are in the range of 413.4 to 826.8 kPa (60 to 120 psi). Some have used pressures as high as 1206 kPa (175 psi) for removing paint from bridges. Most sandblasting tanks, the part that is pressurized, are rated for 1378 kPa (200 psi) per the ASME code. This is a strict code because as the pressures increase in a sandblasting system, the wear rate of the tank and other components (i.e., hoses, valves, etc.) increases exponentially, possibly resulting in a dangerous situation for the operator or people near the sandblaster. If a sandblaster is used in a cold environment, a heater and air-water separator should be used to prevent the formation of ice, which may block orifices and hoses. When air is compressed, the temperature increases and, in a cold environment, moisture will condense out of the air and freeze.

Information was also obtained on abrasives. Some of the abrasives considered for this project were glass beads, aluminum oxide, silicon carbide, steel shot, steel grit, plastics, ice chips, silica sand, Black Beauty, and solid carbon dioxide. Most of the abrasives listed first are expensive. Ice chips and solid carbon dioxide require special equipment to produce and a special system for introducing into the compressed air stream. It was decided to conduct the initial laboratory tests with three types of abrasive: steel grit, silica sand, and Black Beauty. As a result of the preliminary tests, it was desired to use an abrasive that had a large mass and sharp edges. Each of the abrasives has advantages and disadvantages.

Steel grit has sharp edges and high mass, but it may be too expensive. The steel grit used for the laboratory tests was a 50-mesh grit and cost $52/45 kg (100 lb). Steel grit may rust and bond to the road, leaving an undesirable appearance. Silica sand is less expensive [$15/45 kg (100 lb), 45-mesh grit] but may cause silicosis when used in an enclosed area. Black Beauty is inexpensive [$4/45 kg (100 lb), 12- to 40-mesh grit] but may be carcinogenic if used in an enclosed area. If Black Beauty did work well, a flint rock abrasive may be used in its place as it has very similar characteristics and costs about the same. Bulk quantity prices are assumed to be proportionally lower for each of the three abrasive materials.

In most body shops or other places where small-scale sandblasting is done, ceramic converging-type nozzles are common. Air velocities through a converging-type nozzle may approach Mach 1 speeds. For projects requiring large areas to be blasted and heavy materials to be removed, a converging-diverging or venturi-type nozzle is used. When enough volumetric flow rate is available, the venturi nozzle will develop air and particle velocities up to Mach 3, which would assist removal of the compacted snow and ice. The venturi nozzles are made of tungsten carbide, cost $135 each, and last approximately 300 hr, depending on the abrasive. A venturi nozzle could not be used in the laboratory because there was not enough air flow available from the compressor used in the tests.

LABORATORY TESTS

A series of laboratory tests was conducted in a cold room to determine optimum parameters for removing ice and compacted snow from roads.

Test Fixtures

A fixture was fabricated such that a sandblasting nozzle could be fixed above a table at various heights and angles. Four 0.3- × 0.61-m (1- × 2-ft) road surfaces were formed following ASTM specifications and procedures; two were concrete and two were asphalt. A mold similar to an aluminum cake pan was fabricated to freeze water on top of the simulated road surfaces and form ice layers to desired thicknesses. The table was designed such that the road surface could be pulled at a constant speed underneath the nozzle. Speed could be varied from 0 to 1.93 km/hr (1.2 mph) to allow a relationship to be established for depth of ice removal versus traverse speed. Ice was used for most of the tests since it was understood to be more dense and difficult to remove. Some tests were run using compacted snow but only to determine how much deeper the cut would be than that of ice. The tests were run with a small compressor and sandblaster. The pressure was generally 999 kPa (145 psi) at the compressor, and the volume flow rate was 0.28 m^3/m (10 ft^2/m) or less. A ceramic converging-type nozzle with a 6.35-mm (0.25-in.) orifice was used. Figure 1 is a photograph of the laboratory test fixture.

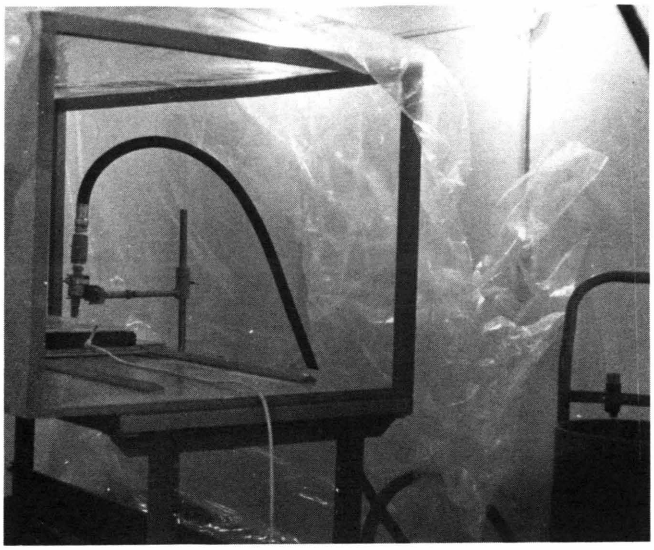

FIGURE 1 Photograph of laboratory test fixture.

Test Descriptions and Data

Tests were conducted to determine optimum air pressure, nozzle height, abrasive type, traverse speed, and nozzle angle versus depth of cut into the ice.

The first series of tests was conducted with a slab of ice 6.35 mm (0.25 in.) thick on the road surface and, because of the slow traverse rate, the abrasive cut through the ice and into the substrate material. Some aggregate was exposed. This occurred equally for the concrete and the asphalt road surfaces. The abrasive air jets tend to wear the ice away rather than disbond it from the road surface, which led to the reasoning that ice samples up to 51 mm (2 in.) thick could be used because only the depth of cut into the ice was important.

Initial tests with the nozzle in the vertical position (90 degrees from the horizontal) and in the 60-degree position showed that the cuts were deeper in the vertical position. Keeping in mind that these first tests were at very low traverse rates, from 0.08 to 0.37 km/hr (0.05 to 0.23 mph), it can be seen that at low speeds the nozzles should be fixed vertically. At traverse rates up to 32.2 km/hr (20 mph), it has yet to be determined if the nozzle will perform better at a slight angle because of the vehicle speed and abrasive velocity relationship.

The laboratory system was set up to run at speeds up to 0.37 km/hr (0.23 mph). Later in the study the system was modified to run at speeds up to 1.93 km/hr (1.2 mph). Some of the results in this paper were run at the lower-speed range only. In some cases it was not necessary to conduct the tests in the higher-speed range.

Tests for air pressure versus depth of cut into the ice were run with silica sand as the abrasive. Tests were all run at a 76.2-mm (3-in.) nozzle height and at 0.37 km/hr (0.23 mph) with the nozzle at 90 degrees; the temperature was −11.6°C. The data are presented in the following table and show that as the pressure increases, the depth of cut increases, but at a decreasing rate.

Air Pressure (kPa)	*Depth of Cut (mm)*
689	6.35
827	12.70
999	14.00

From these laboratory tests it is difficult to determine if increasing the air pressure higher than 999 kPa (145 psi) would significantly improve the depth of cut, but it is assumed that the component wear rate would increase and not be very safe.

Tests were conducted for nozzle height versus depth of cut for all three types of abrasive. The tests determined which abrasive performed the best and how nozzle height affected the depth and width of cut. Pressure was 999 kPa (145 psi), traverse rate was 0.37 km/hr (0.23 mph), temperature was −11.6°C, and nozzle angle was 90 degrees. The results showed that Black Beauty was the most effective abrasive; the best results were obtained at a 76.2-mm (3-in.) height in the vertical position, above the ice surface. Although the steel grit was more dense, the Black Beauty was slightly larger in size and appeared to have a more erosive effect. These data are presented in Table 1; Figure 2 is an example of the abrasive cut into the ice.

Toward the end of the laboratory tests (when the higher-speed tests were run), tests were run at 76.2- and 25.4-mm (3- and 1-in.) nozzle heights with Black Beauty at 999 kPa (145 psi) of pressure and 1.93 kPa (1.2 mph). There was no difference in depth of cut, but width of cut was reduced using the 25.4-mm (1-in.) nozzle height. Therefore, for these conditions, the 76.2-mm (3-in.) nozzle height was the most effective.

Another set of tests was made using compacted snow on the simulated road pavements. These were run for both the 90- and 60-degree nozzle angles, at the four highest rates of speed (for the laboratory tests). Black Beauty was used as the abrasive, at 999 kPa (145 psi) of pressure and at a 76.2 mm (3 in.) nozzle height. The results are presented in Table 2. Again, even at the relatively higher speeds, the 90-degree position proved to be the most effective. Figure 3 shows the effect of the abrasive air jets on compacted snow.

The final data gathered during the laboratory tests were traverse speed versus depth and width of ice cut. The tests were carried out using Black Beauty at 999 kPa (145 psi) of air pressure and a 76.2-mm (3-in.) nozzle height at 90 degrees and at −11.6°C. Data generated from these tests are presented in Table 3 and shown graphically in Figure 4. These

TABLE 1 Nozzle Height Versus Depth and Width of Cut

Abrasive Type	Nozzle Height (mm)	Depth (mm)	Width (mm)
Silica Sand	76.2	19.1	25.4
Silica Sand	152.4	16.0	31.8
Silica Sand	228.6	12.7	50.8
Steel Grit	76.2	20.6	25.4
Steel Grit	152.4	17.5	31.8
Steel Grit	228.6	16.0	50.8
Black Beauty	76.2	22.4	25.4
Black Beauty	152.4	20.6	47.8
Black Beauty	228.6	19.1	66.8

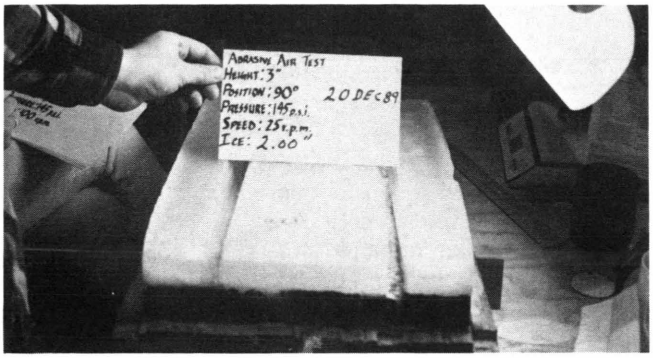

FIGURE 2 Typical abrasive air jet results on ice.

data show that as traverse speed increases, the depth of cut decreases.

In summary of the laboratory tests, it was found that the most effective results for the conditions tested occur when Black Beauty is used as the abrasive at a 76.2-mm (3-in.) nozzle height, in the vertical position, at an air pressure of 999 kPa (145 psi). These results were used to calibrate the analytical model and then extended to predict the depth of cut at 32.2 km/hr (20 mph). The model work is discussed in the next section.

MATHEMATICAL FLOW MODEL CORRELATION

A mathematical flow model for water/abrasive jets, developed by Hashish (*5*), was modified for the study of abrasive air jets. The model is fairly complex and considers the input parameters that follow:

- For the abrasive
  - Particle radius
  - Particle mass
  - Young's modulus
  - Poisson's ratio
  - Particle density
  - Abrasive mass flow rate
  - Initial particle velocity
  - Moment of inertia
  - Particle roundness
- For the ice
  - Flow stress
  - Coefficient of friction
  - Yield strength
  - Poisson's ratio
  - Young's modulus
  - Flow stress coefficient
- For the cutting system and air
  - Traverse rate
  - Jet diameter
  - Air jet velocity at nozzle exit
  - Loading ratio
  - Air density
  - Air pressure
  - Air flow rate
  - Particle velocity
  - Mixing efficiency

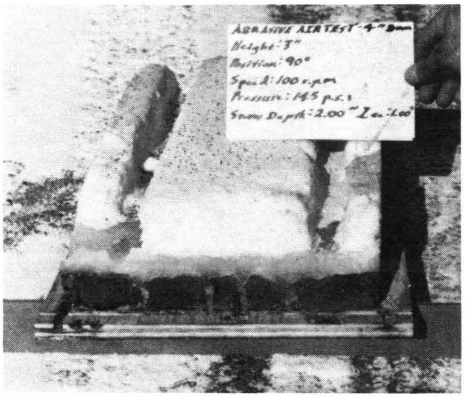

FIGURE 3 Typical abrasive air jet results on snow.

Some of the parameters were estimated, and some were converted from water to air since the model was originally developed for water.

First, the model data were correlated to the experimental data given in Table 3 for speeds up to 1.93 km/hr (1.2 mph). Figure 5 shows the model and experimental data for depth of cut versus traverse rate. After the model was developed to correlate at speeds up to 1.93 km/hr (1.2 mph), it was extrapolated to 32.2 km/hr (20 mph) to predict depth of cut into the ice. This is presented in Figure 6, which shows that at 999 kPa (145 psi), approximately 1.59 mm (0.0625 in.) of ice could be removed at a speed of 32.2 km/hr (20 mph). Because the depth-of-cut curve tends to decrease at a lower rate, at vehicle speeds greater than 16.1 km/hr (10 mph), it appears that ice removal may be possible at speeds greater than 32.2 km/hr (20 mph).

TABLE 2 Traverse Rate Versus Depth and Width of Cut

Traverse Rate (km/h)	Nozzle Angle = 90° Depth/Width (mm)	Nozzle Angle = 60° Depth/Width (mm)
0.48	88.9/38.1	76.2/38.1
0.97	50.8/38.1	28.7/38.1
1.45	31.8/31.8	25.4/31.8
1.93	28.7/31.8	23.9/25.4

TABLE 3 Traverse Speed Versus Depth and Width of Cut

Traverse Rate (km/h)	Depth of Cut (mm)	Width of Cut (mm)
0.08	31.91	50.8
0.15	25.4	25.4
0.26	19.1	22.4
0.37	14.1	19.1
0.97	9.7	25.4
1.45	7.9	31.9
1.93	6.4	25.4

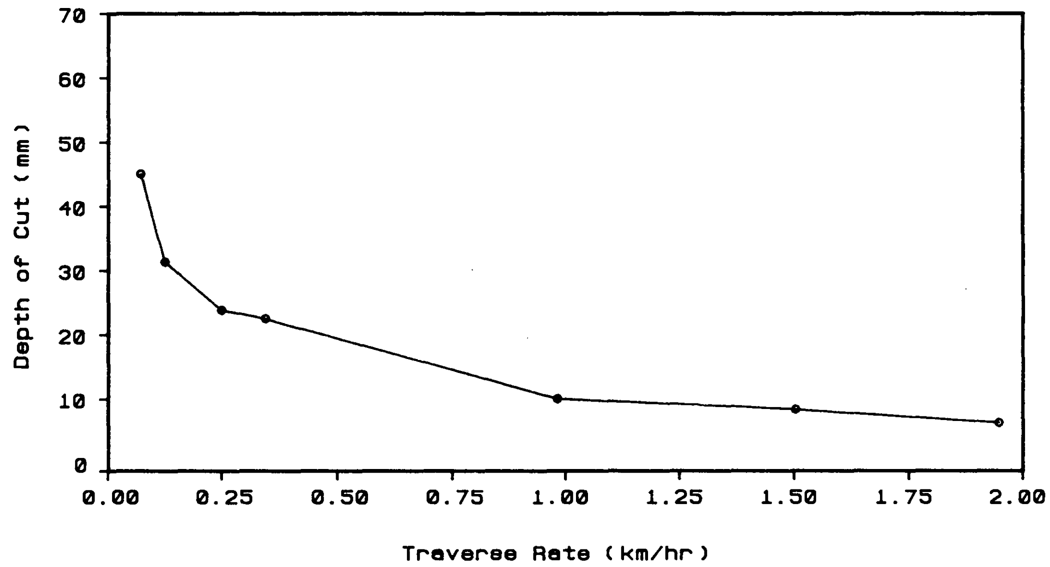

FIGURE 4 Depth of cut versus traverse speed, experimental data.

INITIAL FIELD STUDIES

In an attempt to verify removal of ice at 32.2 km/hr (20 mph), a large portable air compressor [10.5 m^3/m (375 ft^3/m) at 689 kPa (100 psi)] and a 272.4-kg (600-lb) pot sandblaster, including a 9.5-mm (0.375-in.) venturi nozzle, were borrowed from a local sandblasting company. For this test, ice 25.4 mm (1 in.) thick was formed on 0.61- × 1.22-m (2- × 4-ft) wooden sheets that were carried outside from the cold rooms for testing. A short series of tests was carried out at 8.1, 16.1, 24.2, and 32.2 km/hr (5, 10, 15, and 20 mph). The sandblaster was placed in the back of a pickup truck, and the air compressor was towed behind the truck. At 8.1 km/hr (5 mph), a layer of ice 6.4 mm (0.25 in.) thick was removed. At 16.1, 24.2, and 32.2 km/hr (10, 15, and 20 mph), a layer of ice 1.59 to 3.18 mm (0.0625 to 0.125 in.) thick was removed. As the model predicted, there was not much difference in the depth of cut between 16.1, 24.2, and 32.2 km/hr (10, 15, and 20 mph). These tests were conducted at 689 kPa (100 psi), and if a system were built, 999 kPa (145 psi) of pressure would be used, enhancing the ice removal process. Also in this test, the compressor was pulled behind a pickup truck and 7.6-m (25-ft) air supply lines and sandblasting lines were used. In a field unit the compressor and sandblaster would be mounted in the back of the truck where shorter supply lines and hoses could be used to ensure more efficient use of the air being supplied by the compressor, because the line losses can be significant, especially in a multinozzle system. Figure 7 shows

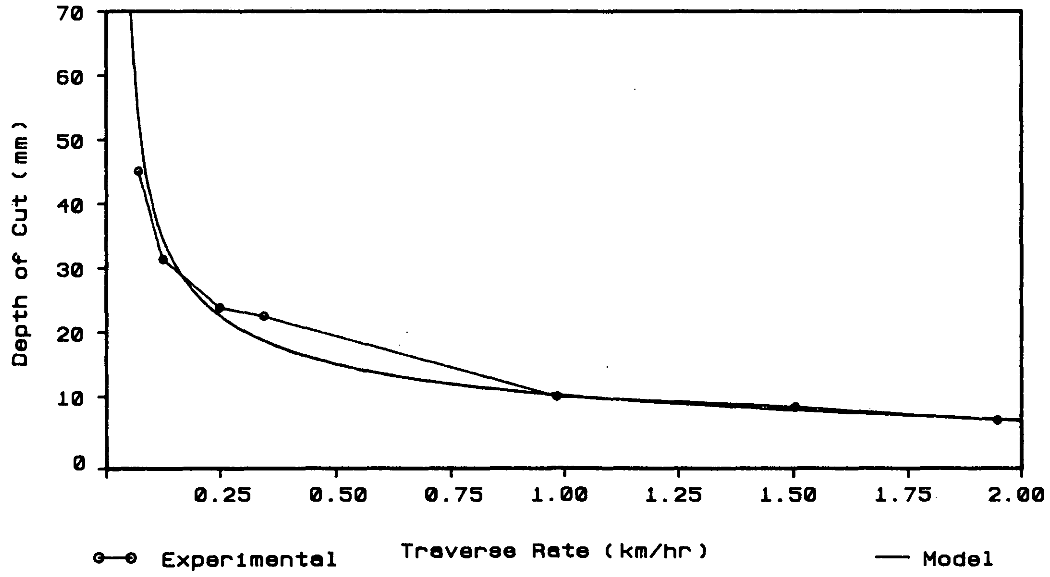

FIGURE 5 Model versus experimental data up to 1.93 km/hr.

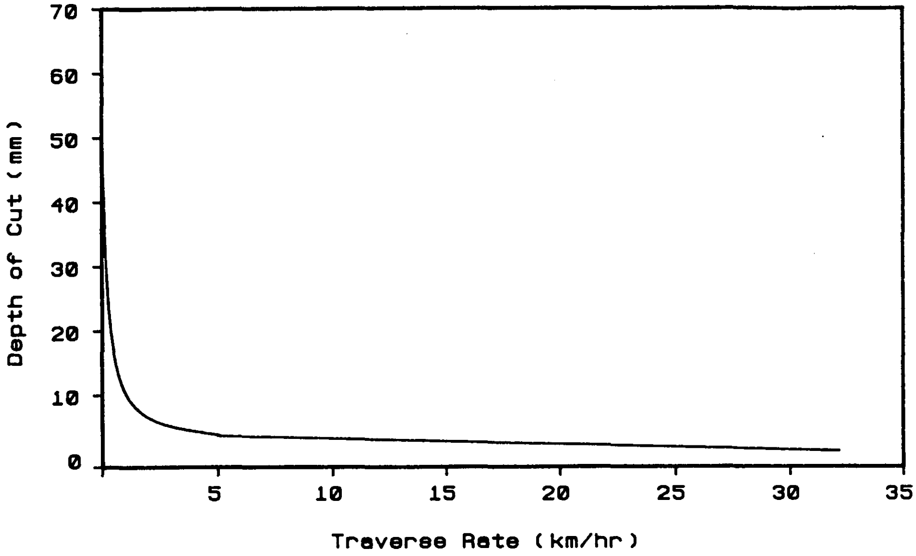

FIGURE 6 Model data extrapolated to 32.2 km/hr.

the plot of final depth of cut versus traverse speed for Black Beauty with both experimental and computer model data up to 32.2 km/hr (20 mph).

OTHER CONSIDERATIONS

Although it has been shown that an abrasive air blast system can remove ice at traverse rates of 32.2 km/hr (20 mph), more research needs to be conducted. A field unit needs to be developed with multiple nozzles for removing wide sections of roadway. The original tests were conducted with a small compressor and converging-type nozzle, so tests should be conducted to determine optimum nozzle size, abrasive type and size, and nozzle control for a large-scale system and venturi nozzle. Tests should be carried out on actual roadways with ice and compacted snow. Operator or automatic control systems need to be developed for the nozzles and air compressor to obtain maximum removal without pavement damage under all road conditions.

Pavement damage is currently being studied. It may appear to be a problem, but when tests were conducted at KRC at speeds of 8.1, 16.1, 24.2, and 32.2 km/hr (5, 10, 15, and 20 mph), some of the abrasives were blasted at the asphalt pavement in the parking lot with no apparent damage. The problems will most likely occur at intersections when the vehicle slows or stops.

There are two ways to effectively control snow and ice removal: one is to raise or lower the nozzles and the other is to control nozzle output through a shut-off valve at the nozzle. There are essentially two areas of concern for controlling system performance without pavement damage. One is the

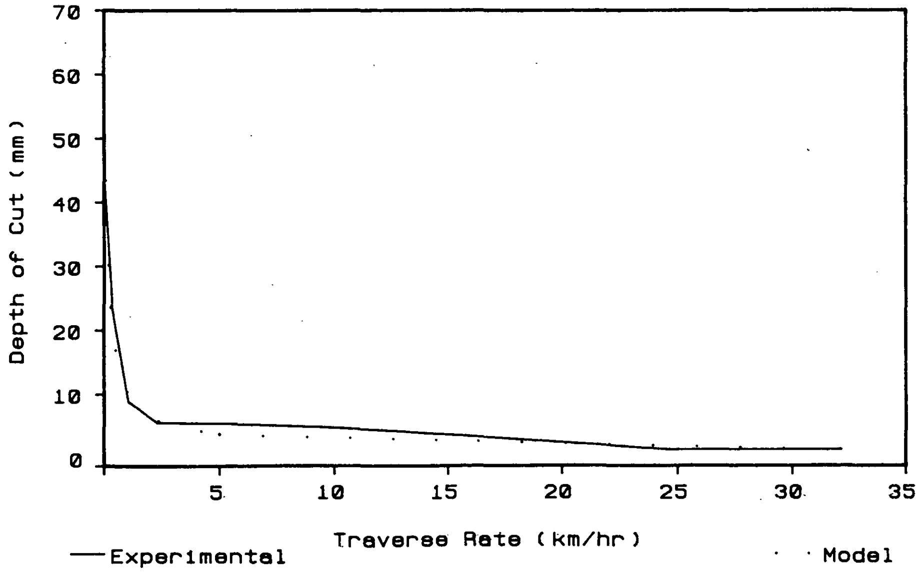

FIGURE 7 Model and experimental data at speeds to 32.2 km/ hr.

method of sensing snow and ice thickness or the absence of snow and ice, and the other is that of controlling nozzle height and operation.

Currently, KRC has a research grant to design and build a single-nozzle system with a control system to prevent pavement damage. The nozzle control system will consist of a hydraulic cylinder positioning servosystem with sensors such that nozzle height may be adjusted to avoid pavement damage.

Determining the conditions under which pavement damage occurs is a crucial step in designing the control system. Pavement damage will occur when the nozzles are at a height such that the depth of cut is deeper than the existing snow or ice thickness or when no snow or ice is present. For example, since pavement damage occurs at slower speeds, nozzle height must increase when the vehicle comes to a stop at an intersection. The control system is being designed to avoid these conditions and will operate in either a manual or an automatic mode. In the manual mode, the nozzle position will be set by a manually controlled transducer (potentiometer). In the automatic mode, the nozzle height will be adjusted automatically by discrete control.

Friction sensors are being designed such that the friction on the road surface and thickness of the snow or ice is continuously measured before and after the nozzles. It is well known that the coefficient of friction for a tire on dry pavement is about .7; on snow, .3 to .4; and on ice, .01 to about .2. Each friction-measuring system will consist of a set of wheels connected by gears and chains so that one wheel will be driven at vehicle speed while the other wheel will be driven at a speed approximately 12 percent slower when on dry pavement. This will result in a generation of torque on the second wheel that can be converted into a frictional force between the pavement and the tire. On snow and ice the torque will be reduced because of the slippage between the tire and the ice or snow surface. Tests will be run to set up the parameters for when ice, snow, or pavement is present. Two sets of the wheel friction-measuring device will be used: one ahead of the nozzle banks and one following the nozzle banks. Each set of wheels will also have a vertical displacement–measuring device for determining height differences between the front and rear sets of friction-measuring wheels. This will determine the depth of cut. The combination of depth of cut and friction measurement after the nozzle bank will determine if the cut is sufficient. The information will be continuously input to a microprocessor unit, which will control the hydraulic cylinders that raise or lower the nozzle banks, making continuous adjustments as the vehicle travels down the roadway.

During the 1992–1993 winter, tests will be conducted with the single-nozzle system and the control system. The tests will be conducted to set up the parameters for on-road use. In addition, since venturi-type nozzles can now be used, parametric studies can be conducted to develop new curves for the depth of cut versus traverse speed, nozzle angle, and type and size of abrasive for optimum removal.

FUTURE DEVELOPMENT

After the successful development of a control system for a single-nozzle system, KRC plans to seek funds to design, fabricate, and test a full-scale system that would include full-size compressors and sandblasting pots. The research has shown that one 44.8-m^3/m (1,600-ft^3/m) compressor will run four nozzles continuously all day long. An appropriate system could have eight nozzles and, depending on the nozzles used, could cover most of a road lane. Each compressor would have a corresponding 7264-kg (8-ton) sand pot that would contain enough abrasive to last an 8-hr shift. There are also air heaters and dryers available that would be incorporated into the system.

Another aspect that should be investigated is the vac-blast concept. After tons of sand are blasted on roadways all winter, the sand must be removed. Although current estimates for the amount of sand applied by the abrasive air blast system are about 90.8 kg (200 lb)/lane-mi versus the currently used 181.6 kg (400 lb) that is spread (not blasted) on roads in Michigan, the abrasive material will build up over time and will have to be removed. The vac-blast concept consists of a vacuum head and hose integral with the nozzle. The vacuum head surrounds the nozzle so that very little abrasive is left on the surface being blasted. The system has merit and needs to be investigated. The vac-blast system may be capable of removing most of the debris and would also contain the abrasive such that it is not blasted toward people or cars behind the abrasive air blast truck.

ACKNOWLEDGMENTS

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New Ideas and Equipment for Winter Maintenance in Finland

RAUNO KUUSELA, TAPIO RAUKOLA, HEIKKI LAPPALAINEN, AND ANTTI PIIRAINEN

New Finnish winter maintenance equipment and methods are summarized. Examples include a station for liquid salt production, liquid salt spreaders for maintenance areas with low traffic volumes, new types of snowplows, the Finnish multifunction road maintenance vehicle, video camera control, an alternative antiskid treatment, and heated-sand tests.

The Research and Development Unit of the Finnish National Road Administration (FinnRA) at Tampere specializes in winter maintenance development, mainly through field tests. Its staff works closely with the maintenance personnel at the road districts and maintenance areas; the unit operates on the basis of work orders from these personnel and central administration. There are three other research and development units at FinnRA; they concentrate on different fields of development. The units exchange information and have contacts with foreign agencies as well.

This paper summarizes the newest Finnish ideas and equipment for highway winter maintenance.

BRINE PRODUCTION UNITS

There are about 40 factory-made units for brine production in Finland. If the self-made models are included, there are about 100 units altogether. Brine is used mainly for liquid salt application but also as a prewetter of granular salts.

Development began when some FinnRA technicians started to plan an efficient and reliable model from the self-made mixing units; some private companies did the same. A maximum production capacity of 60 m^3/hr can be reached now. Small self-made models are still needed for areas with low traffic volumes or just for prewetting (Figures 1–4).

SIMPLE LIQUID SALT SPREADERS AND PREWETTING SYSTEMS

Less-expensive equipment is needed where traffic volumes are low, where only limited stretches of the highways are treated with salt, or where the low winter temperature range prevents the use of liquid in the middle of the winter. Many simple spray bar and spinner spreaders have been developed. They cost about 20 percent of what the most expensive liquid spreaders cost, and they have been shown to be appropriate (Figures 5 and 6).

The salt can be prewetted at the spinner or just before it drops to the spinner. When the prewetting takes place at the end of the screw conveyor, the liquid is better absorbed because of a longer contact time (Figures 7 and 8).

Prewetting with water in a truck is a good method for areas that need only a little salt. The most even wetting result is achieved by spraying water into the salt through a specially designed nozzle. If salt is wetted from above, a few jets of water give the quickest result (Figures 9 and 10).

QUICK CHANGE ACCESSORIES

Quick change accessories and equipment have been developed for emergencies; one example is a brine tank with its own legs. The tank can be easily loaded into the truck. The legs of the tanks are often dimensioned to carry the full load when loading or unloading a truck or when storing liquid. A corresponding system can also be built on a demountable body of a truck (Figures 11 and 12).

SNOWPLOWS

Slush removal is important but difficult if there are deep ruts on a pavement. A dual-blade plow has been designed to take slush away from ruts. The first cutting edge is made of steel, and the second, of flexible rubber. Synthetic materials have also been tested to replace rubber. A good plowing speed is 30 to 60 km/hr (19 to 38 mph), depending on the type of slush or snow. The plowing width is 2.8 to 3.0 m (9 to 10 ft), and the maximum height of the plow is about 1.5 m (5 ft) (Figures 13 and 14).

Extendable hydraulic plows can adjust plowing widths from 2.8 to 3.5 m (9 to 11.5 ft). The extension component can be on the right or left side of the plow. For a left-hand extension, the whole plow moves an equal step to the right. The wing height is 1.2 to 1.6 m (4 to 5 ft), and the plowing speeds are 40 to 60 km/hr (25 to 28 mph) (Figure 15).

UNDERBODY PLOWS

Underbody plows are in extensive use in Finland for removing snow and slush and for leveling softly packed snow layers.

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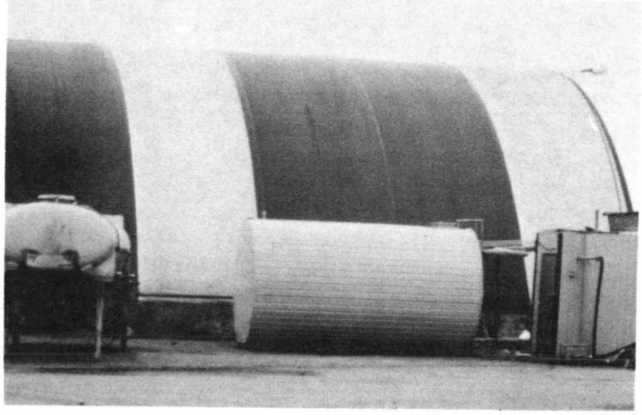


FIGURE 1 Semiautomatic mixing unit with a 10-m^3 mixer and a 20-m^3 storage tank made of stainless steel.

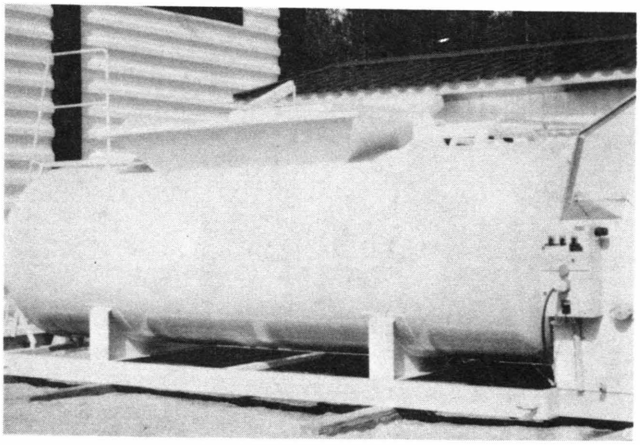


FIGURE 2 Mixing unit for prewetting liquids. Tank is made of epoxy-coated steel.

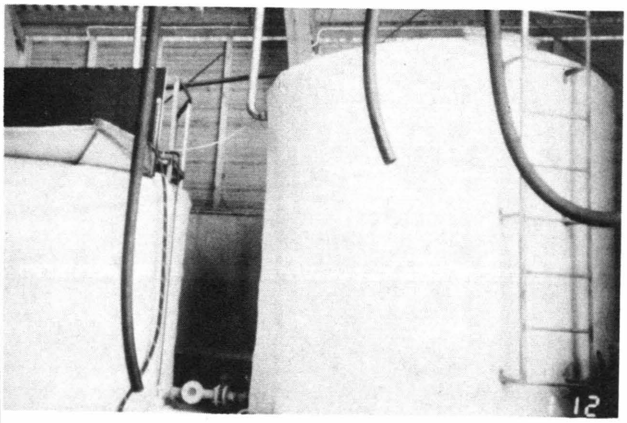


FIGURE 3 Automated mixing unit (10 m^3) with storage tank (20 m^3) made of fiberglass.

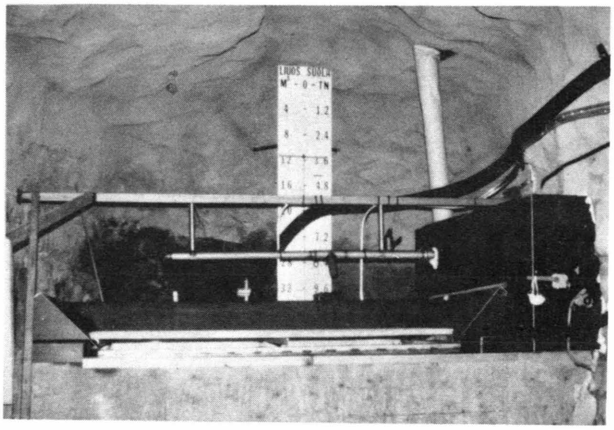


FIGURE 4 Efficient (up to 60 m^3/hr) mixing unit in the rock. Salt and sand are stored in the same cave.

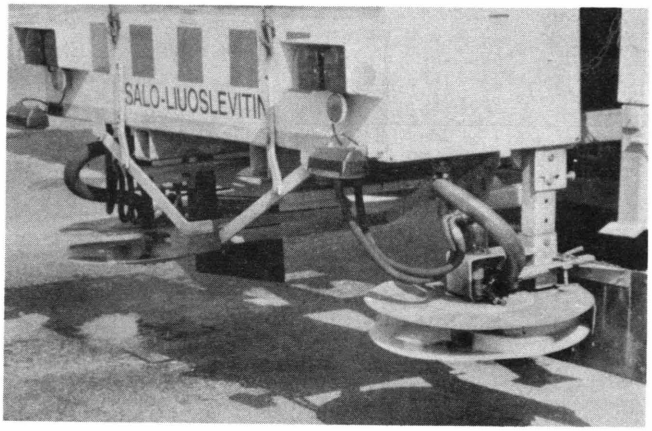


FIGURE 5 Spinner liquid spreader with operating speed of 40 to 55 km/hr.

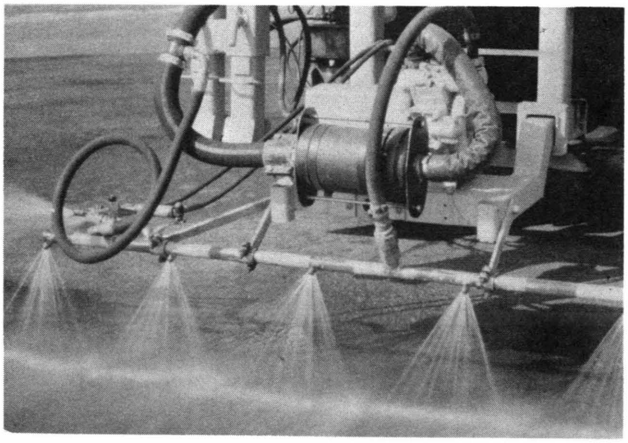


FIGURE 6 Spray bar liquid spreader with operating speed of 50 to 70 km/hr. Solid leg of the tank for full tank handling can be seen.

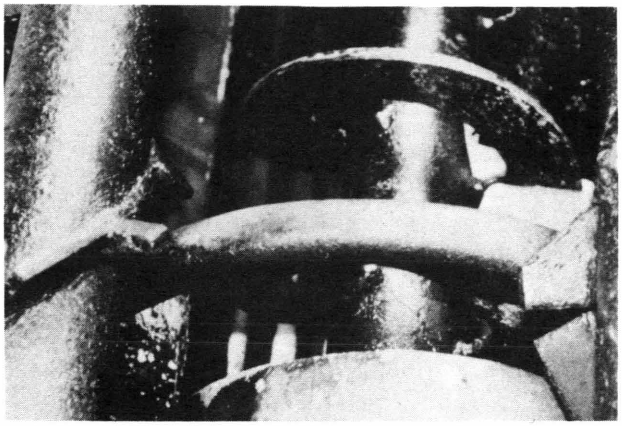


FIGURE 7 Inside view of spinner-type spreader hopper. Prewetting pipe is at end of screw conveyor.

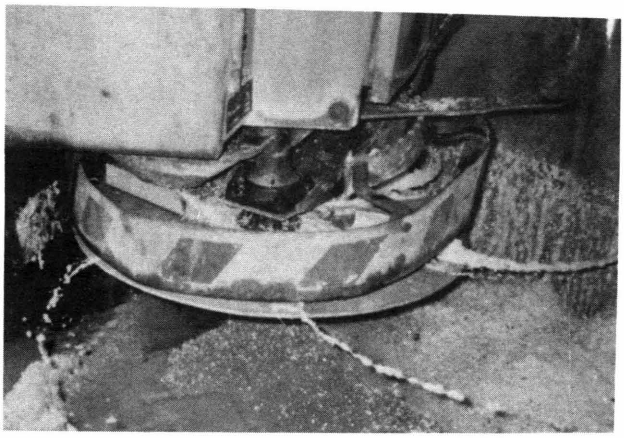


FIGURE 8 Spreader of Figure 7 seen from outside. Prewetted salt is dripping wet. Amount of prewetter is 20 weight percent.

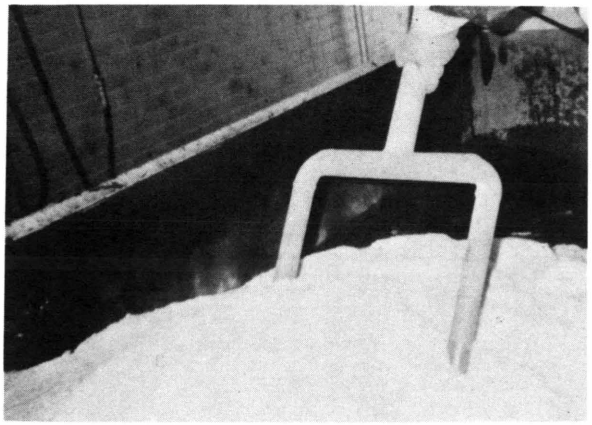


FIGURE 9 Salt can be prewetted in a truck by using a special nozzle.

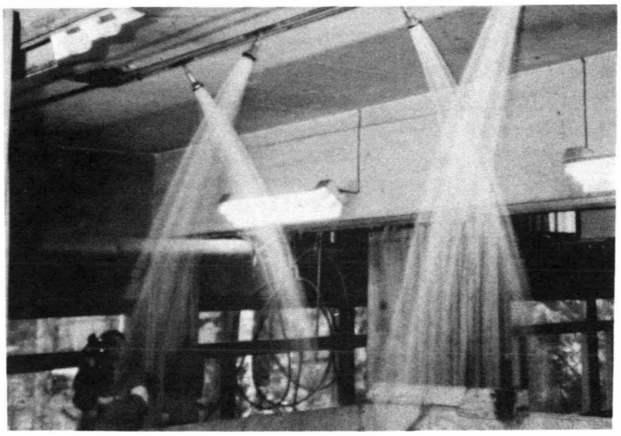


FIGURE 10 Water jets from the ceiling prewet the salt quickly in the truck.

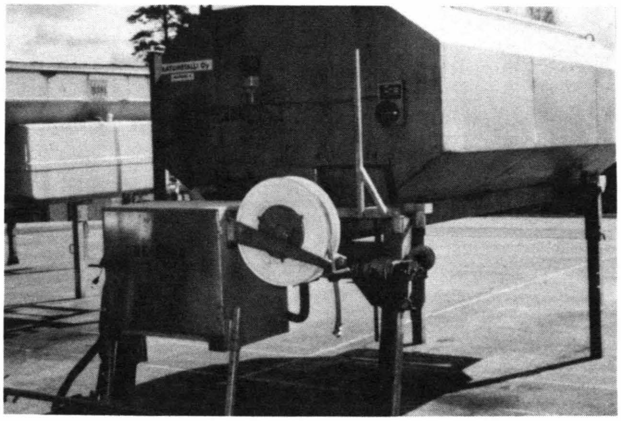


FIGURE 11 Steel tank for storing and transporting liquids. At rear of tank is a spray bar spreader that can be converted to a washer for bridges using a hose. The legs and other structures are often strengthened to allow handling of the full tank.

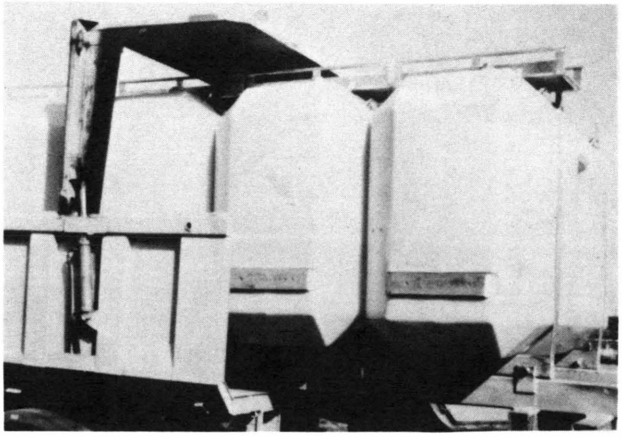


FIGURE 12 Tank system made of glass fiber blocks. Number of blocks is chosen according to the need and space available.

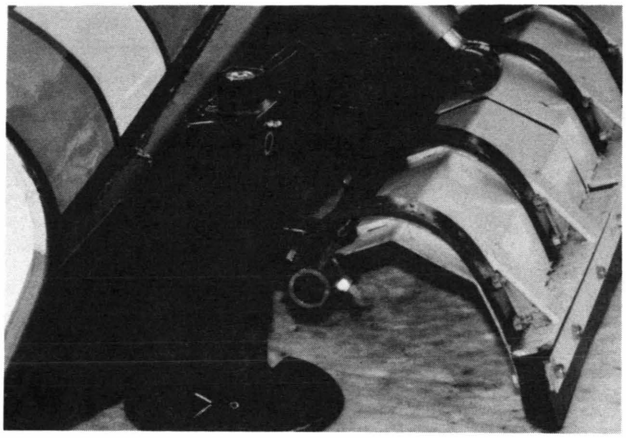


FIGURE 13 Dual-blade plow. The flexible rubber blade is behind the steel cutting edge. This type of a plow meets well the requirements of rutted pavements.

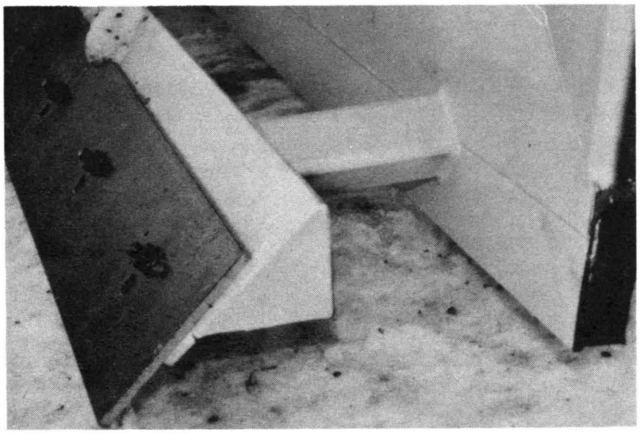
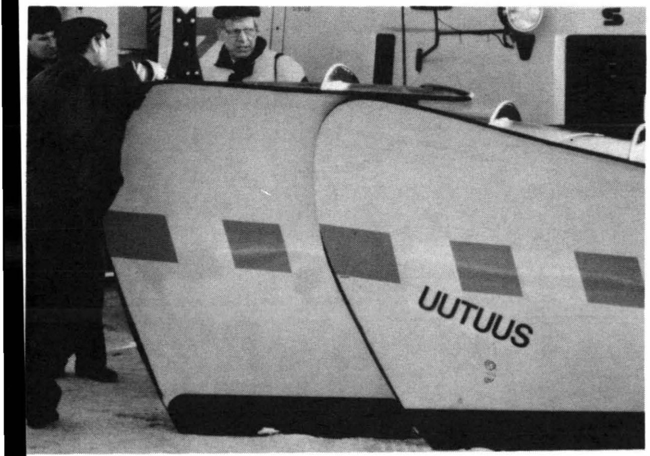


FIGURE 14 Another type of dual-blade plow. The steel cutting edge is set in a fixed outward position.



IGURE 15 Extendable one-way plow. The extension is to the ight.

Therefore, the use of motor graders is postponed on the packed snow. All kinds of cutting edges are possible. A side wing can be used at the end of the underbody plow to cast snow further. The plowing speed is 25 to 35 km/hr (16 to 22 mph), and the leveling speed for packed snow is about 20 km/hr (13 mph). The blades of the underbody plows are multipurpose accessories because they can be used for summertime purposes as well (Figures 16 and 17).

MULTIFUNCTION VEHICLE

Different winter activities are often carried out simultaneously. The multifunction vehicle has a one-way plow, a side wing (sometimes in connection with an underbody plow), and a combination spreader. This type of spreader can take liquids and granulars simultaneously and spread them separately or mixed (Figures 18 and 19).

SKID RESISTANCE CONTROL FOR MONITORING LEVEL OF SERVICE

The quality of road conditions is measured all over Finland throughout the winter. The number of evaluations is statistically calculated for 10 percent accuracy. In Häme district a skidometer with a data logger is used (Figure 20). For roads with average daily traffic (ADT) below 1,500, deicing operations should be initiated when the friction coefficient is less than 0.30.

CAMERA CONTROL

Camera control is in experimental use to monitor road conditions and to supplement the information from road weather stations. The requirements for traffic control and road condition monitoring are different. Traffic control requires online information, and low-resolution pictures are accepted. Road condition monitoring works best with high-quality but still frames. Only a few reliable (but expensive) systems were

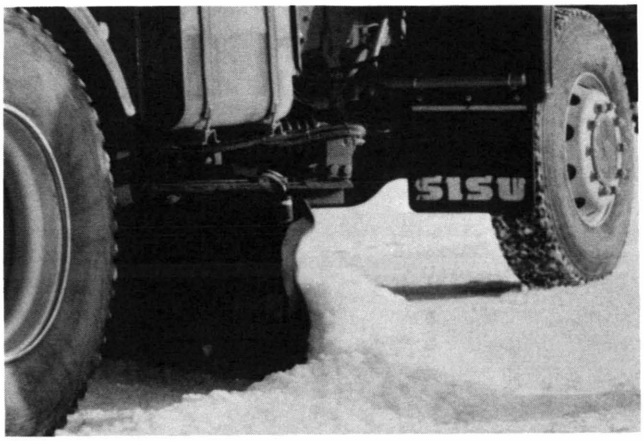


FIGURE 16 Underbody plow leveling a layer of packed snow.

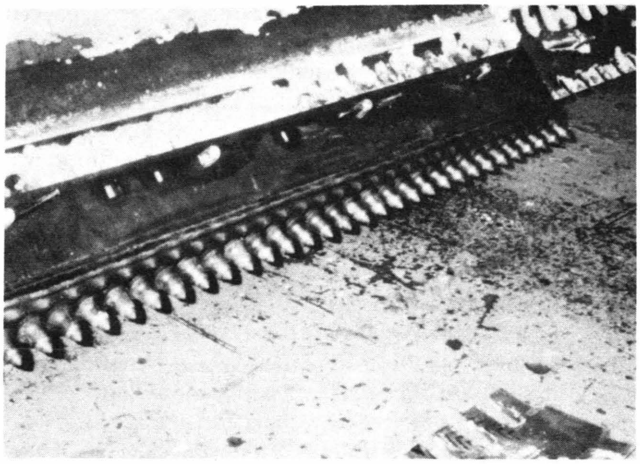


FIGURE 17 All kinds of cutting edges can be used with underbody plows.

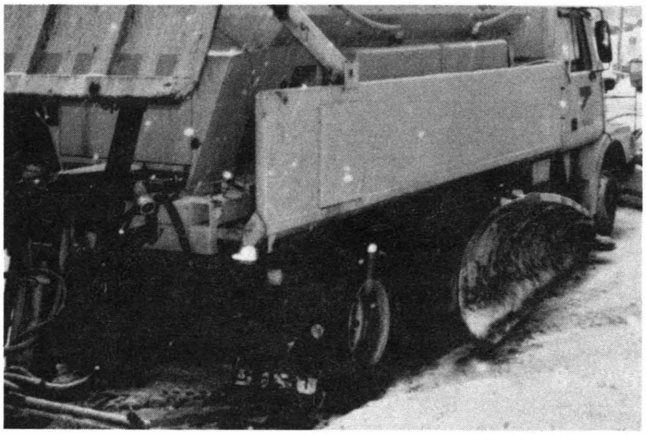


FIGURE 18 Fully equipped maintenance truck with plow, side wing, and combination spreader. Tailgate has a hydraulic control that can be used to decrease the turbulence behind the truck. Tank can be handled through the tailgate.

FIGURE 19 Reversible plow on multifunction truck.

FIGURE 20 Material storage in a rock including sand, granular salt, and mixing unit for brine. Storage is filled from upper level.

formerly available. The new cameras do not need any difficult bidirectional control for fine-tuning the picture. They take clear 640- × 512-resolution black-and-white pictures, in an illumination of only 0.15 lux (Philips) and at night with the help of 300- to 500-W infrared light sources. An inexpensive PC with a high-performance frame grabber (Screen Machine) packs the picture 1:25 and sends it through a communications network or an ordinary telephone line (US-Robotics V.32 bis). The delay time for one picture is 1 min, but only two or three pictures an hour are needed for a sufficient level of control. Full-color pictures are possible without any modification. The picture history makes it possible to extrapolate snowfall rates and such. Almost all equipment and software are off the shelf, so new computer technology will lower the prices dramatically (Figures 21–23).

REINDEER AND CALCIUM MAGNESIUM ACETATE

Reindeer cause more than 4,000 traffic accidents a year in northern Finland. In winter they gather to the highways to

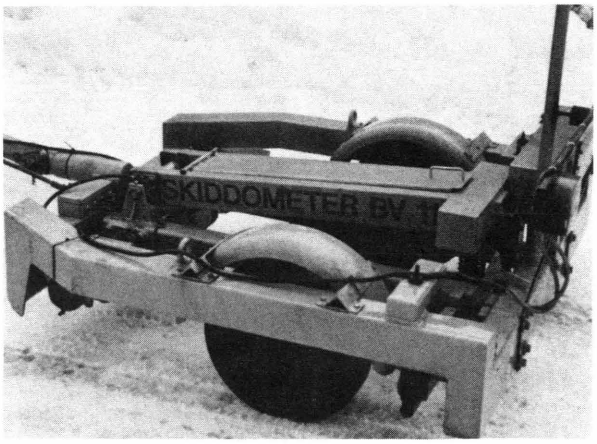


FIGURE 21 The centralized friction measurements collect equal data from different areas.

FIGURE 22 Camera control post in connection of a road weather station. The camera has infrared light for night use.

eat salt mixed with sand. It was assumed that calcium magnesium acetate (CMA) would not attract reindeer because it smells like vinegar. Tests proved this to be so: the reindeer are so eager to eat salt that they must be pushed away with vehicles, but when roads have been treated with a sand-CMA mixture, the reindeer become timid and run away.

ALTERNATIVE ANTISKID TREATMENTS

Sand and Liquid Salt Mixes

Spraying liquid salt onto sand in a truck is done regularly in one maintenance area with positive results so far.

FIGURE 23 Post in Figure 22 is situated in a difficult and remote stretch of highway.

Junction Treatments with Sand and Spray of Liquid

The junctions and interchanges are treated first with salt and then immediately with a spray of liquid NaCl mainly in cold conditions. It has been found that the spray binds the sand well with a usual application rate of 10 g/m^2.

Heated-Sand Field Tests

In January–February 1991, two heated-sand studies were made in the Lappi and Oulu districts of FinnRA. The objective was to study whether the heated sand would stay longer on roadways than sand mixed with small amount of sodium chloride. The ADTs of the study highways were roughly between 250 and 500. The roadways were mainly covered with ice 15 to 20 mm (0.6 to 0.8 in.) thick. During the studies the road surface temperatures varied from about −10 to −20°C (−14 to 4°F).

The best results were achieved in the Oulu district, where the sand was heated using a drying drum at an old asphalt plant. The highest temperatures measured in the truck were about 250°C (482°F).

Even in the best of cases, the measured friction values returned to the initial state within 24 hr. It was shown that sand temperatures must be clearly above 100°C (212°F) to lead to penetration of sand particles and increased friction. Large particles kept the heat, but small ones did not. After some time only large particles could be seen here and there sunk into the ice. For increased skid resistance, fine particles also would have been needed, but they were blown away.

According to the tests, the heated-sand method is not technically feasible for a long-term increase in friction values on ice packs (Figure 24).

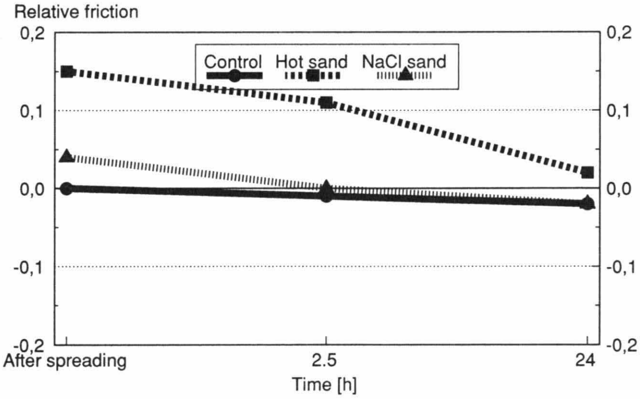


FIGURE 24 Curves of changes in friction values in best case.

Analytical Model for Two-Stage Rotary Snowplows

DAVID J. STEVENS AND KEVIN B. POWERS JR.

An analytical model for the performance of two-stage rotary snowplows is developed to consider both high-velocity operations and the effect of snow properties on machine performance. The analysis determines the power required to cut and disaggregate the snow, the snow removal rate, and the total power required by the system. The purpose of the model is to perform parametric assessments of the rotary snowplow's performance and efficiency. The model results show that the strength of the snow has considerable effect on the power required by the auger to disaggregate the snow and on the total power required for removing the snow. Unfortunately, the available data from field tests of full-scale rotary snowplows are limited and no quantitative verification of the model can be made; however, the model does allow qualitative assessment of the effects of changing the rotary snowplow configuration or the properties of the snow.

In the past, the development of snow removal equipment (both displacement and rotary snowplows) has been performed on a trial-and-error basis. This lack of a rigorous approach was discussed by Minsk (*1*), who pointed out that the "snowplow industry in the United States is composed of small, widely dispersed firms, none with the resources to finance a significant research program. Furthermore, there is no industry association to attempt a cooperative research effort funded by contributions from manufacturers. There is little incentive for manufacturers to spend the necessary amounts required for a comprehensive research program."

In addition, the existing designs and analyses of snow removal equipment have been developed without sufficient consideration of the properties of snow—that is, that "snow is snow." The properties of snow (density and strength) vary greatly from snowfall to snowfall or even hour to hour and, thus, strongly affect the performance of both displacement and rotary snowplows. Proper consideration of the properties of the snow in the design process should aid in improving the performance and efficiency of snow removal equipment.

In this paper, an analytical model for the performance of rotary snowplows is presented. Previous developments (*2,3*) are extended to include high-speed plowing and are improved by considering the effects of snow properties on the power required by the machine.

In the computer implementation of the model, the power requirements of the auger, impeller, and vehicle are evaluated under different operating conditions; the model is applied to a series of forward speeds, auger and impeller rotational speeds, snow depths, snow densities, and snow strengths. Unfortunately, experimental data to provide quantitative verification of the model are not currently available; however, the results appear to be qualitatively reasonable and the model provides a means of assessing the influence of parametric changes.

BACKGROUND

Unlike the displacement snowplow, which lifts the snow from the surface in front of the vehicle and transfers it to the side, a rotary snowplow cuts or disaggregates the snow and then propels the disaggregated mass away from the machine. A one-stage rotary snowplow uses a single element to perform both cutting and casting. A two-stage rotary snowplow consists of two elements: a rotating auger with three or four helical steel ribbons that disaggregate (or cut) the snow, and an impeller with four or five rotating paddles that discharge the material. Figure 1 shows a schematic of a rotary snowplow, and Figure 2 shows a large rotary snowplow in action. The power requirement of the system includes the power to drive the auger and impeller and the power to propel the vehicle. For large machines, separate engines are commonly used to propel the vehicle and to drive the collecting apparatus; in some commercial machines, a 450-kW (600-horsepower) engine drives the auger and impeller and a 200-kW (260-horsepower) engine propels the vehicle. Typically, these large snowplows are used to clear military and civilian runways, mountain roads, the shoulders of roads after heavy snowfalls, and urban areas where the snow is loaded directly into a truck. High-speed plowing is obviously critical for runway operations.

One of the first studies of rotary snowplows was performed by Croce, who tested and analyzed one-stage machines and primitive two-stage machines (*2*). In a later publication, Croce applied his theories to a single machine (*4*). Croce noted that the mechanical energy needed to cut the snow depends on the hardness, but he did not explicitly consider the effects of snow properties on system performance.

Later, Shalman investigated the energy requirements of the cutting element (auger) and the throwing element (impeller) separately (*3*). Shalman's work was analytical, and no correlation between the analysis and actual machine operations was drawn.

SNOW PROPERTIES

Minsk defined snow removal as a (relatively) simple task of material handling (*1*). The complexity, though, lies in the large variability of the material's properties. Density can range

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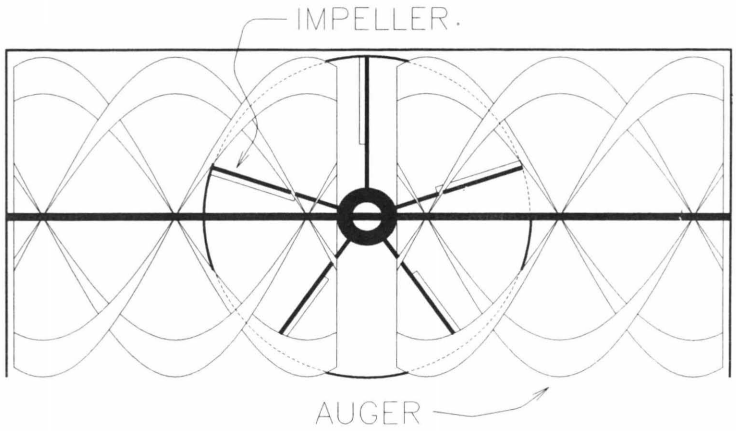

FIGURE 1 Components of a two-stage rotary snowplow: front view.

from 48 kg/m^3 (3 lb/ft^3) for new snow to 593 kg/m^3 (37 lb/ft^3) for snow that has been windblown or plowed. In addition, snow can be compressed as much as eight times, or up to 800 kg/m^3 (50 lb/ft^3). Hardness can range from less than 6.9 kPa (1 lb/in.^{2}) for freshly fallen, low-density snow to 206.9 kPa (30 lb/in.^{2}) for well-bonded, high-density snow.

One of the interesting properties of snow is its ability to increase strength with time after it has been mechanically agitated or processed (*5–7*). For instance, snow that has just been plowed will exhibit an increased density but little immediate strength gain; however, within an hour or two, the windrow can be strong enough to support the weight of a person, even though the density is unchanged. This age strengthening occurs through the process of sintering, in which the number and size of bonds between the snow crystals increase with time (*8*).

Much work has been performed to determine and relate other snow properties, such as density, compressive strength, and shear strength; see work by Powers and Stevens (*9*) for a detailed discussion of these studies. However, for later use, two studies are discussed here.

First, Gold analyzed the dependence of the compressive strength (hardness) of snow on density, temperature, and crystal size (*10*). Gold expressed the relationship between density and hardness as

$$H = 6.67e^{10.24\rho} \qquad \rho \le 0.15 \text{ g/cm}^3$$

$$H = 35{,}500\rho^{3.92} \qquad 0.15 \text{ g/cm}^3 < \rho < 0.4 \text{ g/cm}^3 \tag{1}$$

where H is the hardness and ρ is the density. It should be noted that, as is typical with most naturally occurring materials, there is significant scatter in the measured data.

FIGURE 2 Rotary snowplow in action.

Second, Perla et al. used a shear frame with an area of 0.25 m^2 (38.75 in.^{2}) to measure the shear strength of snow in the field (*11*). They related the shear strength to the density as

$$\tau = \tau_i(\rho/\rho_i)^k \tag{2}$$

where

τ = shear strength,
ρ = density,
ρ_i = characteristic density = 917 kg/m^3 (57 lb/ft^3),
τ_i = 397.5 kPa (5,760 lb/ft^2), and
k = 2.7

ANALYTICAL MODEL

An analytical model of a two-stage rotary snowplow is developed to determine the power required to disaggregate and remove snow. As discussed earlier, a two-stage rotary snowplow contains a rotating auger that cuts the snow and an impeller that discharges the material (Figure 1).

In this analysis, two topics are investigated: the dynamics and kinematics of the auger, impeller, and truck; and the effect of changing snow properties on the system performance. The investigation focuses on the power required to disaggregate the snow by the auger. The analysis of the power required by the impeller for casting is based on previous research (*3*), and the power used in plowing the snow with the back of the auger housing is based on experimental studies (*9*). And, as with previous researchers (*2,3*), a number of simplifying assumptions are made regarding the movement of snow within the auger and impeller because of the complexity of the system.

Auger Mechanics

The investigation of the auger considers the cutting path of the blades, the power required for cutting the snow, and the power required to move the snow to the impeller.

Auger Cutting Path

The cutting path of each auger blade is represented by a set of parametric equations that define the position of the blade:

$$x = \frac{U\theta}{\omega} + R \sin \theta y = R \cos \theta \tag{3}$$

where

U = vehicle velocity,
ω = auger's angular velocity,
R = auger's radius, and
θ = angular position of blade (Figure 3).

The blade path can be uniquely determined by the ratio of angular velocity of the auger, ω^*, to forward velocity, U^*.

According to Shalman (*3*), it was assumed that the forward velocity term $U\theta/\omega$ in Equation 3 could be taken to be negligibly small in comparison with the angular velocity; thus, the blade path is a circle, following approximately the same path as the previous blade path and effectively taking only a small "bite" from the snow mass. This assumption only holds for low-speed plowing. For high-speed plowing, the forward velocity term in Equation 3 becomes significant, and the trajectory of the blade is a cycloid with slip, creating loops in the path (Figure 4). Therefore, the length of the cutting arc for the outside and inside of each blade will increase as the overlap of the previous blade path is reduced (Figure 5). The lengths of both the outside and inside cutting arcs reach their maximum when the blade face no longer crosses the previous path. For very high speed plowing, the forward velocity term dominates the equation, and the blade trajectory approaches the path of a true cycloid.

In high-speed plowing, a part of the snow mass is not cut (Figure 6) but is instead plowed by the back of the auger housing or moved directly into the impeller. In this situation, the truck will have to provide more driving power to overcome the plowing force. The proposed model includes an approximation of the plowing effect of the auger housing, as discussed later.

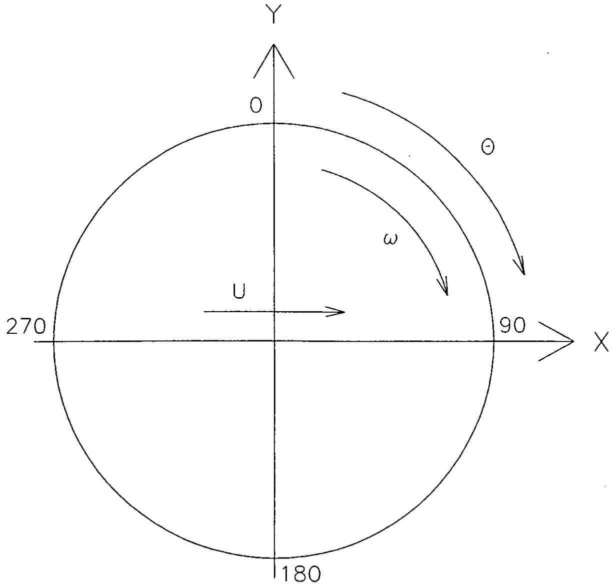

FIGURE 3 Coordinate system of auger.

Auger Power

The analysis by Shalman of the cutting force of an auger blade was developed for low-speed plowing and did not consider the forward motion of the machine, which underestimates the cutting force required for high-speed plowing (*3*).

The analysis begins by considering the increment in cutting force as a function of the resistance to cutting:

$$dF = kdB \tag{4}$$

where

dF = increment in cutting force,
k = coefficient of cutting resistance, and
B = width of the cutting blade.

However, because the cutting resistance is a function of both the shear strength and compressive strength of the snow, it is assumed, in this model, that the cutting resistance can be taken as follows:

$$k = k_c b_\theta + n k_s \tag{5}$$

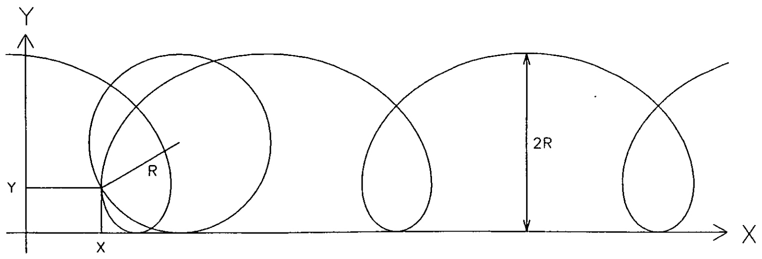

FIGURE 4 Path of a cycloid with "slip."

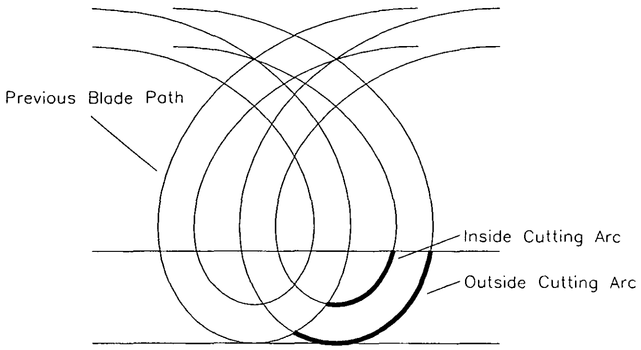

FIGURE 5 Inside and outside cutting arcs of auger.

where

k_c = compressive strength of snow,
n = number of shear faces ($n = 1$ or 2),
k_s = shear strength of snow (force/unit length), and
b_θ = thickness of the snow layer being compressed and is a function of the position of the blade in the snow.

The strength value k_c is identical to the hardness H, given in Equation 1, and k_s is the shear strength τ, from Equation 2, multiplied by the length of the shear box. Figure 7 illustrates the shear and compression resistance of the snow. If the snow is deep enough, the auger blade will also cut on the inside edge (i.e., $n = 2$), assuming that the inertia of the snow is sufficient to resist the cutting force.

It is well-known that snow is a rate-dependent material, exhibiting greater strength and stiffness at higher strain rates, but rate effects are not considered in the initial version of this model and will be considered in later development.

The thickness b_θ of the compressed snow layer is a function of the blade position but is limited to the overall width of the blade when the snow is sheared by both edges of the blade ($n = 2$). The determination of b_θ for different plowing conditions when only one edge is cutting ($n = 1$) is discussed in detail by Powers and Stevens (*9*).

The increment of work done to overcome the cutting force is expressed as

$$dW = zdFdl \tag{6}$$

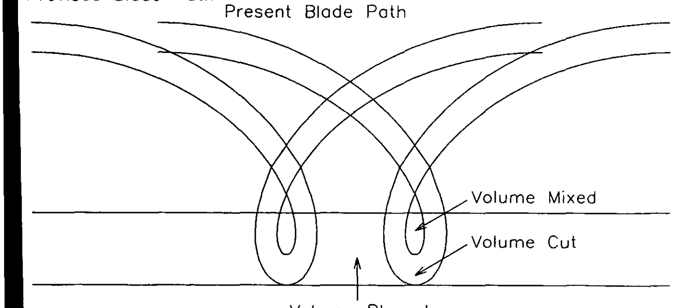

FIGURE 6 Volumes of snow that are mixed, cut, and plowed.

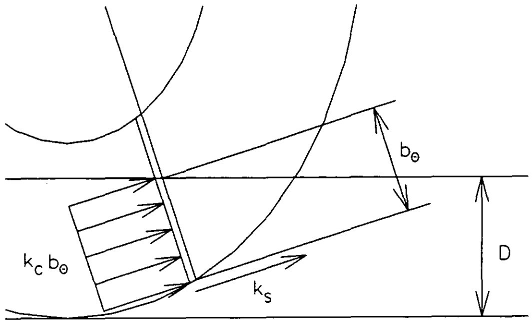

FIGURE 7 Resistance of snow to shear and compression.

where dl is the differential length of the path taken by the blade and z is the number of auger blades. The term dl is derived in terms of the velocity in the parallel and normal direction of travel, and, with a constant angular velocity, it is found to be

$$dl = \frac{\sqrt{U^2 + (R\omega)^2 + 2UR\omega \cos\theta}}{\omega}\, d\theta \tag{7}$$

The work differential is written by substituting Equations 4 and 7 into Equation 6. By considering the full width B, multiplying by the angular velocity, and integrating, the power required for cutting by the auger, P_{a1}, is found as

$$P_{a1} = zB \int_{\theta_{in}}^{\theta_{out}} (k_c b_\theta + nk_n) \times \sqrt{U^2 + (R\omega)^2 + 2\,UR\omega \cos\theta}\; d\theta \tag{8}$$

where θ_{in} and θ_{out} are the angles at which the blade enters and leaves the snow, respectively.

Auger Power Required for Snow Movement

In addition to the power needed to disaggregate the snow, the auger is required to accelerate the snow that is cut (P_{a2}) and move it into the impeller (P_{a3}). Additional power is required for snow that is rehandled in the mixing of the uncut snow (P_{a4}). Due to space limitations, the derivation of expressions for these terms is omitted from this paper; the interested reader is referred to work by Powers and Stevens (*9*), which follows, with some exceptions, the work of Shalman (*3*).

Last, the total power required by the auger is then $P_a = P_{a1} + P_{a2} + P_{a3} + P_{a4}$.

Impeller Power Requirements

Shalman showed that the required impeller power is composed of three components: (a) the power to transfer kinetic energy to the snow moving through the impeller (P_{i1}), (b) the power to overcome the friction of the snow against the impeller housing (P_{i2}), and (c) the power to raise the snow to the height of the discharge chute (P_{i3}). Again, because of space limitations, the derivations of the equations for these terms are omitted and the reader is referred to Powers and Stevens (*9*), which follows Shalman (*3*), with some modifications.

The total impeller power, P_i, required for discharging the snow is given by $P_i = P_{i1} + P_{i2} + P_{i3}$.

Plowing Power

For high-speed removal, part of the snow mass entering the auger is not cut by the auger blades (Figure 6) but is instead plowed by the back of the auger housing. The proposed model includes an approximation of the plowing power (P_p) based on the experimental work by Powers and Stevens (*9*).

Snow Properties

One purpose of this study is to characterize the performance of snow removal equipment with respect to snow properties. Therefore, three general relationships are introduced into the model so that continuity of the material properties is maintained; these relationships are compressive strength versus density (Equation 1), shear strength versus density (Equation 2), and the degree of compaction of the snow during the removal process. All of these relationships are considered as bulk properties and are assumed to be constant for the entire cutting arc; therefore, instantaneous changes are not considered.

The relationships between shear strength and density and between compressive strength and density are used to determine the coefficient of cutting resistance (Equation 5). Thus, given a particular density, the cutting resistance can be determined; however, it should be noted that the model can consider shear strength, compressive strength, and density as uncoupled if so desired.

Last, the amount of compaction (or increase in density) that the snow undergoes during processing by the auger is determined from the experimental observations of Croce (*2*). The relationship between degree of compaction and initial density was digitized and applied in the computer model to the analysis of the mass balance of the snow as it enters and exits the auger.

Computer Model

The computer application of the auger analysis determines the bounds of the integral for P_{a1} in Equation 8, by comparing the entering and exiting positions of two consecutive blade paths. Once the crossing patterns are known, a bisection algorithm is used to determine the angle of intersection. This two-step operation is used to calculate the applicable angles of intersection between the outside edges of the current and previous blade paths and the inside edge of the current blade path and the outside edge of the previous blade path (Figure 5). Numerical integration of Equation 8 is performed by using the trapezoidal method on the subsections of the cutting arc.

The model also evaluates P_{a2}, P_{a3}, and P_{a4}: the amount of auger power required to accelerate the snow, to move it to the impeller, and to mix it, respectively. The power required to accelerate the snow is applied only to the volume of snow directly struck by the blade; however, the power to move the snow into the impeller is applied to the entire volume of snow.

For the impeller, the computer model calculates the thickness of the snow layer (*9*) and compares it with the paddle length. The smaller of the two lengths is used to calculate the absorption capacity. If the mass flow rate exceeds the absorption capacity, the impeller is working to its full capacity and excess snow is plowed in front of the machine; at that point, the operator would have to reduce forward speed or increase the impeller speed. Finally, the three components of impeller power (P_{i1}, P_{i2}, and P_{i3}) are calculated from the amount of snow passing through the impeller.

APPLICATION OF MODEL AND RESULTS

The model is developed so that all significant constants can be changed for parametric evaluations. Thus, the user can evaluate the effect on system performance of changing: snow properties, number and size of auger blades and impeller paddles, gear ratio between impeller and auger, width of the auger or length of the impeller arms, and so forth. In the data presented later, the parameters of a commercially available machine designed to remove snow at a rate of 27 MN/hr (3,000 tons per hour) are used. This machine uses a four-ribbon (or blade) auger, with an outside radius of 0.56 m (22 in.) and an inside radius of 0.43 m (17 in.). Each blade of the auger extends half of the spiral pitch along the auger's axis (Figure 1). The impeller has an overall diameter of 1.14 m (45 in.) and five 0.3-m (12-in.) paddles. The depth along the axis of rotation of the impeller is 0.46 m (18 in.), and the angle of discharge is 60 degrees.

In the following application of the model, three components of the machine's performance were evaluated: the power required by the auger to cut the snow (P_{a1}), the total power required ($P_a + P_i + P_p$), and the percentage of total power required by the auger for cutting [$P_{a1}/(P_a + P_i + P_p)$].

As reported (*9*), the model has been applied to a range of auger rotational speeds, forward velocities, snow depths, and snow strengths to investigate the effect that operational parameters and snow properties have on the machine operation. Four auger rotational speeds were chosen, from 75 rpm, which is typically used for deep, dense snow, to 150 rpm, which can be used for high-speed removal of "virgin" snow. The depth was chosen in increments of 10.2 cm (4 in.) up to 40.6 cm (16 in.). Finally, the shear strengths included virgin snow, [1.20 kPa (25 lb/ft^2)] and three shear strengths corresponding to processed snow: 4.79, 9.58, and 14.36 kPa (100, 200, and 300 lb/ft^2, respectively). The corresponding densities were back-calculated from Equation 2, and the compressive strength was determined from Equation 1. Again, the material properties did not incorporate rate effects.

In the following, only a few cases are presented; the full set of results is described elsewhere (*9*).

Cutting Power of Auger

The cutting power required by the auger to disaggregate the snow is plotted versus the forward speed in Figures 8 and 9;

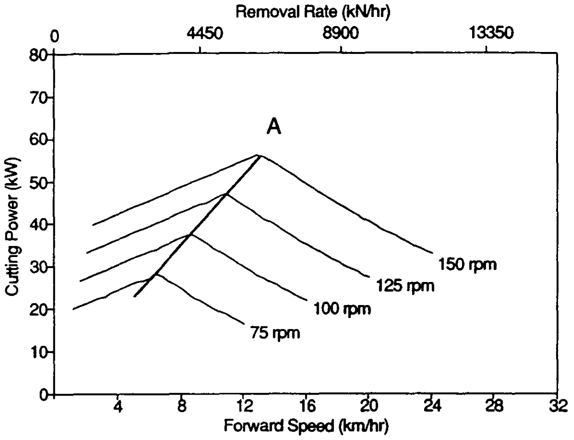

FIGURE 8 Cutting power versus forward speed: snow depth = 10.2 cm (4 in.); shear strength = 4.79 kPa (100 lb/ft^2); density = 204.4 kg/m^3.

in both figures, the shear strength (and corresponding density and compressive strength) are the same. Two depths of snow are investigated: 10.2 cm (4 in.) in Figure 8 and 30.5 cm (12 in.) in Figure 9.

For a depth of 10.2 cm (Figure 8), the cutting power of the auger is an increasing linear function of forward speed as the cutting arc is increased. The cutting power peaks at Line A when the maximum overall cutting arc is achieved. As the ratio ω^*/U^* continues to decrease past Line A, the relationship between cutting power and forward speed decreases linearly as the overall length of the cutting arc is reduced and less snow is disaggregated by the auger.

For a depth of 30.5 cm (Figure 9), several points of inflection in the relationship between cutting power and forward speed occur because of changes in the cutting paths of the auger blades as the forward speed increases. For low-speed plowing, the cutting power is an increasing linear function of forward speed as the effective cutting arc length is increased. The curve increases sharply at Line A as the inside edge of the auger blade begins to cut the snow. As the inside cutting arc of the auger blade approaches its maximum at Line B, the cutting force increases sharply as the inside cutting arc length increases significantly with the change in forward speed. As the inside cutting arc approaches its maximum length, the cutting force increases sharply, from Point B1 to Point B2 on the 150-rpm curve. The peak power requirement occurs when the maximum outside cutting arc is attained at Line B. For increased forward speeds (lower ω^*/U^* ratio), the relationship becomes a decreasing linear function as the length of the cutting arc is reduced. Finally, at Line C, the relationship decreases quickly because the inside cutting arc is reduced when it overlaps its own path.

In addition, a study of the effects of snow properties was also performed, as reported elsewhere (*9*). For the same depth of snow and auger speed, it was found that, relative to virgin snow with a shear strength of 1.2 kPa (25 lb/ft^2), the cutting power increased 255, 705, and 1,175 percent for shear strengths of 4.29, 9.58, and 14.36 kPa, respectively. This range corresponds to density increases of 67, 116, and 151 percent, respectively.

Total Power

The total power [the sum of the auger, impeller, and plowing power ($P_a + P_i + P_p$)] is plotted versus forward speed in Figures 10 and 11 for shear strengths of 1.20 kPa (25 lb/ft^2) and 9.58 kPa (200 lb/ft^2); the depth is 30.5 cm (12 in.).

For the virgin snow (Figure 10), the total power increases at a constant rate with respect to forward speed. Once the point of maximum cutting power is attained (Line A), the power continues to increase as the amount of snow that is plowed increases sharply.

For processed snow with a shear strength of 9.58 kPa (200 lb/ft^2) (Figure 11), the total power required for removal is dominated by the cutting power up to the point of maximum power required, Line A. Once the maximum total power is achieved, the total power remains relatively constant and then decreases. At this point, the rotary snowplow is pushing or plowing the snow instead of processing it through the impeller; the operator would have to reduce the speed.

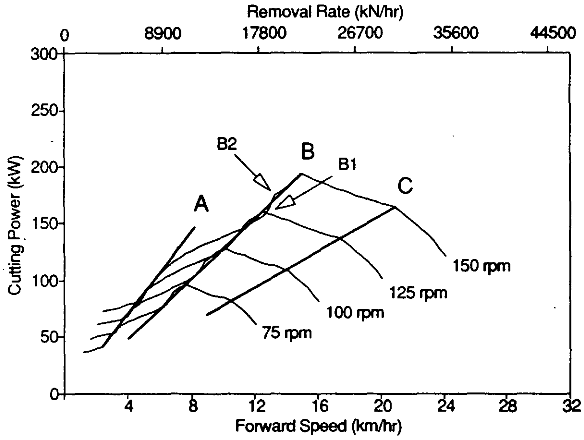

FIGURE 9 Cutting power versus forward speed: snow depth = 30.5 cm (12 in.); shear strength = 4.79 kPa (100 lb/ft^2); density = 204.4 kg/m^3.

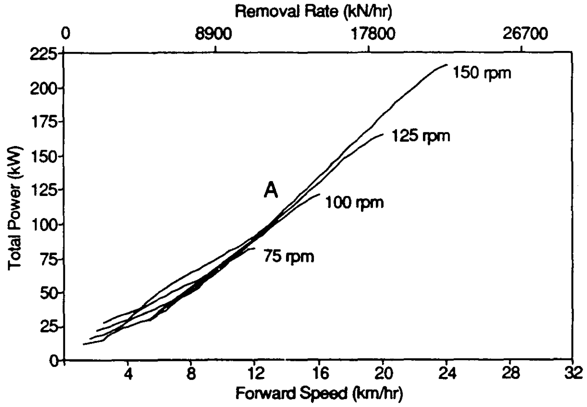

FIGURE 10 Total power versus forward speed: shear strength = 1.20 kPa (25 lb/ft^2); depth = 30.5 cm (12 in.); density = 122.2 kg/m^3.

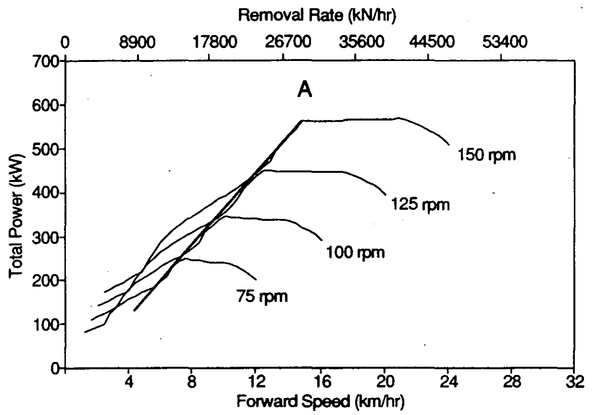

FIGURE 11 Total power versus forward speed: shear strength = 9.58 kPa (200 lb/ft^2); depth = 30.5 cm (12 in.); density = 264.5 kg/m^3.

Percentage of Total Power Used by Auger

Finally, the ratio of cutting power to total power is plotted versus forward speed in Figure 12 for 30.5 cm (12 in.) of snow with a shear strength of 4.79 kPa (100 lb/ft^2).

The percentage of total power required to disaggregate the snow is higher at lower forward speeds since most of the snow is struck by the auger blade and less power is required for mixing and plowing uncut snow. Figure 12 shows that for the high-strength snow, more than half of the total power is required to disaggregate the snow, regardless of the forward speed.

CONCLUSIONS

In this study, an analytical model was developed to study the operation of two-stage rotary snowplows and the effect of the snow properties on the system performance. The model was developed by considering the power requirements in each stage of the rotary snowplow. The model incorporates the dynamics and kinematics of the auger and impeller, the motion of the snow within the system, and the effects of the snow properties on the system. The effect of higher-speed plowing was considered in the derivation.

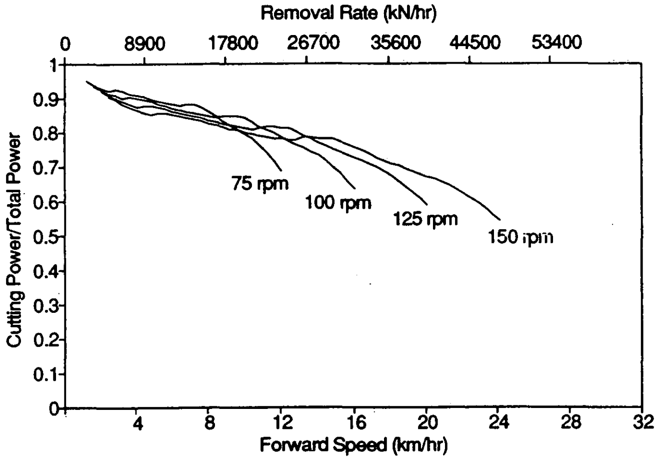

FIGURE 12 Proportion of cutting power to total power: shear strength = 4.79 kPa (100 lb/ft^2); depth = 30.5 cm (12 in.); density = 204.4 kg/m^3.

The results of the cutting power analysis show that the power required to disaggregate snow with the same material properties is a function of the ratio of forward speed to the rotational speed of the auger, indicating that the length of the cutting arc (both inside and outside) significantly affects the required cutting power. The investigation of the effects of material properties showed that an increase in shear strength significantly increased the cutting power requirement. The graphs indicate that, for processed snow and low-speed plowing, the total power required for removal is dominated by the cutting power. And the cutting power, as a percentage of the total power, was highest at lower speeds, since little power is required for mixing and plowing and the impeller is not working to its full capacity. Finally, the percentage of the total power was found to be slightly affected by the rotational speed of the auger.

The casting capabilities of the rotary snowplow were not included in the model because the focus of the model was on the power required for removal. The analysis of casting performance should be considered in future development of the model.

Finally, analytical theories should be validated with full-scale experimental results by instrumenting the engines and drive shafts of a commercial vehicle. Although the present model may not be quantitatively accurate, it appears to be qualitatively correct and provides a means of assessing the influence of changing operational and material parameters.

ACKNOWLEDGMENT

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Field Testing of New Cutting Edges for Ice Removal from Pavements

WILFRID A. NIXON, TODD R. FRISBIE, AND CHENG-HUA CHUNG

One of the more severe winter hazards is ice or compacted snow on roadways. Three methods are typically used to combat ice—salting, sanding and scraping—but relatively little effort has been applied to improve methods of scraping ice from roads. A new test facility is described, including a truck with an underbody blade that has been instrumented such that the forces to scrape ice from a pavement can be measured. A test site has been used that is not accessible to the public, and ice covers have been sprayed onto the pavement and subsequently scraped from it while the scraping loads have been recorded. Three cutting edges have been tested for their ice scraping efficiency. Two of the blades are standard (one with a carbide insert, the other without), and the third blade was designed under a SHRP project and has several unusual features. Results from the tests indicate that the SHRP blade removed ice more effectively than the other two blades under equivalent conditions and did so with greater efficiency and more control. Given these results, further field testing of the SHRP prototype blade is warranted.

Each winter, more than half of the roadways in the United States are subject to icing, either through compaction, melting and refreezing of snow, or directly from freezing rain or sleet. The presence of ice on roads is a severe hazard. Typically, this hazard is dealt with by salting, sanding, or scraping, or some combination of these. This study is solely concerned with improving the mechanical methods of ice removal. Specifically, the aim of the work in this project has been (a) to measure forces involved in scraping ice from roads, using a truck with an underbody plow, and (b) to use this mobile test bed to compare the behavior of three cutting edges. One of the cutting edges (referred to hereafter as the prototype) was developed under the Strategic Highway Research Program's (SHRP's) Project H-204A.

In developing the design for the prototype blade, two concerns were paramount. First, the blade had to make the best use of the results found in the laboratory study (*1,2*). In particular, some way of maintaining a nonzero clearance angle was required, since this appeared to be the key parameter from the laboratory study. The second concern was ensuring that the cutting edge was sufficiently robust that it could withstand the shock loading common to ice scraping (e.g., when a pavement joint is encountered). It should be noted that other concerns—such as the wear characteristics and the cost of the blade, which would be very important should such a cutting edge go into production—were not given great weight in the design process. These issues fell beyond the scope of the current study.

The prototype cutting edge is different from existing cutting edges in several ways. In particular, the carbide insert is mounted flush with the front face, so that carbide is exposed to the ice directly (Figure 1). This means that the carbide used is somewhat softer than typical carbide inserts for cutting edges, so as to obtain better shock resistance. Also apparent from Figure 1 is the nonzero clearance angle, which should remain in place during the life of the blade. No estimate of blade lifetime is available yet, for reasons indicated earlier. Four identical cutting edges of this type, each 128 cm (48 in.) long, were obtained from Kennametal, Inc., in Latrobe, Pennsylvania.

The purpose of this project was to develop a test system whereby a truck with an underbody blade could be instrumented to measure the forces required to scrape ice from a pavement, and to do so in a location that was not accessible to the public so that issues relating to safety of the driving public were not a concern. A secondary purpose was to compare the performance of three cutting edges (two standard and one specially developed) when removing ice from the pavement.

EXPERIMENTAL METHOD

Tests were conducted using a 22.7-Mg (25-ton) truck with an underbody plow blade, supplied by the Iowa Department of Transportation (IDoT) for use in its Project HR-334. The truck is shown in Figure 2. The underbody blade can be adjusted to a variety of orientations. The blade angle is the angle that the cutting edge has with the pavement. It might also be called the angle of curl of the blade. When this angle is zero, the front face of the cutting edge is perpendicular to the road surface. The blade angle is controlled by a cylinder on each end of the blade. These two cylinders were connected in parallel so that the blade angle was uniform with the pavement across the full length of the blade.

For this series of tests, three cutting edges were tested. The first of these was the standard steel blade that came with the truck. This blade was 1.9 × 12.7 × 244 cm (0.75 × 5 × 96 in.) and had no carbide inserts. The second cutting edge was a commercially available blade with a carbide insert. The third cutting edge was the prototype edge. The three blades are shown in Figure 3.

The loads that the blade experiences during scraping were recorded by the use of pressure transducers connected by a T-section to the hydraulic supply lines of the cylinders. The pressure gauges used were International Pressure Products

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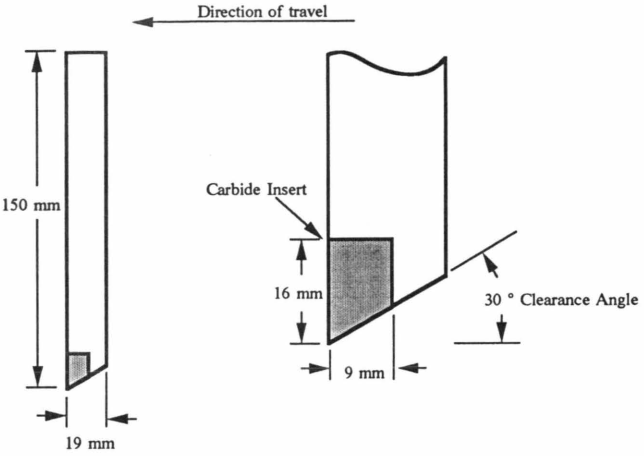

FIGURE 1 Schematic of prototype blade.

ST-420 0- to 20.7-MPa (0- to 3,000-psi) gauges. A transducer was located in each of the vertical motion cylinders to measure the down pressures on each side of the blade. Another transducer was located in the supply hose for the cylinders that rotate the blade angle. This gauge recorded the loads that the blade experienced in the horizontal direction.

The angle that the cutting edge made with the pavement was measured by means of an inclinometer. A Schaevitz Angle Star Protractor System was used. The inclinometer was on the left side of the blade.

Data from the sensors were collected on a portable PC: a Kontron IP Lite, chosen because it is shock-rated for operation up to 5 *g*. The shock rating was needed to guarantee normal data acquisition because the truck bounced greatly during testing. An analog-to-digital circuit board in the PC allowed the software to collect and store the data. A Metrabyte DAS-8 analog-to-digital board was used along with the CODAS data acquisition software by Dataq Instruments. Data were written to the hard drive of the PC during testing and were examined and analyzed after testing at the ice laboratory at the Iowa Institute of Hydraulic Research (IIHR). Power for the computer and sensors was obtained from the truck batteries through a power inverter and filter system built at IIHR.

A 2800-L (750-gal) tank of water in the truck was used to create the ice necessary for the testing. A 2.2-kW (3-hp) pump at the back of the tank delivered the water at 413 kPa (60 psi) to a spray nozzle on a boom offset from the truck, as seen in Figure 4. The spray nozzle allowed the water to be sprayed uniformly over the pavement with a spread 6 m (20 ft) wide. Further details on the method of spraying are reported elsewhere (*3*). Testing took place at the spillway apron of the Coralville Reservoir when weather conditions were favorable. The area covered by spraying was approximately 6 × 55 m (20 × 120 ft). The total weight of the truck during scraping was 20 000 kg (44,000 lb). Air temperature, concrete temperature, ice thickness, and ice condition were recorded before testing. The angle of the blade was set, and as the truck approached the ice sheet, the down pressure was applied to the blade. The tests were performed at about 6.7 m/sec (15 mph) over the entire length of the ice sheet.

FIGURE 2 Truck used to conduct tests.

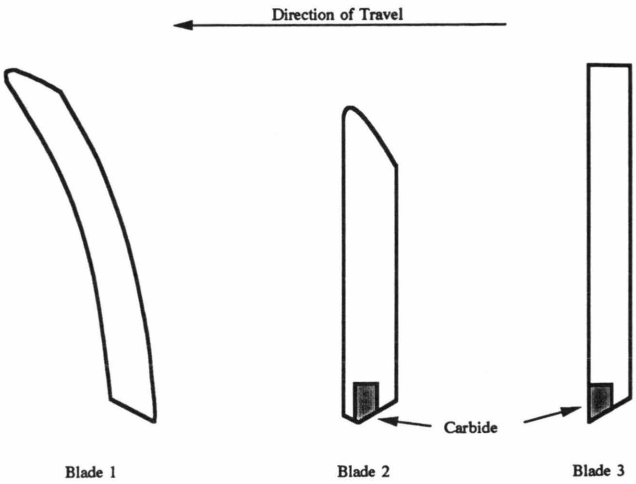

FIGURE 3 Geometry of blades used in tests.

The testing parameters to be studied were the cutting edge type, the down pressure, and the angle of the blade. For each of the three cutting edges previously described, the down pressure was tested at a low value and a high value: 3450 kPa (500 psi) and 8370 kPa (1,200 psi), respectively. These values were set on the blade by adding enough pressure to the down pressure to get within these ranges as seen on the computer screen in the cab. The angle of the blade was varied from a set of 0, 15, or 30 degrees. These values were set by using

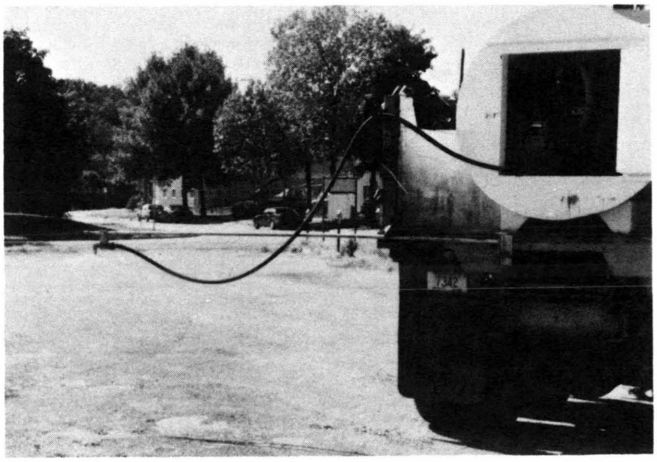

FIGURE 4 Spraying equipment used to make ice sheet.

the display of the inclinometer in the cab and adjusting for the desired value. Because the angle of the cutting edge changed when the truck moved forward, this angle was set low. As the truck pulled ahead with the desired down pressure applied, the angle adjusted to the correct value. Only one test with high down pressure was performed on Blade 3, because the blade cut the ice so effectively and so deeply in this configuration that the truck could not provide enough horizontal force to continue cutting.

EXPERIMENTAL RESULTS

Tests performed with the standard (noncarbide) blade showed that the ice was completely removed from the pavement in only a few places. Much of the ice was removed only partially or not at all. Accordingly, no single value for the thickness of ice removed in each test has been reported here. From observations it appeared that more ice was removed with a high down pressure and a 0-degree blade angle for this blade. At the high down pressure it was more difficult to maintain a constant velocity because of a loss of traction. Typical data output from the gauges for a test is shown in Figure 5. Table 1 provides a listing of the vertical and horizontal loads for all tests, indicating also whether the down pressure was low or high and giving the angle of the blade.

Because the second and third (prototype) cutting edges were not of the same geometry as the first, the 0-degree case could not be achieved and only the 15- and 30-degree cases could be studied for the two carbide blades. As with the standard blade, the second and third blades performed best at the smallest blade angle and highest down pressure. The second blade appeared to remove more ice than the first blade and maintained its shape much better because of the carbide insert.

The final blade tested was the prototype blade. This cutting edge provided superior performance for ice removal. The blade was able to remove half of the ice thickness, typically

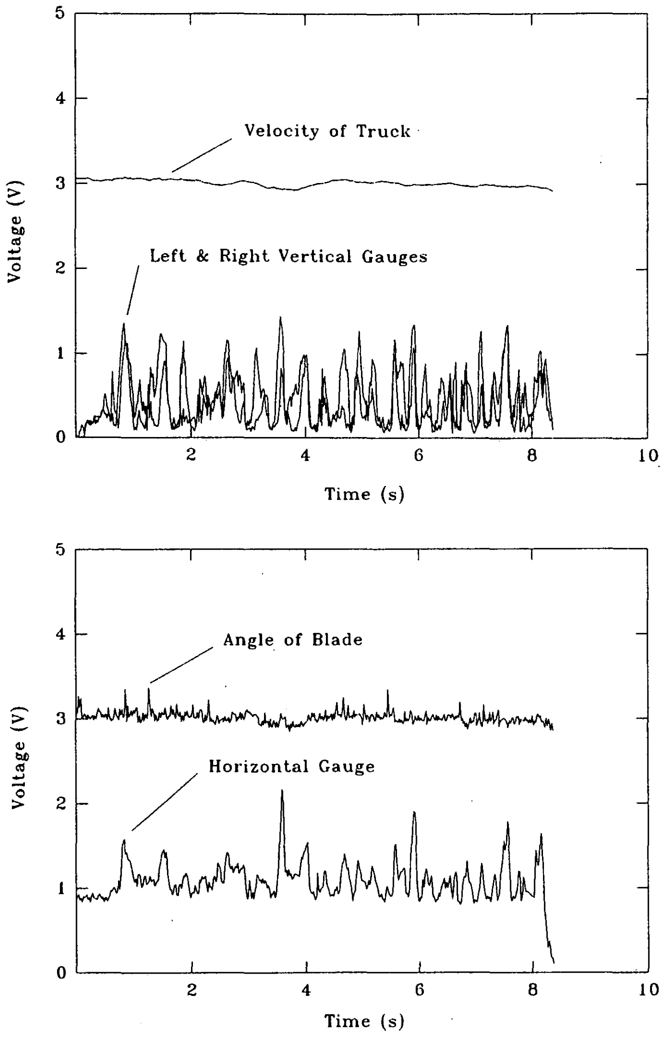

FIGURE 5 Data output from gauges for Blade 2 at 15 degrees and low down pressure.

TABLE 1 Forces Measured for Test Series

		Horizontal Force (kN)		Vertical Force (kN)		Ratio vert/horz	
Blade	load/Angle	Mean	Peak	Mean	Peak	Mean	Min
1	Low 0°	83.9	126	68.9	119	1.22	0.473
1	Low 15°	76.3	106	105	177	1.42	0.532
1	Low 15°	62.9	112	87.2	137	1.49	0.468
1	Low 30°	67.7	104	67.8	85.7	1.06	0.258
1	High 0°	90.5	250	127	174	1.70	0.635
1	High 15°	69.9	121	112	140	1.71	0.586
1	High 15°	78.9	182	112	151	1.46	0.626
1	High 30°	92.6	179	125	147	1.63	0.722
1	High 30°	39.9	76.6	83.2	101	2.32	1.21
2	Low 15°	103	174	76.6	131	0.793	0.138
2	Low 15°	33.9	93.6	30.5	84.6	0.952	0.509
2	Low 15°	49.9	96.5	30.0	73.7	0.581	0.181
2	Low 30°	34.4	76.2	49.6	94.2	1.46	0.789
2	Low 30°	20.2	61.7	37.1	70.6	2.19	0.919
2	Low 30°	46.0	96.0	76.0	104	1.73	0.754
2	High 15°	77.7	204	101	149	1.33	0.686
2	High 30°	76.6	127	101	127	1.44	0.883
2	High 30°	54.6	95.2	91.0	119	1.78	1.04
3	Low 15°	87.0	235	63.2	141	0.701	0.133
3	Low 15°	97.3	235	75.1	139	0.789	0.160
3	Low 15°	78.9	169	50.9	133	0.607	0.192
3	Low 30°	46.7	123	36.0	66.5	0.838	0.341
3	Low 30°	56.3	137	41.3	82.2	0.799	0.391
3	Low 30°	76.8	159	58.7	128	0.761	0.243
3	High 15°	173	263	134	158	0.781	0.489

0.6 to 1.2 cm (0.25 to 0.5 in.), across the entire 2.4 m (8 ft) length of the blade at low down pressure. In the one high-down-pressure test performed with this blade, the cutting edge removed nearly all the ice except for a small residual layer across the length of the blade. This performance was significantly better than the other two blades.

DISCUSSION OF RESULTS

In reviewing data from the tests, it became apparent that the loads alone did not provide the full story. Indeed, it appeared that the higher the horizontal load was during a test, the more successful the scrape was, insofar as more ice was being scraped. The horizontal load seemed to correlate very well with the depth of ice scraped, though it should be noted that no direct measurements have been made of scraping force as a function of depth of ice scraped, either in the laboratory or in the field. In addition to the horizontal force indicating the depth of cut, the vertical force also gave a good indication of the difficulty of the cut. The higher the vertical force, the harder it was to control the vehicle, and the more the opportunity for damage to the pavement. Thus, two factors were important in evaluating the tests: the depth of cut, as indicated by the horizontal load, and the ratio of the vertical to horizontal load. If the latter was low, the truck was easily controlled. If the former was high, much ice was scraped.

Figures 6 through 8 show the horizontal and vertical loads for the three blades in the low-pressure configuration at one scraping angle (15 degrees). From these figures it is apparent that the prototype blade gave the greatest depth of cut and had the best factor of controllability (ratio of vertical to hor-

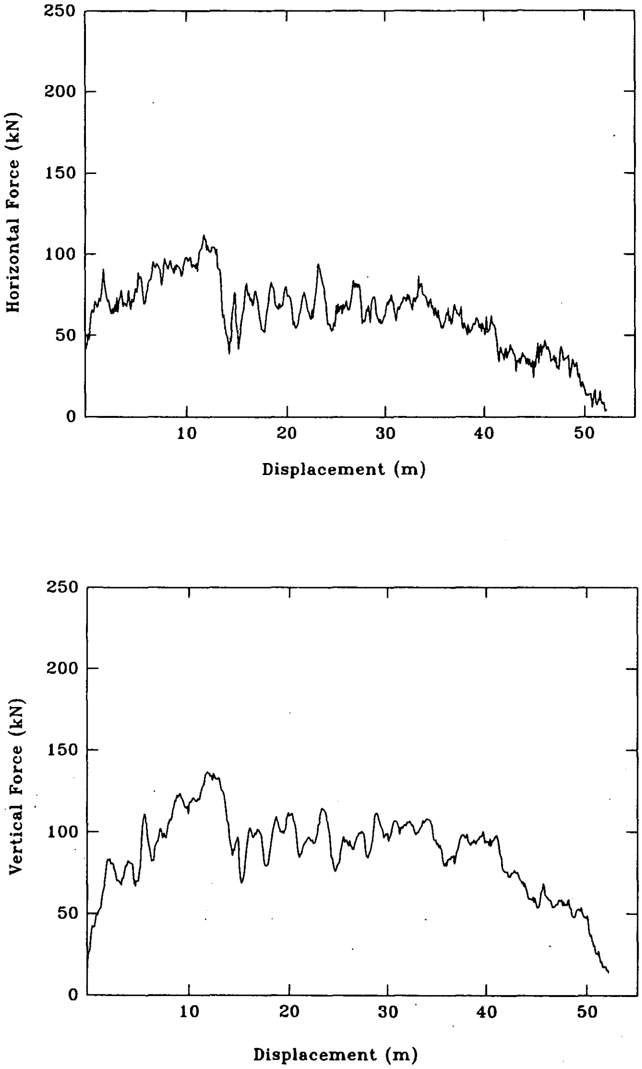

FIGURE 6 Forces on Blade 1 at 15 degrees and low down pressure: *top*, horizontal (maximum = 112 kN, average = 62.9 kN); *bottom*, vertical (maximum = 137 kN, average = 87.2 kN).

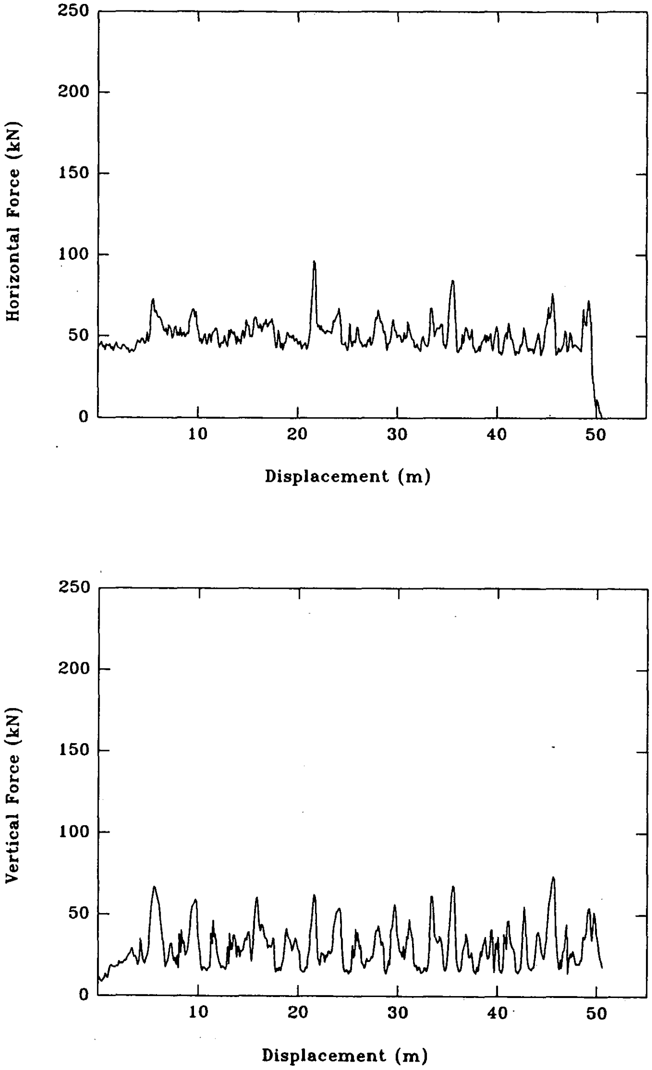

FIGURE 7 Forces on Blade 2 at 15 degrees and low down pressure: *top*, horizontal (maximum = 96.5 kN, average = 49.9 kN); *bottom*, vertical (maximum = 73.7 kN, average = 30.0 kN).

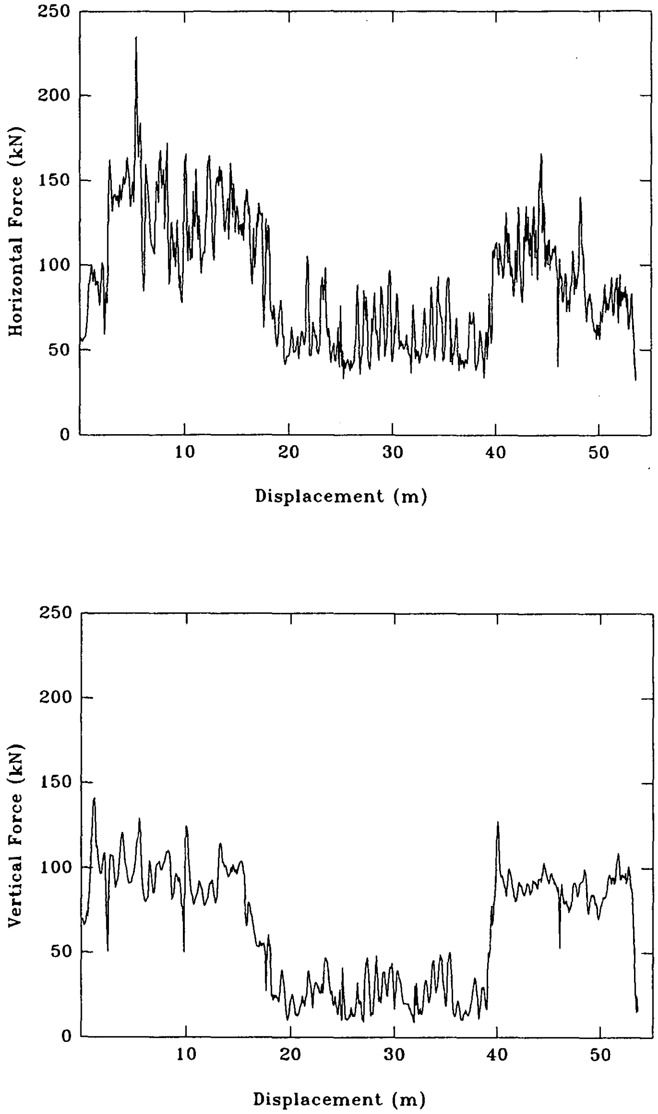

FIGURE 8 **Forces on Blade 3 at 15 degrees and low down pressure: *top*, horizontal (maximum = 235 kN, average = 87.0 kN); *bottom*, vertical (maximum = 141 kN, average = 63.2 kN).**

izontal forces) of the three blades. The controllability is seen clearly in Figure 9, which shows the ratio of vertical to horizontal forces for the three blades for all tests. It is apparent that the prototype blade gives the best performance.

CONCLUSIONS

A mobile test system mounted on a truck with an underbody blade has been developed and shown to be capable of measuring the force required to scrape ice from pavement. A series of tests have been performed to evaluate the performance of three cutting edges. From the results of these tests, and from the visual observations made in the preceding, it appears clear that the prototype cutting edge provides significantly better ice scraping than either of the other two

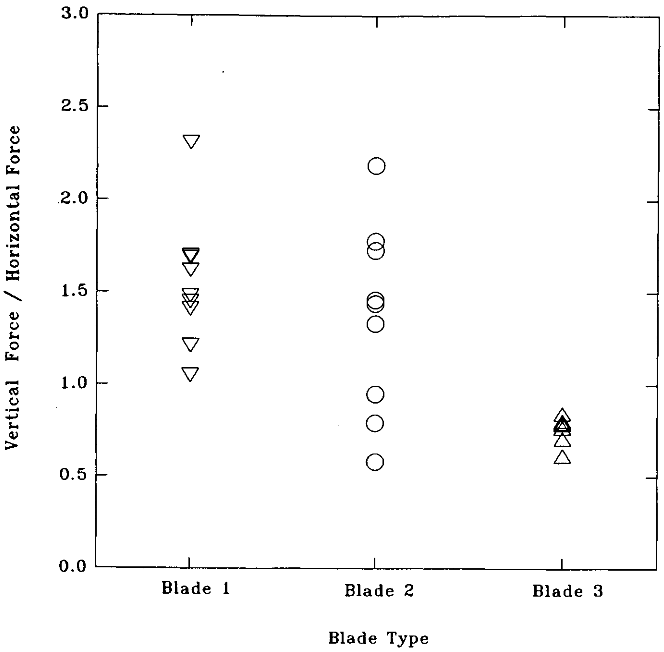

FIGURE 9 **Ratios of vertical to horizontal forces for different blades.**

blades. However, although the prototype cutting edge has performed very well in these controlled field situations, it has not yet been tested in the field, where issues of durability and ruggedness will be important. Nonetheless, results to date indicate that the prototype blade may be a major improvement over existing cutting edges.

It should be noted that the prototype cutting edge was not fabricated with wear resistance in mind. Nonetheless, it retained its shape throughout the tests reported here. In later testing, reported elsewhere (*3*), the blade experienced significant wear when scraping cold ice at −15°C (5°F).

ACKNOWLEDGMENTS

The research described herein was supported by IDoT. Permission was given to use the test site at the Coralville Reservoir by the U.S. Army Corps of Engineers. The prototype blade was developed under a project of SHRP, which is a unit of the National Research Council that was authorized by Section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987. The assistance of these organizations, without whose support the tests could not have been conducted, is gratefully acknowledged.

The experiments described within this document were performed at IIHR, a unit of the College of Engineering at the University of Iowa. The support of the director of IIHR, John Kennedy, and of the acting director (from June 1991), Robert Ettema, is gratefully acknowledged. The shop staff at IIHR, led by Jim Goss, made these experiments possible with their aid and insight. Eric (Cheng-Hua) Chung and Todd Frisbie performed the experiments with the assistance of Larry Weber and Michael Pokorny.

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PART 6

Pavement Surface Condition

Frensor: A New Smart Pavement Sensor

David I. Katz

A new solid-state pavement sensor, called Frensor, designed to measure the freezing point of moisture on bridge decks, roads, and runways is described. To optimize the use of deicing chemicals, the most important question is, Are there enough chemicals on the pavement to prevent ice formation? In other words, Is the freezing-point temperature of the water on the pavement surface well below the pavement temperature to be expected, or will it freeze unless more chemicals are applied? Using the Peltier principle and controlled by a microprocessor, the Frensor actively changes the temperature of the moisture deposited on its surface and provides an output of the pavement temperature and conditions. The conditions reported include dry, wet, wet but not frozen, dew, frost, and amount of chemicals on the surface. The freezing point is measured to an accuracy of ±0.5°C. The discontinuity plateau that represents the actual freezing point is linear with the amount of salt or chemical present on the pavement, over a calibrated range of −27 to 0°C. Thus, the Frensor provides a direct measurement of the freezing-point temperature of the material on the pavement, with which chemical application decisions can be made.

Significant effort has been spent trying to optimize the spreading of deicing chemicals on the road. Dedicated weather information systems exist today for the roads in several countries. One of the most important functions of these systems is to supply information to the people who decide when and where to spread deicing chemicals.

As is well known, the timing and dosage of the chemical is critical. It may be straightforward to make the decisions when there is no chemical left on the roads from earlier actions, but it is a much more difficult situation when chemicals have been spread earlier and precipitation and heavy traffic continue. The question is then, Is there enough chemical left on the road or not? or more precisely, Is the freezing point of the moisture on the surface well below the future temperature forecast for the road, which will then result in the liquid's freezing unless more chemicals are spread?

Several sensors on the market are designed to provide information about the road's surface; few, if any, actually measure the freezing point of the liquid on the surface. The Frensor described in this paper does measure the freezing point.

THEORY

A crystalline structure develops in a substance when it freezes. At the same time, the latent heat of freezing is released. Figure 1 shows a temperature-versus-time plot for water that is cooled below the freezing point. The temperature is essentially constant during the period of ice formation, after which it continues to fall. The inflection point in the curve at the freezing point of the water is caused by the release of latent heat of the water. The plot also indicates that the water is supercooled before freezing takes place. This happens if the water is quiescent and if few freezing nuclei are present.

A solution of salt in water has a freezing point lower than pure water. The freezing point is lowered by approximately 0.7°C per percent of sodium chloride in the solution. Figure 2 shows a temperature plot for a 5 percent salt solution; the freezing point is lowered to approximately −3.5°C. The existence and location of the inflection point in the temperature-versus-time plot is used to determine the status of the road surface.

SENSOR DESIGN

The design and installation of the Frensor is shown in Figure 3. There is a shallow cup in the upper side of the Frensor. Inside the Frensor is a Peltier element that is used to cyclically cool or warm the material in the cup, and the temperature of the moisture in the cup is measured as the Peltier element cycles. The temperature-versus-time data are measured by this sensor, and a microprocessor connected to the Frensor is programmed to use the measurements to determine the inflection point in the time-versus-temperature plot.

The Frensor is designed to ensure reliable and safe operation. The tires of passing cars and trucks press into the cup at the top of the Frensor, flushing the liquid material periodically. This forces new liquid into the cup so that the Frensor measures the solution on the road's surface as it changes. The cup is mounted in a tube that is pressed downward as the road and Frensor surface are worn down. The surface of the Frensor can be worn down more than 20 mm without performance being affected. Test results indicate that the lifetime of the Frensor will be more than 4 years, even on roads on which studded tires are used for 6 months of the year.

The power dissipated by the Frensor is less than 100 mW, and the Frensor is cast in an epoxy compound with thermodynamic properties matched to normal pavement. This means that the effect of the Frensor on the measurement of the freezing point of the material on the road's surface is negligible.

MEASURING ACCURACY

Figure 4 shows the arrangement of a Frensor and a reference platinum temperature sensor for a test of the Frensor's accuracy. The platinum sensor is glued to the bottom of the measuring cup. The Frensor is then activated so that the bottom of the cup is cooled, and the temperature of the cup

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Climatronics Corporation, 2865 South Eagle Road, Suite 369, Newtown, Pa. 18940.

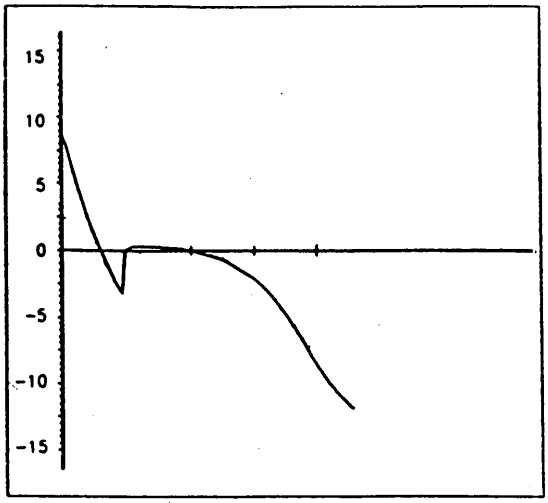

FIGURE 1 **Time-versus-temperature plot for water; temperature is in degrees Celsius, and time marks are 5 sec apart.**

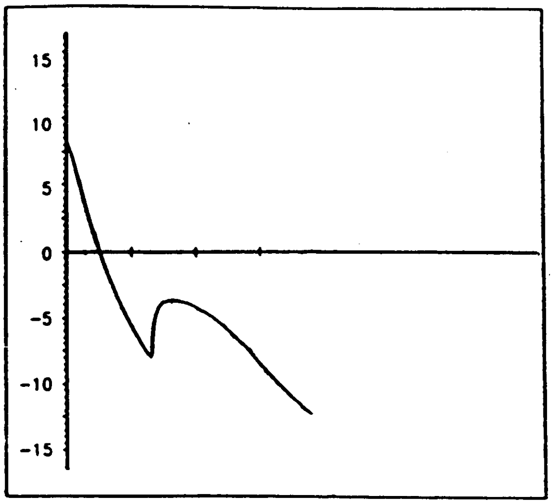

FIGURE 2 **Time-versus-temperature plot for 5 percent salt solution; temperature is in degrees Celsius, and time marks are 5 sec apart.**

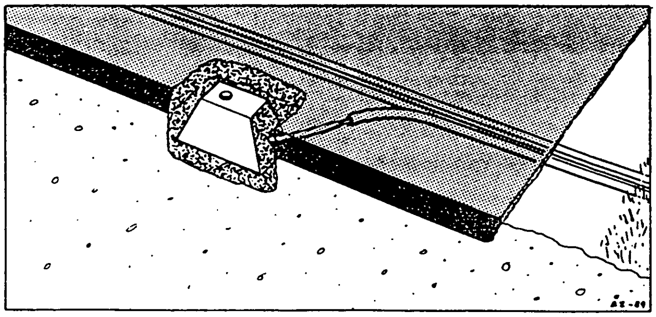

FIGURE 3 **Design and installation of Frensor.**

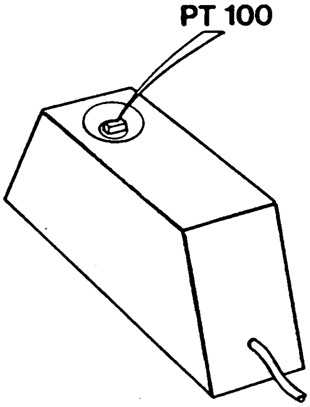

FIGURE 4 **Arrangement of Frensor and reference PT 100 temperature probe for test of Frensor accuracy.**

bottom is measured with both the Frensor and the platinum sensor.

Figure 5 shows the plot of the two temperatures versus time. The two temperatures drop from 12 to −11°C, and the two curves are very close to each other. To highlight the difference in the measurements, the Frensor data were subtracted from the reference data, multiplied by 10, and plotted on the graph. This is the curve that runs mostly above the 0°C line. The figure indicates that the Frensor reports temperatures that are slightly lower than the actual freezing-point temperature. The errors are less than 0.5°C, and since the Frensor underreports the actual liquid freezing point, decisions to add deicing chemicals to the road surface will be fail-safe—that is, made slightly more often than they would be otherwise and ensure the public safety.

SENSOR OUTPUT

The Frensor is connected to a microprocessor controller board when placed into operation. The microprocessor controls the

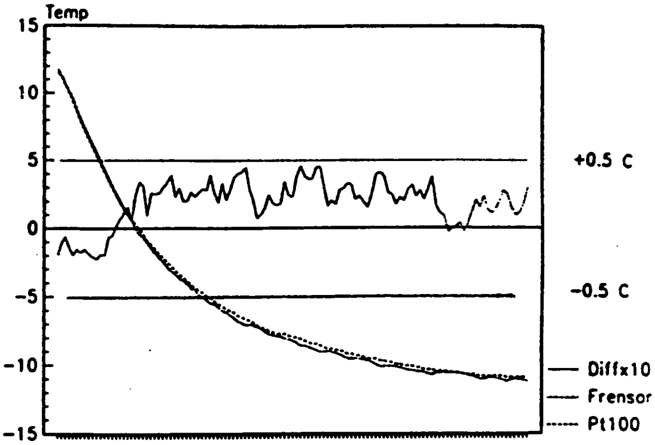

FIGURE 5 **Time-versus-temperature plot for Frensor accuracy test.**

measuring cycles and processes the signals. During each measurement cycle, the Frensor temperature is first measured and then the Peltier element is cycled seven times. The time required to complete a measurement cycle ranges from 2 min, when the material on the pavement freezes all seven times, to 5 min, for cold, dry pavement.

When the surface is wet, a freezing point is calculated. If there is very little moisture on the road surface or if it is frozen, then the microprocessor may not be able to calculate a correct freezing point. The output is then "moisture" or "ice." Outputs from the controller are both analog current levels and digital as RS-232C.

One notes that when the pavement is covered with material that freezes rapidly and the conditions are most dangerous, the Frensor completes a freeze-thaw cycle in 17 sec, minimizing the chance for errors to occur due to changes during the measurement cycle. Also, as part of the internal programming of the microprocessor, the road condition reported by the Frensor is based on all seven cycles and the reports from the Frensor.

Figure 6 shows data from a 3½-day period in February 1990. The installation consisted of a Frensor, a precipitation detector, a surface temperature sensor, and the microprocessor controller board. The Frensor was located near the tire track on a road with heavy traffic. Highway maintenance personnel recorded observations of the road surface and the application of salt during the period.

The precipitation detector showed precipitation falling on Wednesday and Thursday. The solid curve shows that the surface temperature started near 0°C on Wednesday, dropped to −6°C on Friday morning and then to −9°C on Saturday morning, after which it rose to 3°C.

The Frensor signal was recorded every 30 min. The freezing point of the surface material was reported as 0°C for most of Wednesday and Thursday and −2°C for a short time on Wednesday. It drops to −6°C on Thursday evening and then reports a moist surface through much of the night. During the day on Friday, the Frensor reported freezing points, a moist surface, and ice on the surface. From late in the day on Friday into Saturday, the Frensor reported a dry surface.

The observation logs show that salt was spread on the road at 6 p.m. Wednesday, but freezing conditions still occurred. The salt was diluted by the precipitation. Salt was again spread on Thursday evening. This coincides with the drop in freezing point shown by the Frensor to −6°C. The road surface was fairly dry during this period so that the amount of water in the Frensor cup was so low that it could only indicate "moist."

Snow on the side of the road thawed around noon on Friday and came out onto the road. The Frensor indicated a freezing point of about 0°C. As the road surface dripped during the afternoon and evening on Friday, the Frensor indicated lower freezing points due to the higher salt concentration. A few indications of "moist" and "ice" occurred in cases when the Frensor could not accurately measure the freezing point. The observation log showed that the road surface was dry from Saturday morning to the end of the study period; the Frensor also indicates this.

The Frensor data are used by road maintenance personnel to determine the action needed to keep the road safe. When the Frensor reports that the material on the pavement is freezing at temperatures above the pavement temperature, the road must be deiced. When the material is freezing below the road surface temperature, deicing can be halted. The decision of what action to be taken when there are reports of "moist" and "ice"—as well when to recommend deicing when precipitation continues—should be made by considering the Frensor reports of the road conditions, the weather forecast, and a knowledge of the road and how it has been affected by previous storms.

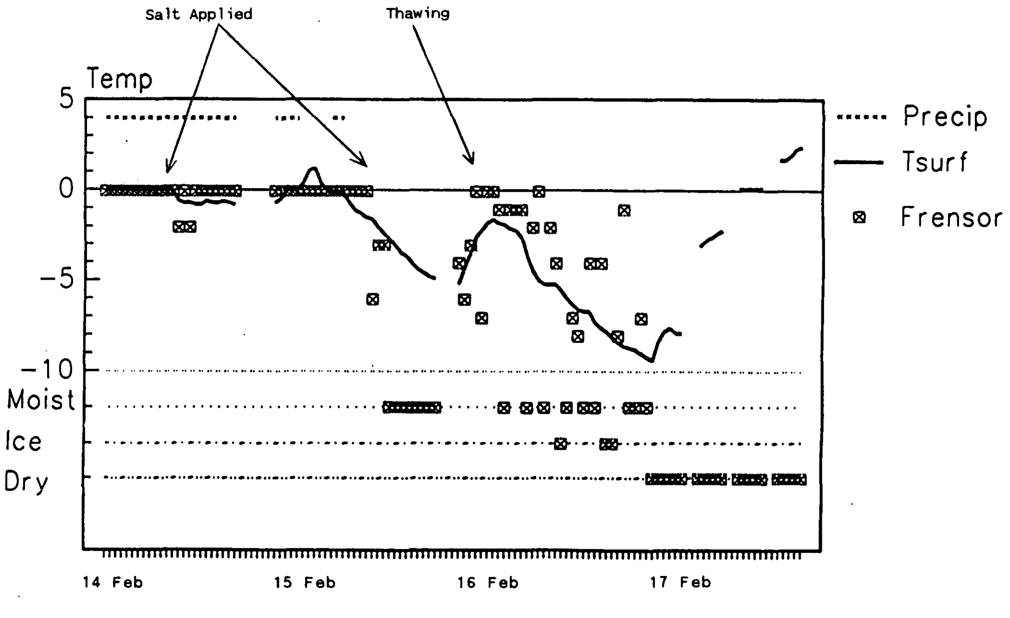

FIGURE 6 Data from 3½ days in February 1990 showing Frensor reports compared with surface temperature data and manual observations.

CONCLUSION

A new solid-state pavement sensor, Frensor, designed to measure the freezing point of moisture on bridge decks, roads, and runways has been presented. Using the Peltier principle as controlled through a microprocessor, the Frensor actively changes the temperature of the moisture deposited on its surface and provides an output of the pavement temperature and conditions. The conditions reported include: dry surface; wet surface; wet, but not frozen; dew; frost; and amount of chemicals on the surface.

The freezing point is measured to an accuracy of ±0.5°C, over a calibrated range of −27° to 0°C. Thus, the Frensor provides a direct measurement of the freezing point temperature of the material on the pavement, with which chemical application decisions can be made.

Performance Evaluation of Pavement with Deicing Materials

HIDEHIKO NINOMIYA, KIYOSHI TAKEICHI, AND KAZUYUKI KAWAMURA

As part of countermeasures to slippery roads in Japan, deicing pavement has been investigated. Deicing materials such as chloride and ground rubber were added to the pavement. Deicing pavements are under construction in various districts in Japan, but evaluation methods have yet to be established. The effectiveness of deicing pavement containing a flaked deicing material (Verglimit) consisting primarily of calcium chloride was evaluated, chiefly with a dielectric pavement freezing detector and a fixed camera. As a result, melting action and chloride solution on the pavement with deicing materials were evaluated.

In snowy and cold regions, controlling snow and ice on the roads is of major importance in ensuring safe, smooth traffic flow in winter. In Japan, studded tires have been popular for their convenience and effectiveness. However, the damage that they do to the pavement and related environmental issues pose grave problems. A law prohibiting the use of studded tires in designated areas was enacted in June 1990.

Hokkaido is in the northernmost region of Japan and is affected by comparatively heavy snowfalls and cold climatic conditions, leading to frequently frozen road surfaces in winter. Despite this, few specific snow and ice control practices, such as the application of deicing chemicals, have been followed.

To obtain information supporting optimum snow and ice control measures, deicing materials are being studied. In this survey, the effectiveness of pavement containing a flaked deicing material called Verglimit, which consists primarily of calcium chloride, was evaluated, chiefly with a dielectric pavement freezing detector (DPF) and a fixed camera.

SUMMARY OF SURVEY

Survey Site

Figure 1 shows Otaru, the site of the survey, in the western part of Hokkaido. The mean temperature and average snowfall in February for the past 5 years were −2.8°C (27.0°F) and 800 mm (31.5 in.), respectively; the test road was in a mountainous area.

Average daily traffic during the test was about 2,100 vehicles, 16 percent of which were commercial vehicles. The survey was conducted from December 1991 to March 1992. In Sections A, B, and D, 5 percent deicing materials were added to the asphalt mixture. In Section C, deicing material was not added. Section A was paved in 1989, Section B was paved in 1990, and Sections C and D were paved in 1991.

This paper compares and discusses the observations at Sections C and D to evaluate the effectiveness of the deicing material.

Description of Survey

The survey process was as follows:

1. Instrument observation:
   - Regular photographing of the road surface with fixed camera.
   - Monitoring electric capacitance and temperature of the road surface with a DPF.
2. In situ observation:
   - Measuring chloride concentration by sampling packed snow on the road.
   - Measuring reflectivity of snow and ice on the road.
3. Measurement of depth of snow and ice on the road.
4. Measurement of temperature and wind velocity.

Regular Photographing with Fixed Camera

On the basis of photographs, snow and ice conditions on the road surface were identified and road-surface exposure was calculated. Exposure rates were calculated by Equation 1.

$$\text{road surface exposure rate (\%)} = \text{exposed area/total designated area} * 100 \quad (1)$$

Measurement of Reflectivity of Snow and Ice on Road

With an albedometer, the ratio of light reflected by the snow and ice to the incident light was calculated by Equation 2.

$$\text{reflectivity} = \text{reflected light/incident light} \quad (2)$$

Measurement of Surface Electric Capacitance and Surface Temperature

The DPF was developed by applying the dielectric characteristics of snow and ice and condenser theory. The device is

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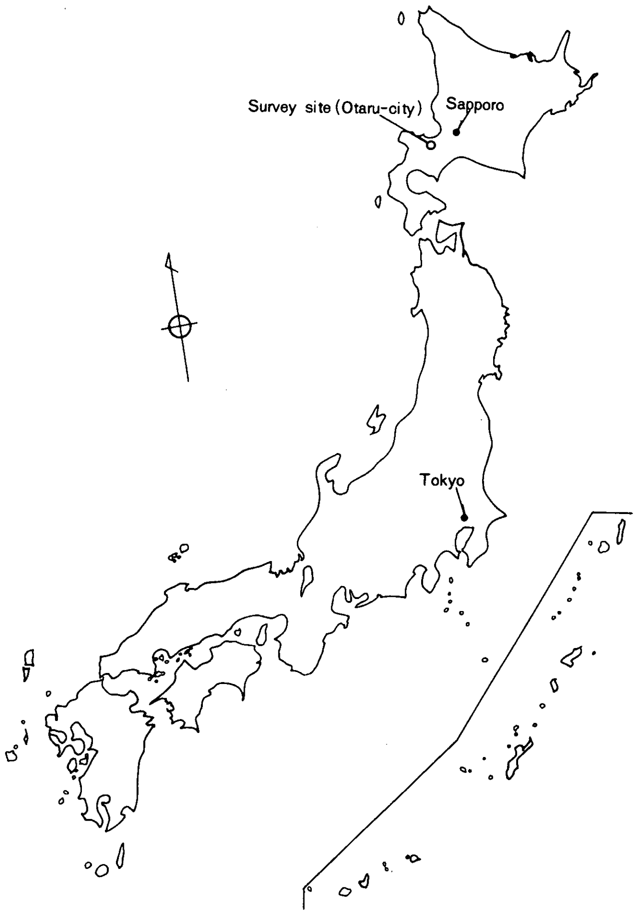

FIGURE 1 Survey site.

used to determine road-surface states on the basis of electric capacitance and temperature. Figure 2 shows a DPF diagram in which the differences in electric capacitance from the dielectric characteristics vary with air, water, and ice conditions. The electric capacitance is determined by Equation 3.

$$C(pF) = 8.854 * \kappa s * A/d \tag{3}$$

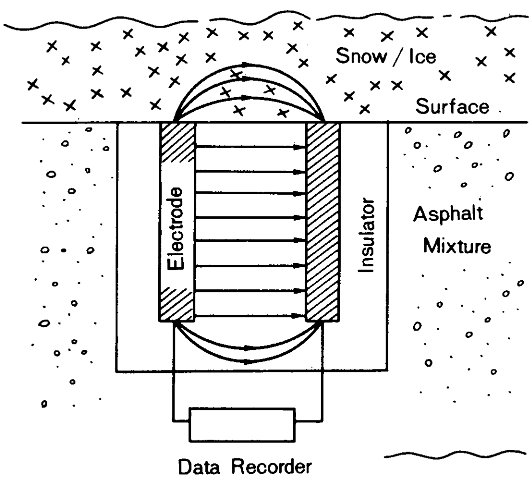

FIGURE 2 Diagram illustrating principle of measurement by DPF.

where

C = electric capacitance,
κs = ratio of dielectric,
A = area of facing pole plates (m^2), and
d = distance between pole plates (m).

The measurement frequency was 72 KHz.

In this survey, the effect of the deicing mixture was evaluated on the basis of the fact that electric capacitance increases with an increase in chloride solution.

Classification of Snow and Ice Conditions on Roads

During winter, the varying properties of snow and ice on the road strongly affect the conditions of the road surface. Snow and ice conditions change with the freeze-thaw cycle, the action of traffic, and other disturbances, and they may be classified as done in Table 1.

ANALYSIS OF PHOTOGRAPHS

The classification of snow and ice on roads and the analysis of road-surface exposure rates were done on the basis of road-surface photos taken from December to February.

Types of Snow and Ice on Roads

The proportions of the different snow and ice conditions are shown in Figure 3. Generally, CS, GS, and IF/IC conditions form slippery and freezing road-surface conditions, whereas SL/WB and DB are relatively safe road conditions.

In Sections C and D, CS is the most common condition (except for DB). In Section C, CS is 63 percent; in Section D, it is 43 percent, or two-thirds that in Section C. The SL/WB

TABLE 1 Classification of Snow and Ice Conditions on Road

Type (Symbol)	Sub-Type (Symbol)
New Snow (NS)	Dry New Snow (DNS)
	Wet New Snow (WNS)
Compacted Snow (CS)	Dry Compacted Snow (DCS)
	Wet Compacted Snow (WCS)
Powder Snow (PS)	Powder Snow (PS)
Grain Snow (GS)	Dry Grain Snow (DGS)
	Wet Grain Snow (WGS)
Slush (SL)	Slush (SL)
Ice Crust (IC)	Dry Ice Crust (DIC)
	Wet Ice Crust (WIC)
Ice Film (IF)	Dry Ice Film (DIF)
	Wet Ice Film (WIF)
Bare (B)	Dry Bare (DB)
	Wet Bare (WB)

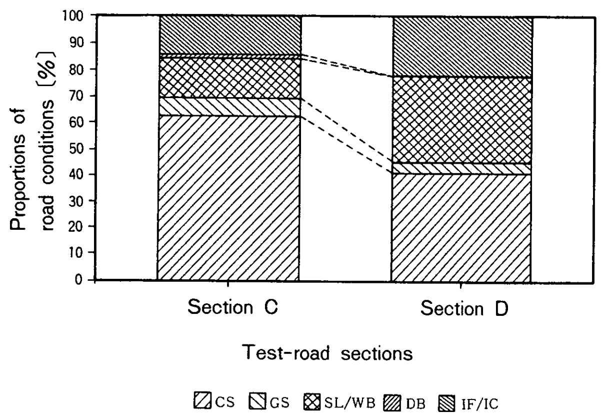

FIGURE 3 Proportions of snow and ice conditions on roads throughout survey period.

and IF/IC conditions in Section C are both 15 percent; in Section D, SL/WB is 29 percent, about twice that in Section C.

Snow and ice on the road by time of day is shown in Figure 4. The SL/WB condition is more common in Section D than in Section C. SL/WB frequencies are highest at 2:00 p.m.: 25.8 percent in Section C and 53.3 percent in Section D. Hence, it is considered that the deicing agent causes the transition from CS (immediately after snowfall) to SL/WB.

In Section D, SL/WB is high at 12:00, 2:00, and 4:00 p.m., and IF/IC is high at 8:00 and 10:00 a.m. This is due to freezing at night, showing that the refreezing of melted snow must be considered when using deicing materials.

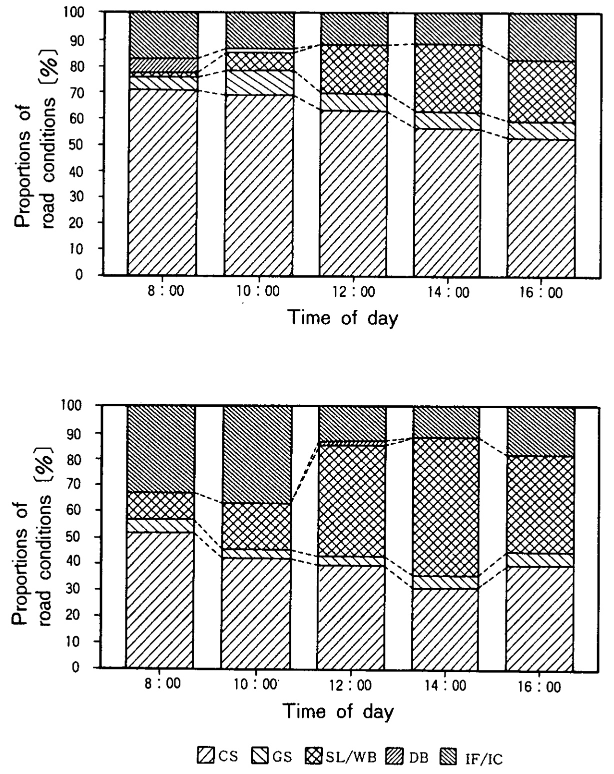

FIGURE 4 Proportions of snow and ice conditions on roads in Sections C (*top*) and D (*bottom*) throughout survey period.

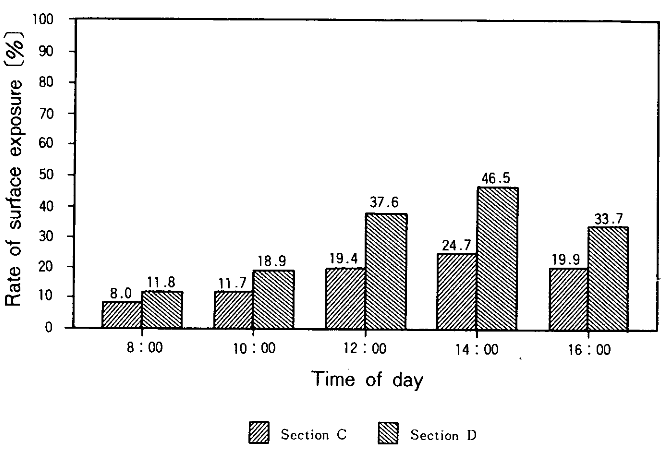

FIGURE 5 Rates of road-surface exposure in Sections C and D throughout survey period.

Road-Surface Exposure

The average surface exposure throughout the observation period is shown in Figure 5. It is seen that road-surface exposure in Section D is higher than in Section C, particularly from 10:00 a.m. to 12:00 p.m., when the difference increases sharply. The road surface exposures at 10:00 a.m. and 12:00 p.m. in Section C are similar to those at 8:00 and 10:00 a.m. in Section D. This suggests that the deicing mixture hastens the exposure of pavement surfaces.

IN SITU OBSERVATIONS

Reflectivity of Snow and Ice on Road Surfaces

Thawing and contamination of snow and ice were investigated by the reflectivity of the snow and ice on the road surface. Figure 6 shows the results on February 13. Reflectivity is low, and there is more contamination of snow and ice in Section D than in Section C. Reflectivity in Section C remains unchanged throughout the day. The contamination of snow and ice in Section D indicates acceleration of melting by the deicing materials.

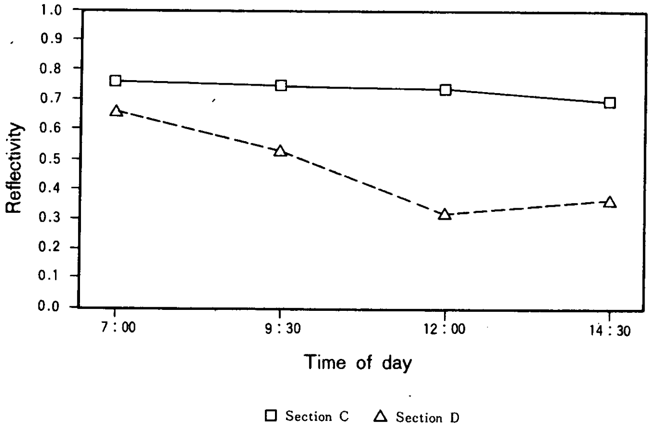

FIGURE 6 Reflectivities in Sections C and D during in situ survey (February 13, 1992).

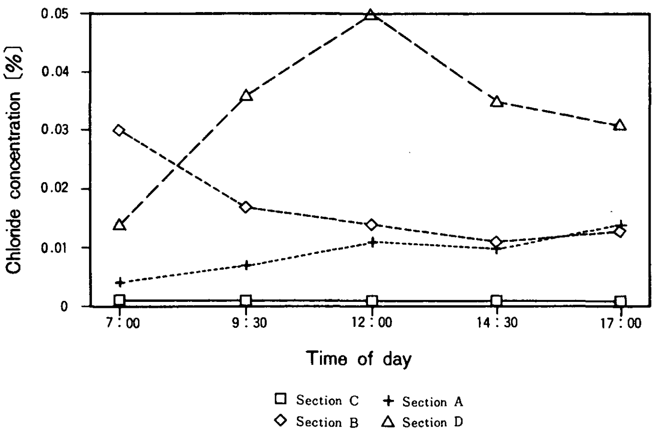

FIGURE 7 Chloride concentrations in Sections A through D during in situ survey.

Measurement of Chloride Concentration

Figure 7 shows laboratory test results on chloride concentration in snow and ice sampled from each section. Section D shows the highest concentration, followed by Sections B and A. Section C, without additives, showed no chloride concentration.

A regression analysis was done on chloride concentrations in snow and ice on the roads, surface temperatures, and electric capacitances as determined with a DPF. The results are given in Table 2. The analysis was conducted on all test-road sections and snow and ice conditions. The variance analysis of the regression for chloride concentration, surface temperature, and electric capacitance showed a highly significant F0 = 27.38 related to F(2,54) = 5.04 with 57 cases with a risk rate of 1 percent. The correlation coefficient *R* determined from the regression analysis was .71, which suggests that the concentration of chloride may be determined from the electric capacitance.

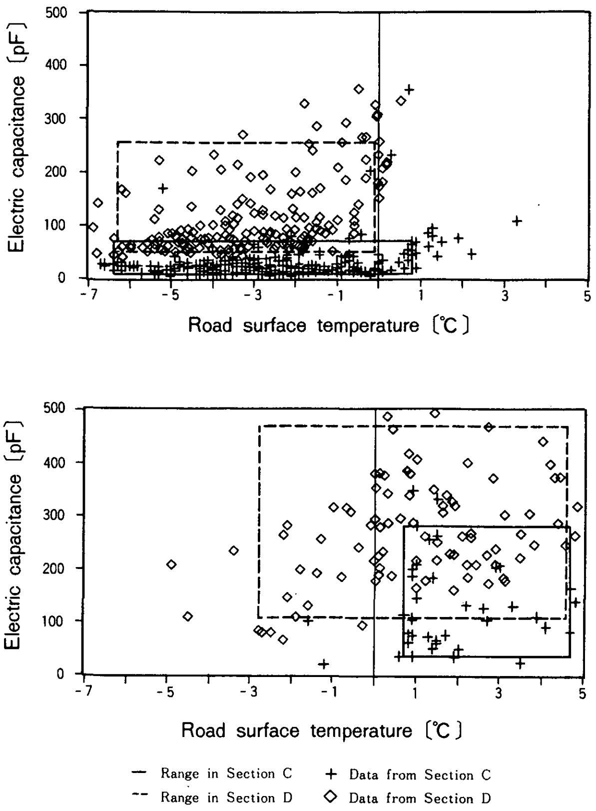

FIGURE 8 Ranges of freezing state (*top*) and SL/WB (*bottom*) in Sections C and D from DPF data.

EVALUATION OF GENERATED DEICING EFFECT OF DEICING MIXTURE

Chloride concentration and electric capacitance were correlated; without deicing chemicals, no other element affected the electric capacitance. From the DPF data for Sections C and D, the effect of road-surface temperature and electric capacitance was evaluated. In Figure 8, the conditions of the road surface were classified into freezing state (excluding SL, WB, and DB) and SL/WB. The confidence interval of the data was 90 percent.

The road-surface temperature range of the freezing state was −6.4 to 0.8°C (20.5 to 33.4°F) in Section C and −6.3 to −0.1°C (20.7 to 31.8°F) in Section D, indicating that the freezing state in Section D occurs at 1°C (1.8°F) lower than it does in Section C. The electric capacitance was between 9.0 and 70.0 pF in Section C and 49.5 and 256.3 pF in Section D, which indicates high electric capacitance in the snow and ice of Section D because of the deicing materials.

The road-surface temperature range of SL/WB was 0.7 to 4.7°C (33.3 to 40.5°F) in Section C and −2.8 to 4.6°C (27.0 to 40.3°F) in Section D, which indicates that SL/WB in Section D occurs at 3.4°C (6.1°F) lower than it does in Section C,

TABLE 2 Multiple Regression Analysis on Road-Surface Temperature, Chloride Concentration, and Electric Capacitance, and Analysis of Variance

Result of Multiple Regression Analysis

Number of cases	Multiple correlation (=r)	R-Square 0.5035 (=r²)
57	0.7095	0.5035

Analysis of Variance

	D.F.	Sum of Square	Mean Square	F-Value(F0)
Regression	2	1,166,020.00	583,011.00	27.38 ≧ 5.04=F(2,54)
Residual	54	1,150,030.00	21,296.80	
Total	56	2,316,050.00		

showing that freezing is restrained. The electric capacitance was between 34.3 and 280.3 pF in Section C and 107.8 and 468.8 pF in Section D, indicating high electric capacitance caused by deicing materials as in the freezing state.

In Section C the transition between the freezing state and SL/WB occurred at about 0.7 or 0.8°C (33.3 or 33.4° F). In Section D, the electric capacitances of the freezing state and SL/WB overlapped at between 100 and 250 pF with road surface temperatures of between −3 and 0°C (26.6 and 32.0°F). This is thought to occur when, and indicate that, the bond between snow and ice and pavement is broken. In such circumstances, snow can be removed quickly.

CONCLUSIONS

- Pavement with deicing material added leads to more slushy and wet bare road conditions, resulting in higher road-surface exposure rates. However, refreezing of thawed snow must be considered.
- Chloride concentration, road-surface temperature, and electric capacitance are correlated, and chloride concentration may be determined from the electric capacitance.
- The minimum surface temperature of slush and wet bare road conditions was about −3°C (26.6°F) in Section D, with deicing pavement, and 1°C (33.8°F) in Section C, without deicing pavement.
- Deicing pavement enables faster snow removal because of the destruction of the bond between snow and ice and the pavement surface, even though snow and ice conditions remain.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the Otaru Development and Construction Office, Hokkaido Development Bureau, and students from the Department of Engineering, Hokkaigakuen University, for their help with this survey.

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PART 7

Safety and Operations

Traffic Volume Reductions Due to Winter Storm Conditions

RASHAD M. HANBALI AND DAVID A. KUEMMEL

When hazardous driving conditions exist on roads, road users have less desire to travel. As a result of snow and icy conditions, a reduction in traffic movement occurs. The decrease in traffic movement is almost unexamined so far. During a research project conducted in 1991–1992 to study the impact of snow and ice control operations on traffic accident rates, the need for estimating the decrease in traffic movement urged such calculations. The reductions in traffic volumes generated as a result of adverse snow and icy conditions were measured, grouped, and correlated during various weather conditions in four states (Illinois, Minnesota, New York, and Wisconsin). Traffic volumes reductions factors during different winter storms conditions were calculated and reported.

During winter, snow and ice storms cause emergency conditions that disturb the normal activities of any community. Effects can range from minor disruptions to major catastrophes that shut down industries, knock out energy and communication lines, and make streets, roads, and highways impassable. Achieving normal conditions as soon as possible depends on the technology used for snow and ice removal, the proper planning and management of snow and ice removal, and the programs and policy for effective use of all available resources. The maximum-benefit policy for dealing with snow and ice problems would be to achieve "bare pavement" (i.e., no accumulation of snow and ice on all streets, roads, and highways) as quickly as possible and without having any adverse side effects. To the other extreme, the minimum-benefit policy is that of no response to snow removal at all. To select a policy between these two extremes, policy makers must decide what goal will be sought to reduce the hazardous driving conditions and impaired mobility (*1*).

During hazardous driving conditions, a reduction in traffic movement occurs; travelers have less desire to travel. The interaction between people (road users) and space (roads) has been studied by economists, demographers, sociologists, planners, and others (*1*). Many factors affect these movements or interactions and can be categorized as follows:

1. A generating factor related to individual trip makers and their willingness to travel,
2. An attraction factor related to the importance (or utility) of the particular destination,
3. A linkage factor related to the difficulty (or cost) of moving from the origin to the destination, and
4. Other related factors.

The behavior of road users relates mainly to the descriptions and understanding of how, and in response to what, they believe in regard to travel. For example, one economic theory of travel behavior considers most travel to be an intermediate good that must be consumed at some monetary and psychological cost to the traveler in order to derive equal or greater benefits in kind from activities indulged in at the trip destination. The response of road users to travel cost and destination choices varies according to the characteristics of the behaviors and beliefs of the travelers.

METHODOLOGY

Traffic volume studies are made to obtain and collect data on the number of vehicles that pass a point on a highway section during a specified period. Normal traffic volume counts are usually measured under dry road conditions. A continuous traffic volume count at a road section will show the variation of traffic volume from time to time. Previous studies proved that this variation is repetitive and rhythmic.

Data Collection

Eleven automatic traffic recorders (ATRs) in operation during various weather conditions on 11 highways outside urban areas were selected randomly with the cooperation of authorities in four states: Illinois (Ogle and Lee counties), Minnesota (Olmsted County), New York (Wayne, Monroe, Steuben, and Onondaga counties), and Wisconsin (Walworth, Kenosha, and Waukesha counties). Table 1 presents all the 11 ATRs used in this study.

Data from all 11 ATRs during the first 3 months of 1991 were collected. Furthermore, additional data from Wisconsin (December 1990) and New York State (December 1989 and January, February, March, and December, 1990) were collected and included in the analysis.

During snowstorms, a reduction in traffic volume occurs. The reduction is a function of time of day, type of highway, normal traffic volumes, level of service, weather conditions, road user behavior and satisfaction, and other factors.

The data collected for this study are given in the following paragraphs.

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TABLE 1 Automated Continuous Count Stations

State	County	Highway	Station#	Location
NewYork	Wayne	STH 104	3732	0.9 Mile E. of RT 14 (Sodus Bay)
NewYork	Monroe	STH 590	4342	0.6 Mile N. of RT 286 (Seabreeze)
NewYork	Onondaga	I - 81	3311	0.8 Mi. N. of Cortland-Onondaga C.L.
NewYork	Steuben	STH 17	6441	NE of S. JCT. of RT 415
Wisconsin	Walworth	USH 12	64-0002	Lake Geneva
Wisconsin	Kenosha	STH 50	30-6109	0.2 Mile W. of USH 45 (Salem)
Wisconsin	Waukesha	I - 43	67-0010	Crowbar RD overpass (Crowbar)
Minnesota	Olmsted	TH 14	212	E. CR 104 Rochester
Minnesota	Olmsted	TH 52	188	S. of ORONOCO
Illinois	Ogle	I - 39	205	S. of CH 20 (Lindenwood)
Illinois	Lee	Ill 38	280	W. of Ashton

Highway Characteristics

To study the reduction in traffic volumes during snow and icy conditions, it is useful, practical, and desirable to know the characteristics of the testing locations (Table 2). The locations used in this study were selected randomly for each jurisdiction area chosen earlier for another research project (*2*); no specific preconditions were set for the selection.

Traffic Volumes

In this study the latest annual average daily traffic and the actual 24-hr counts during each testing period and for each testing location were measured continuously and provided by the authorities in each of the participating states. These counts were used as the base from which to calculate the variations in traffic volumes.

Level of Service

The maximum-benefit policy for dealing with snow and ice problems would be to achieve bare pavement as quickly as possible. The optimum snow and ice policy varied from one participating area to another, but they were all similar in establishing bare pavement as soon as possible. Reducing the level of effort for snow and ice removal and control has immediate consequences on delay, traffic volume, traffic congestion, and public image of the state department of transportation.

Climatic Data

All participating highway agencies responsible for winter road maintenance have been using weather forecasting to aid preparation efforts before a storm begins. For this paper, the following climatic data for each participating area during the study period were collected:

1. Storm period (start and end time: hour, day, and date),
2. Temperature range (high and low), and
3. Depth and type of snow (dry, wet, sleet, etc.).

Climatic data were also derived from the basic data files at the National Climatic Data Center in Asheville, North Carolina, through its monthly report for each state.

Analysis

The approach used in this study to measure reductions in traffic volume during any snowstorm depends mainly on the traffic counts of the ATRs presented in Table 1 and the following.

TABLE 2 General Characteristics of Testing Sections

Rural & Suburban Highways	**Rural & Suburban Freeways**
- Average lane width of about 3.5 meters. - Few restriction to through traffic by traffic control devices - Average shoulder width of about 2 meters. - Mostly level terrain - Average speed limit of 72-88 kilometer/hr.	- Average lane width of about 4 meters. - Divided highways with 2 - 3 lanes per direction - Average shoulder width of about 3 meters. - Mostly level terrain - Average speed limit of 88-105 km/hr.

Traffic Counts

All traffic counts for all snowstorms were categorized and grouped by

1. Normal average daily traffic (ADT) volume. Each ATR was categorized under one of the following ranges on the basis of its normal ADT:
   - –Rural and suburban freeways: 11,000 to 20,000, and 21,000 to 30,000.
   - –Rural and suburban highways: 3,000 to 6,000, and 7,000 to 10,000.
2. Day of week. The day of occurrence of each snowstorm was categorized by weekday (Monday through Friday) or weekend (Saturday or Sunday).
3. Snow precipitation. Each snowstorm was categorized by snow precipitation and temperature range.

Hourly Traffic Volume

For every snowstorm, the hourly traffic volume was measured at the ATR station location and compared to the normal hourly traffic count for the same location during a similar day, and at the same hour, month, and year. From the comparison, hourly reduction factors were derived during each snowstorm. Table 3 presents an example of the hourly traffic volume reduction factors derived during a storm in Wayne County, New York. Similar derivations were made for the traffic volumes for all the other snowstorms in all tested locations. Figures 1 through 4 show two examples of a graphical presentation of hourly traffic reduction percentages during a snowstorm in Wayne County, New York.

Peak Periods

Each similar snowstorm event was divided into hourly periods:

1. Peak-hour periods
   - –Weekdays (morning and evening)
   - –Weekends (variable)
2. Off-peak-hour periods
   - –Early morning
   - –Midday
   - –Late evening

TABLE 3 Example of Calculating Hourly Traffic Volume Reductions During Storm in Wayne County

State: New York **County:** Wayne **Highway:** STH 104
AADT = 6750 **Station Number** = 3732

Date: February 13-14, 1991 **Snowfall** = 25 mm **Temperature range** = -8 to -4 °C
Snow storm period: (23.00) 2 /13 /91 (to) (23.00) 2 /14 /91

Hr.	Normal Vol.	Wednesday (2 / 13 / 91)		Thursday (2 / 14 / 91)	
		Snow Vol.	Factor	Snow Vol.	Factor
- 1	75	77	1.02	73	0.97
- 2	34	36	1.05	26	0.75
- 3	35	35	1.01	34	0.96
- 4	26	27	1.02	20	0.75
- 5	44	45	1.03	36	0.81
- 6	83	84	1.01	80	0.96
- 7	168	177	1.05	155	0.92
- 8	335	342	1.02	325	0.97
- 9	321	305	0.95	276	0.86
- 10	299	290	0.97	284	0.95
- 11	275	269	0.98	240	0.87
- 12	285	285	1.00	248	0.87
- 13	256	228	0.89	246	0.96
- 14	281	283	1.01	293	1.04
- 15	301	313	1.04	271	0.90
- 16	445	427	0.96	436	0.98
- 17	520	520	1.00	536	1.03
- 18	448	439	0.98	444	0.99
- 19	312	312	1.00	272	0.87
- 20	172	174	1.01	148	0.86
- 21	153	153	1.00	126	0.82
- 22	96	85	0.89	90	0.93
- 23	97	86	0.88	94	0.97
- 24	94	90	0.95	103	1.09
	5155	5082	avg. = 0.99	4856	avge. = 0.94

(1) Snow Reduction Factor = (Snow Vol.) / (Normal Vol.) in relative time (hour)

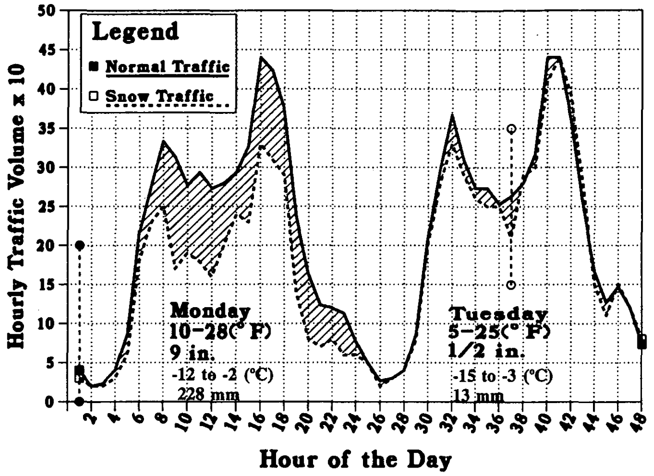

FIGURE 1 Example of traffic behavior at continuous count station in Wayne County during winter snowstorm, Thursday and Friday.

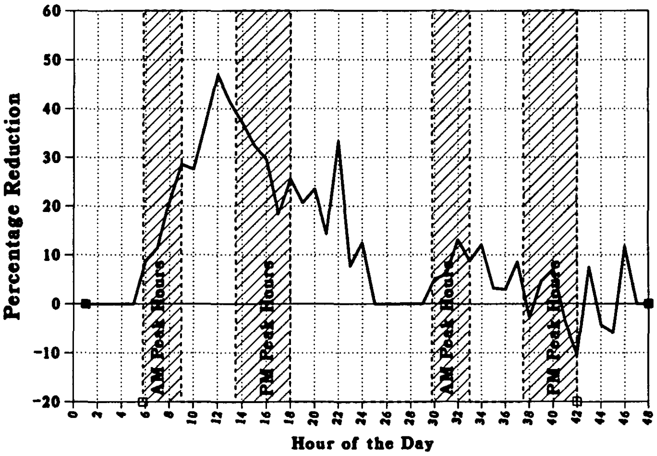

FIGURE 2 Hourly traffic volume reduction for Figure 1.

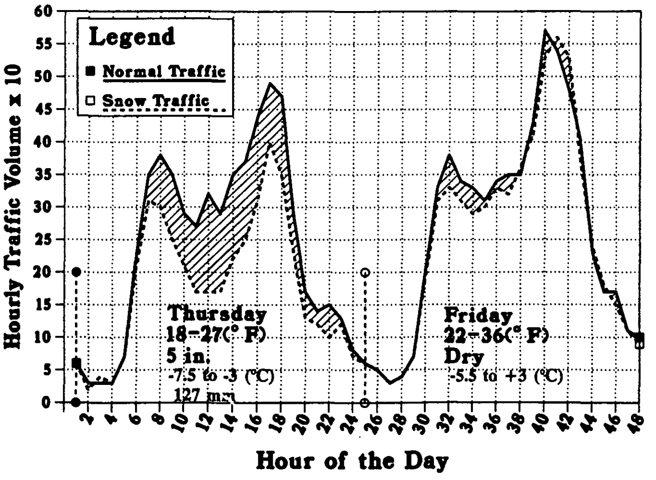

FIGURE 3 Example of traffic behavior at continuous count station in Wayne County during winter snowstorm, Monday and Tuesday.

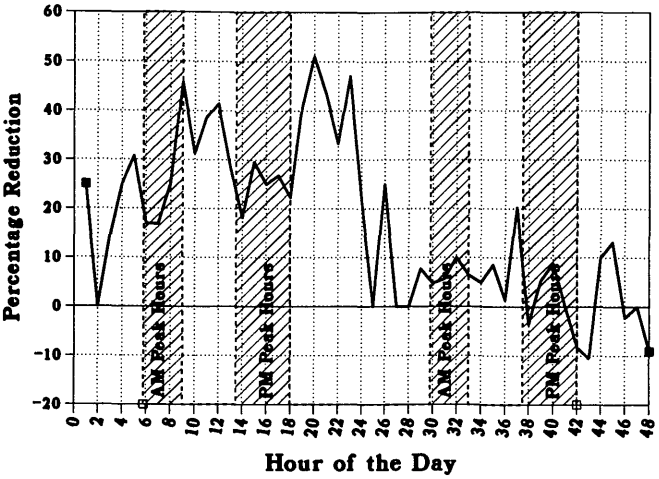

FIGURE 4 Hourly traffic volume reduction for Figure 3.

Traffic Volume Reductions

All traffic volume reductions under the same categorized group were compiled and correlated, and an average reduction was calculated by dividing the sum of hourly reductions by the sum of their respective hourly normal volumes for each compiled categorized group.

RESULTS

For this study, the analysis covered the traffic volumes on highways and freeways outside urban areas in four states (see Table 1). All participating areas in this study had a similar snow and ice control policy to establish bare pavement as soon as possible. The results of the analysis are summarized, given in Table 4, and illustrated in Figures 5 and 6.

CONCLUSIONS

Conclusion One

The average reduction in traffic volume due to winter storm conditions depends directly on weather conditions (the more severe the winter storm, the greater reduction in traffic volume):

- Winter storms with snow precipitation of less than 25 mm have an average traffic volume reduction of 7 to 17 percent during weekdays and 19 to 31 percent during weekends.
- Winter storms with snow precipitation of 25 to 75 mm have an average traffic volume reduction of 11 to 25 percent during weekdays and 30 to 41 percent during weekends.
- Winter storms with snow precipitation of 75 to 150 mm have an average traffic volume reduction of 18 to 43 percent during weekdays and 39 to 47 percent during weekends.
- Winter storms with snow precipitation of 150 to 225 mm have an average traffic volume reduction of 35 to 49 percent during weekdays and 41 to 51 percent during weekends.
- Winter storms with snow precipitation of 225 to 375 mm have an average traffic volume reduction of 41 to 53 percent during weekdays and 44 to 56 percent during weekends.

TABLE 4 Average Traffic Volume Reductions per Average Snow Precipitation per Time of Day per Day of Week

Snow (mm)	Time of Day	Average Traffic Reductions (%)				
		(a)	(b)	(c)	(d)	Range
< 25	1	8	10	11	12	8-12
	2	7	8	9	10	7-10
	3	12	15	16	17	12-17
	4	7	8	9	11	7-11
	5	11	12	13	13	11-13
	6	27	29	31	31	27-31
	7	23	23	21	19	19-23
25-75	1	14	16	21	23	14-23
	2	11	13	17	18	11-18
	3	13	15	22	25	13-25
	4	12	12	14	15	12-15
	5	23	25	28	31	23-31
	6	32	35	38	41	32-41
	7	30	32	35	36	30-36
75-150	1	28	30	31	31	28-31
	2	18	20	19	21	18-21
	3	36	38	38	39	36-39
	4	21	23	25	25	21-25
	5	40	42	43	43	40-43
	6	42	43	45	47	42-47
	7	39	41	41	42	39-42
150-225	1	43	44	45	45	43-45
	2	36	37	38	39	36-39
	3	42	44	44	46	42-46
	4	35	37	38	40	35-40
	5	47	48	49	49	47-49
	6	49	50	50	51	49-51
	7	41	42	44	46	41-46
225-375	1	52	53	51	52	51-53
	2	42	42	41	41	41-42
	3	47	49	48	49	47-49
	4	42	43	43	44	42-44
	5	50	49	51	51	49-51
	6	55	56	55	55	55-56
	7	44	47	48	50	44-50

Rural & Suburb:

- Freeways:
(a)11,000-20,000
(b)21,000-30,000

- Highways:
(c) 3,000- 6,000
(d) 7,000-10,000

Temperature Range:

-13°C to +10°C

Weekdays (Monday - Friday):

(1) Off-Peak Hours (Early AM)
(2) AM Peak Hours
(3) Off-Peak Hours (Mid-Day)
(4) PM Peak Hours
(5) Off-Peak Hours (Late PM)

Weekends (Saturday+Sunday):

(6) Off-Peak Hours (Variable)
(7) Peak Hours (Variable)

*** Holidays and days with special events are not included in this study.**

Conclusion Two

The average reduction in traffic volume due to winter storm conditions is inversely related to the importance of traveler destination and the traveler's willingness to travel.

- The average reduction in traffic volume during weekday peak hours (mostly work and other necessary trips) was less than during weekday off-peak hours (mostly discretionary trips).
- The average reduction in traffic volume during weekday hours was less than during weekend hours.
- The average reduction in traffic volume during weekend peak hours (most likely necessary trips) was less than during weekend off-peak hours (mostly discretionary trips).

Conclusion Three

The influence of both the generating factor (individual trip maker and his or her willingness to travel) and the attraction

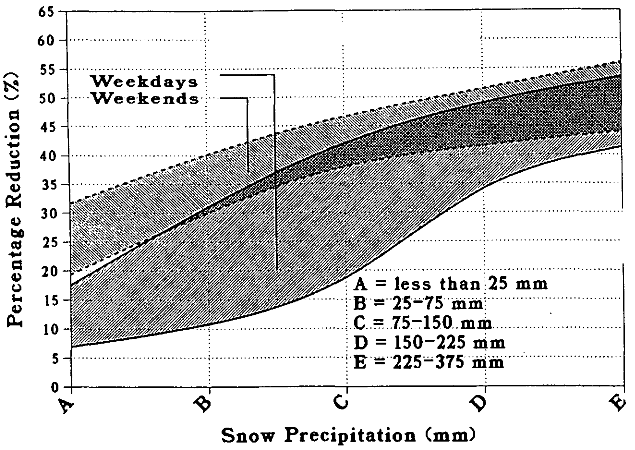

FIGURE 5 Range of traffic volume reduction, weekdays versus weekends.

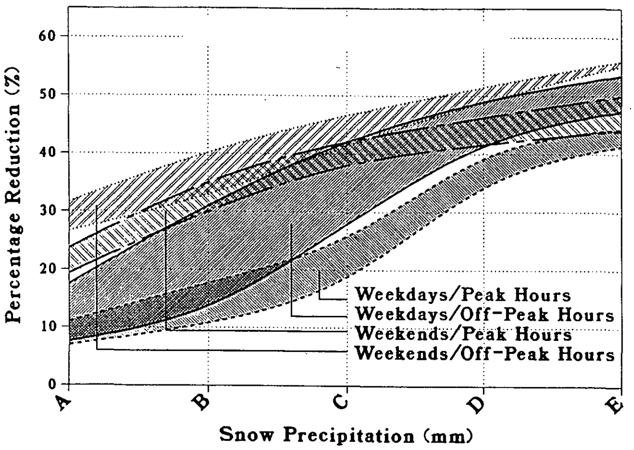

FIGURE 6 Range of traffic volume reduction, peak versus off-peak hours.

factor (importance of the particular destination) on traffic volume reductions is directly related to the severity of winter storms.

- Winter storms with snow precipitation of less than 25 mm have an overlap in the ranges of peak (mostly necessary trips) and off-peak (mostly discretionary trips) average traffic volume reductions.
  - –The average reduction in peak-hour traffic on weekdays ranged from 7 to 11 percent.
  - –The average reduction in off-peak traffic on weekdays ranged from 8 to 17 percent.
- Winter storms with snow precipitation of 225 to 375 mm have more of a separated range of peak and off-peak average traffic volumes reductions.
  - –The average reduction in peak-hour traffic on weekdays ranged from 41 to 44 percent.
  - –The average reduction in off-peak-hour traffic on weekdays ranged from 47 to 53 percent.

Conclusion Four

The range of average reductions in traffic volume during severe winter conditions depends directly on the difficulty and safety of moving from the origin to the destination (linkage factor).

Road users during weekday off-peak hours are more decisive in making or not making a trip when weather severity is low (less than 50 mm) or high (more than 200 mm); and less decisive in making or not making a trip when weather severity is average (between 50 and 200 mm). The range's width of traffic volume reduction is smaller at less than 50 mm or greater than 200 mm than the range's width at less than 200 mm and greater than 50 mm (Figures 5 and 6).

Road users during weekend off-peak hours are more decisive in making or not making a trip as weather severity increases. The range's width of traffic volume reduction decreases as winter severity increases.

Road users during weekday or weekend peak hours are more consistent and decisive in making or not making a trip independent of weather severity. The range's width of traffic volume reduction is mostly constant at different snow and icy conditions.

ACKNOWLEDGMENTS

The authors thank the authorities in the department of transportation of each participating area for their cooperation in providing the data needed for this study. This work is part of a doctoral dissertation submitted to Marquette University by Rashad M. Hanbali (*2*).

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Influence of Regulation of Studded Tire Use in Hokkaido, Japan

NOBUO KONAGAI, MOTOKI ASANO, AND NOBUO HORITA

The law prohibiting the use of studded tires has been in effect in Japan since the 1991–1992 winter; its purpose is to prevent the dust pollution generated by such tires. According to the law, studded tires are to be prohibited (except for emergency vehicles) in areas designated by the Environment Agency. Since April 1992, infringements of the law have been punished with a fine of no more than 100,000 yen. Before the law was effective, tire manufacturers already had voluntarily stopped manufacturing and selling studded tires and had begun developing and supplying high-quality rubber tires with no metal studs—"studless tires." The circumstances that forced the law; the effects of the enforcement of the law on the road environment, road pavement and marking, traffic accidents, and traffic characteristics; and the performance of studless tires are reported.

When the temperature is very low, much snow falls in winter in snowy and cold regions in Japan, especially in Hokkaido. Road authorities remove snow by means of machines such as the snowplow and rotary snow-removal machine. However, salting is not a primary method of snow and ice control. The authorities cannot adopt a bare-pavement policy because of Japan's severe cold and great amount of snow.

Studded tires began to be used widely in Japan in the late 1960s. They were extremely useful in ensuring safety and keeping steady winter traffic in snowy and cold regions. However, studded tires raised problems of dust pollution, road surface damage, and traffic accidents caused by ruts in the 1980s. The dust pollution created by the pavement wearing of studded tires was the serious problem. The causal relationship between the dust and disease was not clear, but the dust that blew up was like a dark cloud veiling a whole city; it obstructed breathing.

Under the circumstances, citizen activists, medical concerns, and lawyers groups appealed to the public to prevent the dust pollution. After many activities and debates, municipal and prefectural regulations related to the prevention of dust pollution have become effective, and tire manufacturers voluntarily stopped manufacturing and selling studded tires. The studded tire prohibition went into effect April 1, 1991, and the punishment of a fine has been in effect since April 1, 1992.

In short, the law prohibits the use of studded tires on nonsnowy or nonfrozen road surfaces (except for emergency vehicles such as fire engines) in areas designated by the Environment Agency. It actually means that vehicles cannot use studded tires even though the vehicles may be passing through these areas only briefly, because we ordinarily do not change tires on the border of these areas.

The following is extracted from the law concerning prevention of dust generation caused by studded tires:

> Article 3 (people's duty): All people must make an effort not to generate dust caused by studded tires and must cooperate with national and prefectural projects that relate to the prevention of dust generated by studded tires.
>
> Article 4 (national, prefectural, and municipal governments' duty): The national government must make an effort to promote basic and general projects related to the prevention of dust generation caused by studded tires such as the diffusion of knowledge related to preventing dust generated by studded tires, improving road facilities, supporting the development of a substitute for studded tires, and promoting education for safe driving. The national government must make an effort to advise or otherwise promote prefectural and municipal government projects that prevent dust generation.
>
> Article 5 (area designation): The Minister of the Environment Agency must designate areas in which people are dwelling densely and in which the environment must be especially preserved and the health of inhabitants protected by preventing dust generation caused by studded tires.
>
> Article 7 (prohibition of studded tires): No one may use studded tires in nonsnowy or nonfrozen sections (except for tunnels and the sections designated by government ordinance) on cement or asphalt concrete pavement in the designated areas. This article excepts fire engines, emergency vehicles, and other vehicles designated by government ordinance.
>
> Article 8 (punishment): Infringement of Article 7 is punished with a fine of no more than 100,000 yen.

STUDY OBJECTIVES

This paper includes a performance test of winter tires and a questionnaire of drivers' concerns; also included are observations of studded tire use, traffic characteristics, and effects on asphalt pavement, road markings, and the environment.

RESULTS

Performance Test for Winter Tires

The Civil Engineering Research Institute was conducting performance tests of winter tires several years before the prohibition went into effect. The measurements tested were stopping distance, lengthwise skid resistance, and sideways skid resistance.

Winter tires of known characteristics manufactured in 1990 were used in the stopping distance test. The stopping distance was observed at 40 km/hr on compacted snow and frozen

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surfaces at the test course in northern Hokkaido; results are given in Table 1. On compacted snow, the stopping distances of studded and studless tires were nearly equal. The stopping distance of used studless tires was also nearly equal. In this case, used studless tires were artificially worn tires that were equivalent to the 10 000-km (6,211-mi) used tire.

On frozen surfaces, the stopping distances of studded and studless tires are also nearly equal. However, sometimes the stopping distance of the used studless tire was longer.

In summary,

- Stopping distances of any tire on a frozen surfaces are longer than those on compacted snow at the test course.
- On slippery compacted snow, the stopping distance of the studless tire is longer than that of studded tire, but on soft compacted snow, the stopping distances are nearly equal. The stopping distance of a studless tire varies according to its manufacturer. On compacted snow, the marginal cornering speed of a vehicle with studless tires was a little faster than that of a vehicle using studded tires.
- On frozen surfaces, the marginal cornering speed of studded tire was faster than that of studless tires.
- The newer the studless tire, the better the stopping performance. Newly manufactured studless tires' stopping performance is more durable than previously manufactured studless tires' stopping performance.
- Although not discussed here, the results of the climbing test are given in Table 2.
- Future objectives are to improve the stopping performance of studless tires on frozen surfaces and the durability of the stopping performance of studless tires.

Percentage of Studded and Studless Tire Use

Since 1986 the Hokkaido prefectural and Sapporo municipal governments have been observing the percentage of tire use in two ways: observation at parking areas and at the roadside. The parking area observation distinguishes tires into three types: studded, studless, and other. The roadside observation distinguishes tires into two types—studded and other—by watching and by listening.

TABLE 1 Results of Stopping Distance Test

types of tire	road surface	
	compacted snow surface	frozen surface
stud tire	23. 3m (-7.7℃) (25. 5yd (18.1°F))	56. 0m (-7.5℃) (61. 3yd (18.5°F))
studless tire A	26. 2m (-7.3℃) (28. 7yd (18.9°F))	56. 1m (-5.5℃) (61. 4yd (22.1°F))
used studless tire A	24. 0m (-3.8℃) (26. 3yd (25.2°F))	51. 0m (-9.1℃) (55. 8yd (15.6°F))
studless tire B	25. 3m (-4.6℃) (27. 7yd (23.7°F))	59. 8m (-5.1℃) (65. 4yd (22.8°F))
used studless tire B	24. 6m (-5.2℃) (26. 9yd (22.6°F))	60. 6m (-7.3℃) (66. 3yd (18.9°F))
studless tire C	22. 5m (-5.2℃) (24. 6yd (22.6°F))	62. 5m (-2.5℃) (68. 4yd (27.5°F))

( ) is road surface temp

TABLE 2 Results of Climbing Performance Test

types of tire	soft compacted snow			hard compacted snow		
gradient	6.3%	8.9%	9.9%	6.3%	8.9%	9.9%
stud tire	100	100	88	100	92	100
studless tire A	100	100	100	100	92	88
used studless tire A	100	100	88	100	42	25
studless tire B	100	100	100	100	92	38
used studless tire B	75	50	25	100	33	0
studless tire C	100	100	100	100	92	50

Figures are percentage of the vehicles that were able to climb.

The percentage of studded tire use has been declining in Hokkaido (Figure 1). Use in the middle of the 1991–1992 winter was 56 percent less than use during the 1986–1987 winter. (Early, middle, and late winter are November and December, January and February, and March and April, respectively.) The percentage of studded tire use is different according to the period of the season. The percentages in the early and late winter are less than in the middle of winter, and the difference in percentages between the early and late winter and the middle of winter has grown since 1988–1989. The percentage of studded tire use will become nearly zero in several years because of the prohibition and fine and because tire manufacturers have stopped manufacturing and selling studded tires and are selling studless tires instead; also, the efficacy of existing studded tires will disappear soon.

Questionnaire Research of Drivers' Concerns

The questionnaire surveyed drivers' concerns about studless tires and whether drivers shifted transportation modes or changed routes during their commutes.

A questionnaire was distributed in Sapporo, which is an area in which the Environment Agency has prohibited studded tires. In Sapporo during 1990–1991, 19.9 percent of drivers used studded tires in the early winter, 41.0 in the middle of winter, and 21.6 in late winter. However, in 1991–1992 the percentages were 6.2, 22.1, and 6.6, respectively.

Of those who usually drive themselves to work in seasons other than winter, 16.9 percent change routes or shift to public transportation on snowy days and 80.9 percent do not change routes or shift modes. Among those who do, 41.6 percent change their routes and 49.5 percent shift from car to public transportation. The main reason for changing routes is that snow is removed better on the substitute route than on the usual route and that the substitute route is safer than the usual route. The main reason for shifting to public transportation is that travel is shorter, more reliable, and safer than travel by car. Those who do not change routes or modes said that they have no substitute or that they are more patient.

In winter, it takes 61.6 percent of those who go to their offices longer than 40 min, but in seasons other than winter, it takes that long for only 36.1 percent. And 25.2 percent commute fewer than 10 km (6.2 mi), 38.9 percent commute

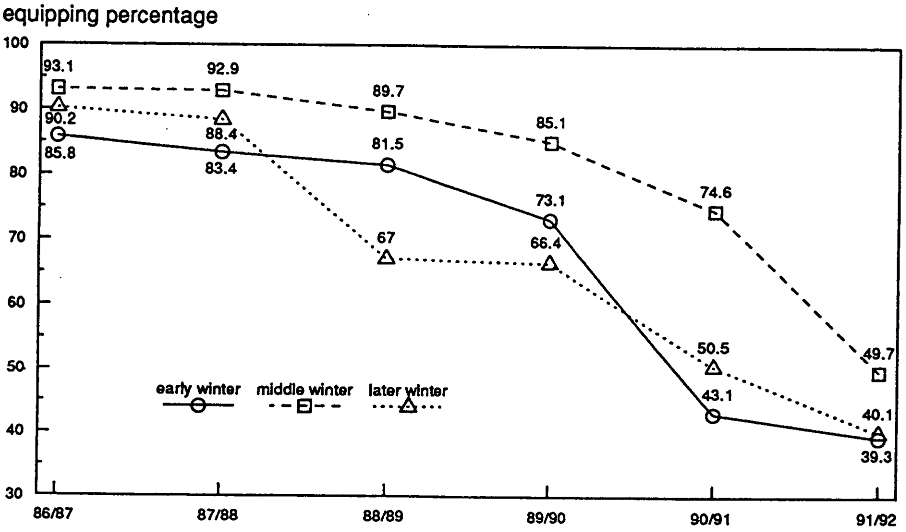

FIGURE 1 Percentage of studded tire use.

10 to 20 km (6.2 to 12.4 mi), and 32.8 percent commute farther than 20 km (12.4 mi).

Since the studded tire prohibition went into effect, 17.6 percent have shifted their modes of long-distance travel from car to another, 51.2 percent travel long distances by car with studless tires, and 26.2 percent travel long distances by car with studless tires and tire chains.

Of those surveyed, 68.7 percent believe that the performance of studless tires is more than 75 percent that of studded tires in soft compacted snow, and 55 percent believe that the performance of studless tires is less than 55 percent that of studded tires in slippery sections such as intersections.

Traffic Characteristics

The observation of traffic characteristics concerned overall travel time, overall travel speed, standing time, standing frequency, running speed, running space, and traffic accidents at the rush hours on snowy or frozen road surfaces in winter urban areas.

The observations were carried out six times by running tests on snowy or frozen road surfaces on six general national road routes going into the center of the city of Sapporo during the rush hour 7:30 a.m. to 9:30 a.m. for 1 hr.

The overall travel time was 15 percent longer in the 1990–1991 winter than in the 1989–1990 winter; the overall travel speed was 20 percent faster in the 1990–1991 winter than the 1989–1990 winter (Figure 2). The standing time in the 1990–1991 winter was 15 percent longer than in the 1989–1990 winter (Figure 3). The stopping frequency was 20 percent higher in the 1990–1991 winter than in the 1989–1990 winter.

In the suburbs of Sapporo, running speed and running space were also observed by means of a sensor wire and video camera on roads going into the suburbs. In this observation, differences of running speed and running space between tudded and studless tires were not observed.

Traffic accidents involving skidding vehicles with studless ires have been increasing. Figure 4 shows the number of such

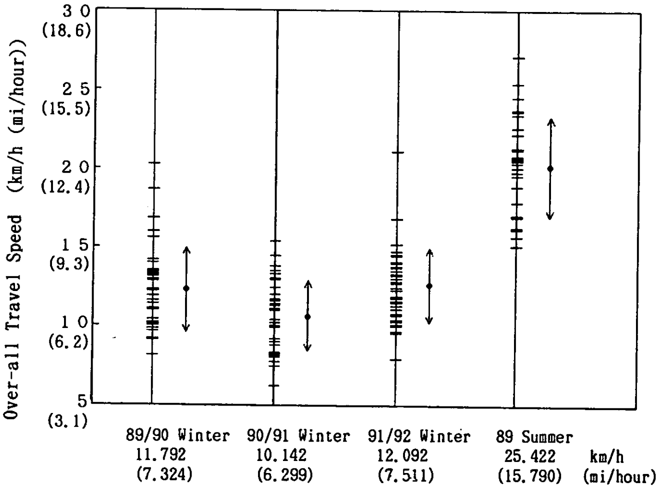

FIGURE 2 Overall travel speed.

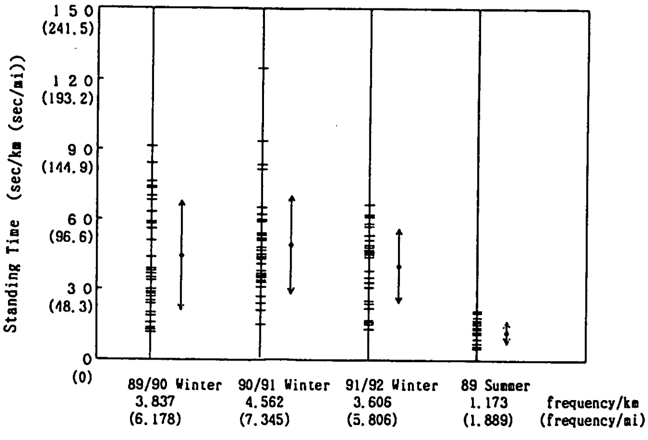

FIGURE 3 Standing time.

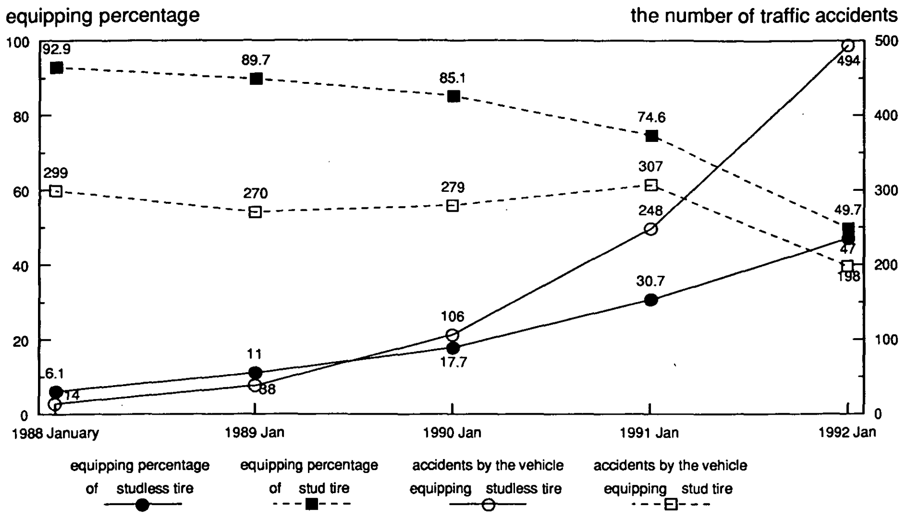

FIGURE 4 Number of accidents and percentage of tire use.

accidents and the percentage of studded and studless tire use in January. The growth in the rate of these accidents is larger than the growth in the rate of studless tire use.

Effects on Asphalt Pavement and Road Markings

The wear on asphalt pavement during winter was observed at a section on Route 36 at which pavement repair was completed in August 1989. This section's surface course is fine- and gap-graded asphalt concrete with rubber. The time it took for road markings to disappear was observed by diffuse reflectometer.

The worn amount of asphalt pavement during the 1990–1991 winter was 33 percent less than it was in the 1989–1990 winter (Figure 5). This drop was linked to the declining percentage of studded tire use. Therefore, we can assume that there is intensive interrelation between worn asphalt pavement and studded tire use.

The disappearance time of road markings in the 1990–1991 winter was shorter than it was in the 1989–1990 winter. The decreasing percentage of studded tire use also affected this aspect. Road markings are so thin and weak that they will disappear even if studded tire use becomes lower than ever.

Effects on Environment

We obtained results of the observation of the density of suspended particulate matter and the amount of fallen and piling dust from the Hokkaido prefectural government and Sapporo municipal government.

The lower the percentage of studded tires, the weaker the density of suspended particulate matter. The average density of suspended particulate matter is shown in Figure 6; according to the environmental standard, the average density of suspended particulate matter must be less than 0.1 mg/m^3 (0.12 moz/ft^3) in 24 hr or less than 0.2 mg/m^3 (0.25 moz/ft^3) each hour.

The Sapporo municipal government set up the amenity standard on the amount of fallen and piled-up dust. The municipal government has been observing it continuously since the early 1988 winter. According to the standard, the fallen and piled-up dust must be less than 200 mg/m^2 (8.44 moz/yd^2) or visibility might be hazy for 200 m (218.8 yd). The numbers of days and hours in which the standard was exceeded are shown in Tables 3 and 4; for example, the visibility standard was exceeded on 40 days during the 1988–1989 winter, but on only 3 days during the 1991–1992 winter. The decline of the percentage of studded tire use has certainly affected these numbers.

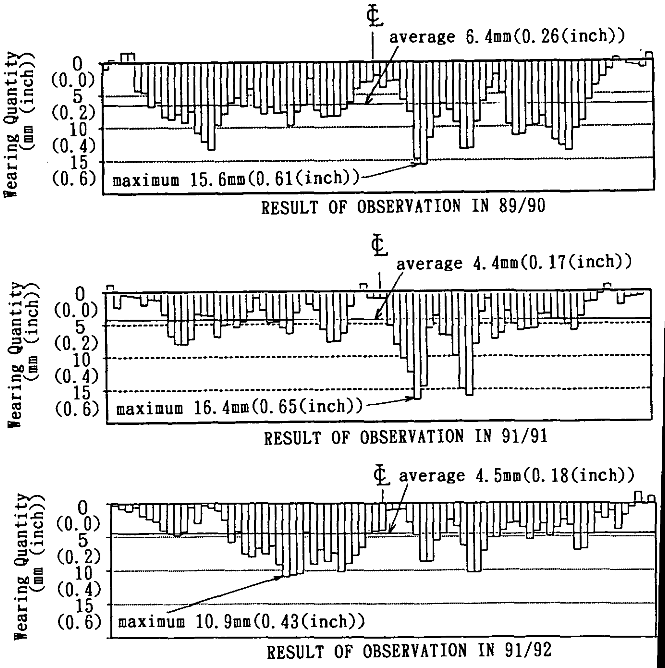

FIGURE 5 Pavement wear.

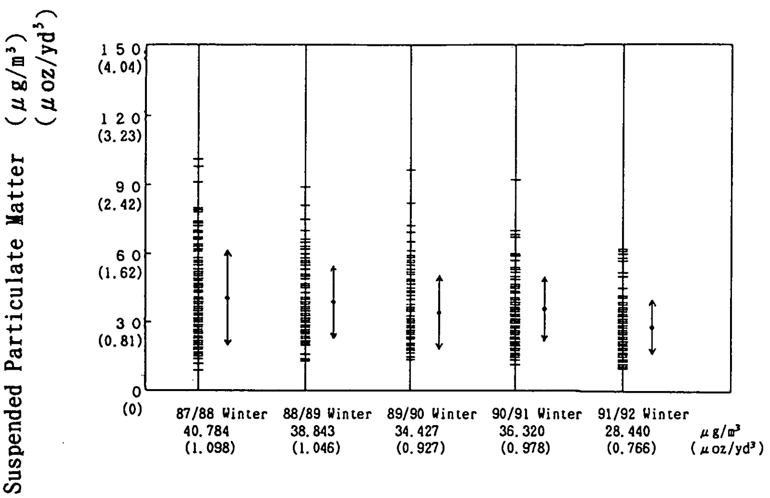

FIGURE 6 Density of suspended particulate matter.

TABLE 3 Number of Days Exceeding and Passing Amenity Standard

	88/89 Winter	89/90 Winter	90/91 Winter	91/92 Winter
Days over the amenity standard	40days	17days	10days	3days
Days clear the amenity standard	61days	84days	91days	98days

from November to December and from March to April 10

TABLE 4 Number of Hours Exceeding Amenity Standard

	November	December	March	April	total
88/89 Winter	21h	36h	102h	11h	170h
89/90 Winter	0h	11h	41h	0h	52h
90/91 Winter	0h	0h	19h	0h	19h
91/92 Winter	0h	0h	6h	0h	6h

CONCLUSIONS

It is certain that the use of studless tires in Japan will increase because tire manufacturers have stopped manufacturing and selling studded tires and the prohibition law has come into effect. However, people are still anxious about the starting and stopping performance of the studless tire. The improvement of the studless tire's performance and more careful control of snow and ice on the roads are expected. To ensure the safety of traffic in winter with the studless tire, not only should tire manufacturers better the studless tire's performance and road authorities improve their methods of snow and ice control, but drivers should adapt their techniques to the characteristics of the studless tire. This study will continue observations until the 1993–1994 winter, when the studless tire will be fully used.

PART 8

Visibility

Variation in Motorist Visual Range Measured by Vehicle-Mounted Sensor

MASAO TAKEUCHI, YOSHIFUMI FUKUZAWA, AND KEISHI ISHIMOTO

A motorist's visibility in blowing snow varies as topography, vegetation, road alignment and elements change along a highway. Traffic accidents caused by the rapid changes of visual range have been increasing in snowy regions of Japan. A vehicle-mounted visual range sensor composed of a light projector and receiver has been developed to investigate the variable visibility at the eye level of motorists. Continuously measured visibility traveling at 80 km/hr showed intense fluctuations changing from 1000 m to 40 m in a few seconds where the highway environment changes from a narrow road cut to an embankment with wide fetch distance. It is important for highway maintenance to detect the locations and conditions of the hazards along a highway beforehand in order to develop mitigation measures. The vehicle-mounted sensor can detect hazards along a highway while driving, and it is also useful for condition monitoring by maintenance patrols.

Highway closures caused by limited visual range and snowdrifts in blowing snow are a major concern in Hokkaido, the northernmost island in Japan. Proper use of snow control facilities such as snow fences, snow-break forests, and snow shelters has been improving visibility and reducing snowdrifts on highways, and the usage of these measures has been studied under the conditions of local topography, weather, and narrow highway right-of-way typical in Hokkaido (*1*). Optical guides such as snow poles, delineators, and roadside trees have been erected to improve traffic safety under conditions of poor visibility. Visual range monitoring has been developed and is operational on a few highways. Short-term predictions of hazardous conditions on highways are developed by using the real-time visual range and other weather data. As a result, the road closures have been decreasing each year. Beginning in 1992, the use of studded tires was restricted on the basis of seasonal and road surface conditions. However, a traffic accident involving 186 vehicles that occurred in a snowstorm on a slippery, snowy expressway between Sapporo and the Chitose airport in March 1992 pointed out the need for a higher level of snow control and technology on winter road maintenance during bad weather. On-board visibility monitoring might be a way to reduce such traffic accidents. The vehicle-mounted visual range sensor has been developed to detect such hazards and to investigate characteristics of visibility at a motorist's eye level.

VISIBILITY SENSOR

Instruments for measuring visibility in blowing snow were developed by Schmidt (*2*) and Tabler (*3*) in the United States and Takeuchi (*4*) in Hokkaido; research in both countries began in about 1971. These monitoring systems have been operational for traffic control on highways. Visibility (V) is defined in terms of the extinction coefficient (σ) on the assumption of uniformity of both light and atmosphere (*5*), that is,

$$V = 1/\sigma \ln 1/\varepsilon \quad (1)$$

where ε is the threshold brightness contrast (*6*) and σ is proportional to concentration of snow, fog, and other airborne particles at eye level. The attenuation of light in traversing distance L is given by the Bouger-Lambert law in the form

$$B = B_0 e^{-\sigma L} \quad (2)$$

where B is the brightness of light at L and B_0 is the initial brightness. From Equation 2,

$$\sigma = 1/L \ln 1/T \quad (3)$$

where T equals B/B_0 and B/B_0 equals the transmissivity. From Equations 1 and 3 visibility can be presented as

$$V = [L/(\ln 1/T)] \ln 1/\varepsilon \quad (4)$$

This is the theory of the transmissometer type of visibility sensor (*4*). The sensor was calibrated simultaneously by observing black square visual targets in snowstorms. The size of the visual targets was designed for a constant visual angle of 0.5 degrees from the observer. The transmissivity measured by the visibility sensor has been shown to compare closely to observed visual range except at visibilities less than 20 m where visibility falls below the theoretical curve (*4,7*). In the lower visibility range, the visible snow particles and their afterimages appear to reduce visibility. In addition, visibility observed by the eye is somewhat shorter than that observed from photographs and television. Because traffic essentially comes to a standstill at visibility less than 30 m, the deviation from the theoretical curve at lower visibilities is not important for practical use on highways. The transmissometer visibility sensor is the standard on highways in Japan today.

VEHICLE-MOUNTABLE VISUAL RANGE SENSOR

Because fixed visibility sensors are installed along the side of highways, their output is not necessarily representative of the

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visibility at motorist eye level, especially in blowing snow because of the vertical distribution of snow concentration and visibility. The vehicle-mountable visibility sensor has been developed to measure continuously the visibility at motorist eye level. The sensor is composed of a light projector and receiver, the optical axes of which cross as shown in Figure 1. The light from the projector is scattered by airborne snow particles in the sampling area, and some of the reflected light from the particles is measured by the receiver. Because the intensity of the received light is in proportion to the snow concentration, visibility is inversely proportional to the intensity. The light from the projector is regulated to make constant brightness and modulated at 1-kHz frequency to reduce the effect of outside light such as sunlight and illumination. Snow accretion on the lenses is prevented by transparent window covers. Because the brightness of the projected light can be reduced by the accumulation of dirt and other contaminants on the window covers and lenses, the brightness is automatically controlled to be constant by an optical guide element attached to the outside face of the lens. Temperature-sensitive elements such as the projector lamp and photo receiver are controlled by feedback from the light guide. The block diagram of the sensor is shown in Figure 2.

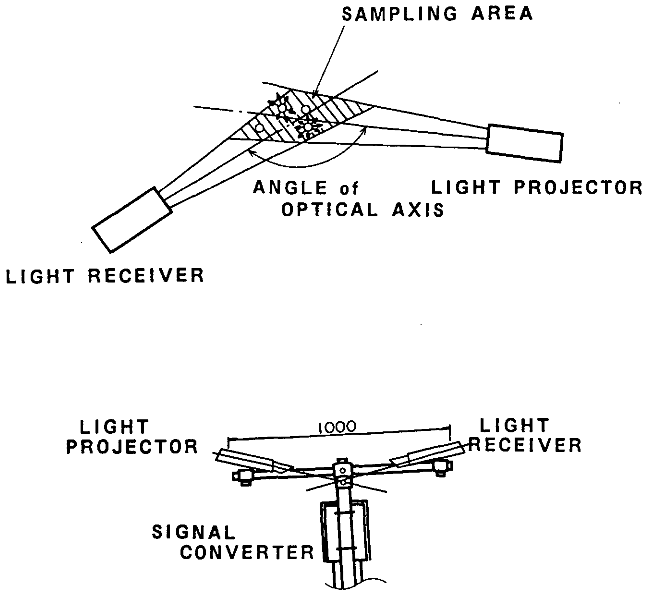

FIGURE 1 Infrared light from projector is scattered by snow particles in sampling area. Some reflected light from particles is received by receiver.

Determination of Optical Axis

The optical axis of the projector and receiver is adjusted at an angle to reduce the size of the sensor. A larger angle is desired to improve the accuracy for the limited dimension required for vehicle mounting. The output voltage in relation to the angle was measured in two conditions: blowing snow and fog. The voltage increases in proportion to the angle as shown in Figure 3. The output characteristic in relation to the angle is somewhat different in blowing snow than in fog. However, the output voltage is the same at the angle of 130 degrees. The 130-degree angle is suitable for measuring vis-

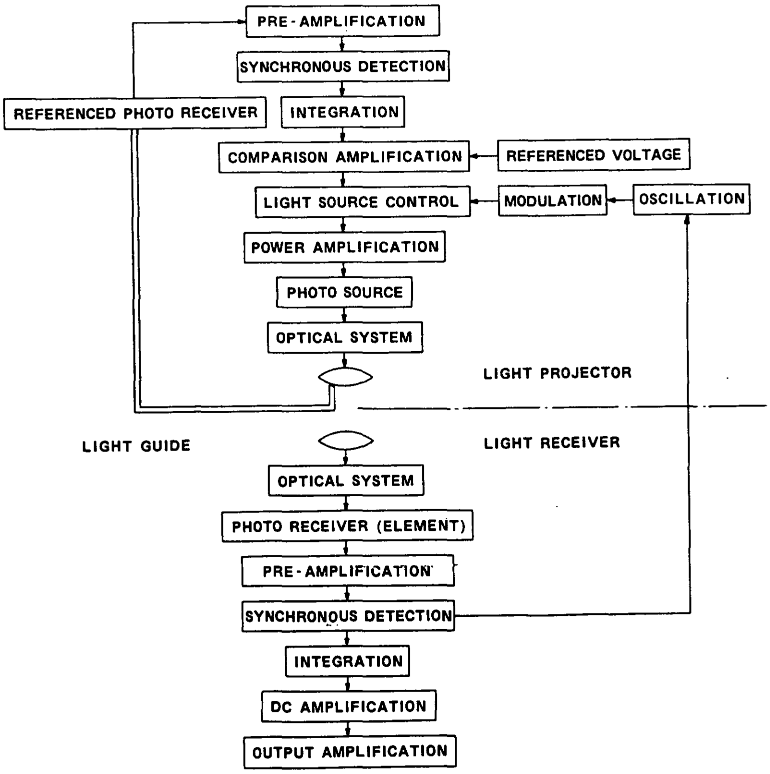

FIGURE 2 Block diagram of vehicle-mountable visibility sensor.

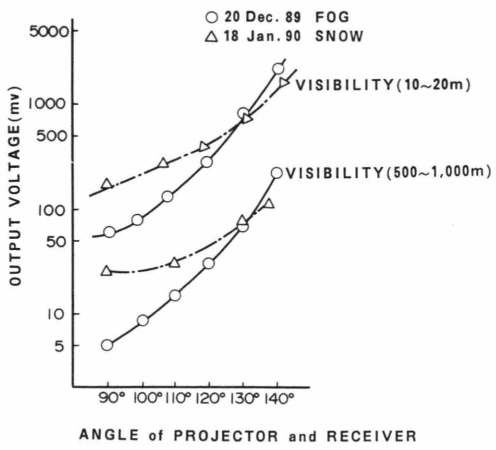

FIGURE 3 Relation between output voltage and angle of axis measured in snow and in fog.

ibility in blowing snow and in fog under comparable conditions (output voltage). Therefore, a 130-degree angle is chosen as the optical axis of the sensor.

Sensor Calibration

Field experiments were conducted to compare the vehicle-mountable sensor with the standard transmissometer visibility sensor (Figure 4). Data are recorded on a two-channel strip chart, with visibility measured by the transmissometer on the left channel and by the sensor on the right, as shown in Figure 5. The transmissometer visibility sensor measures transmissivity, and the sensor being calibrated measures the intensity of the reflection from snow particles in the sampling area. The transmissivity is in inverse proportion to the reflection. As visibility decreases, the trace on the left chart moves to the right while the trace on the right moves to the left. The recorded data in Figure 5 are examples measured in blowing snow with falling snow.

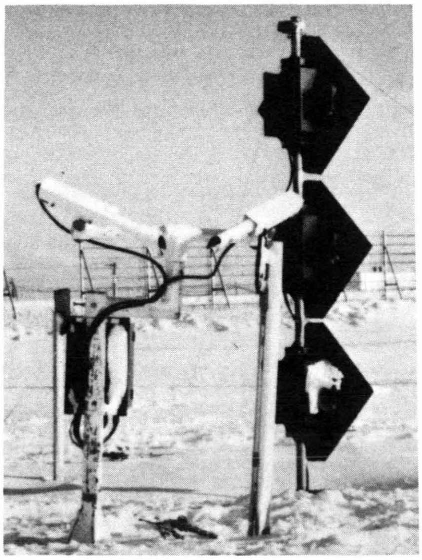

FIGURE 4 Field experiments for calibration of sensor against transmissometer.

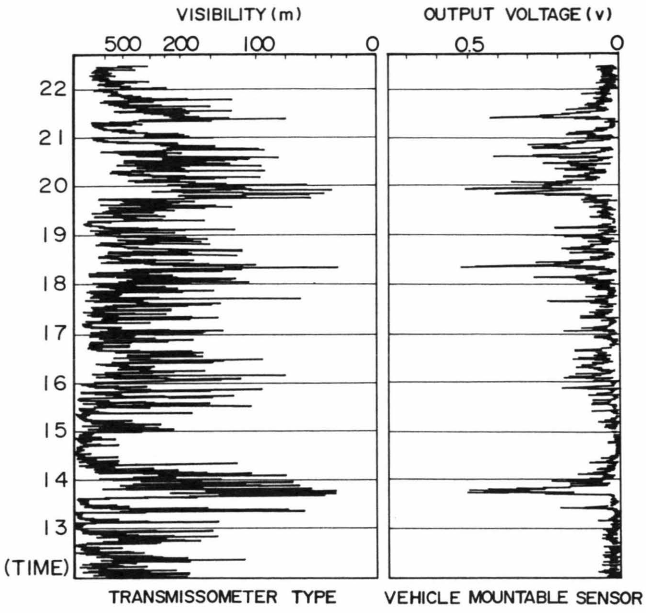

FIGURE 5 Example recorded from field experiment of two types of visibility sensor shows good correlation between them.

The output voltages of the sensor are closely related to the visibility measured by the transmissometer type of sensor as shown in Figure 6. The experimental equation of visibility measured by the sensor can be expressed as a function of output voltage. The vehicle-mounted sensor is therefore able to measure the real-time visibility at motorist's eye level while traveling.

VARIATION IN VISIBILITY

Visibility varies not only in blowing snow but also in falling snow and fog. However, the variation in visibility is most extreme in blowing snow: it causes traffic accidents, which are increasing and becoming serious problems especially on expressways in snowy regions of Japan. Visibility at a point varies because of changes wind speed and intensity of pre-

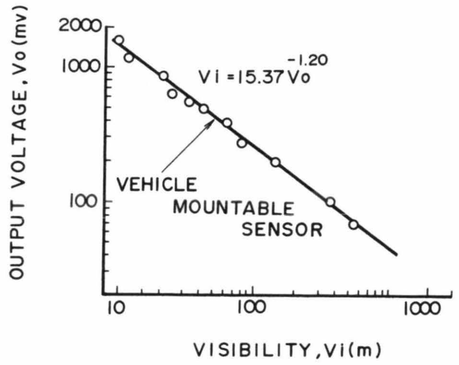

FIGURE 6 Comparison of transmissometer.

cipitation. However, the variation becomes even greater when moving, because of changes in the surrounding topography, vegetation, and road geometry. Motorists encountering whiteout conditions without warning are at high risk of becoming involved in accidents. It is important for snow-control operations as well as for traffic safety to know how visibility varies with location.

Visibility was measured continuously by the vehicle-mounted sensor while traveling along a highway. The sensor was fixed to the front bumper of the vehicle at a 1.2-m height as shown in Figure 7; 1.2 m is the typical motorist's eye level for standard Japanese passenger cars. The data were sampled at 20 per second and recorded on a digital recorder. The measurements were made at 80 km/hr on the 98.6-km-long expressway between Sapporo and Fukagawa. An example of the visibility measured in blowing snow along the expressway is shown in Figure 8. There are two places, noted at the 91.3- and 92.5-km posts in Figure 8, where visibility changed from 1000 m to 40 m in seconds. At both locations the topography changes from forest-covered cuts to bare embankments, resulting in whiteout conditions. Similar variations in visibility in blowing snow were associated with changes in vegetation and road elements along the highway.

Another type of visibility problem is the poor visibility in the whirl of snow generated by high speed vehicles on snow-covered highways. Driving the measurements reported here, the observer encountered snow whirls in the wakes of passing vehicles. The variation in visibility caused by passing vehicles is shown in Figure 9. The poorest visibility in Figure 9 was caused by the passage of a large truck. The variation in visibility is related to the cycle of the wake. During the measurements, visual conditions were monitored simultaneously by a video tape recorder located alongside the vehicle driver. The vehicle driver's perception of visibility conditions and the record taken by video tape recorder agree well with those recorded by the sensor. Because the sensor is installed in front of the vehicle and the sampling area is situated ahead of the sensor, the vehicle generates no turbulence effect during measurement. The resulting measure of visibility did not show any sensitivity to vehicle speed. However, there could be such an effect if there is a strong cross-wind relative to the direction of travel.

FIGURE 7 Sensor mounted on vehicle for observation; sampling area is set at 1.2 m height from road surface.

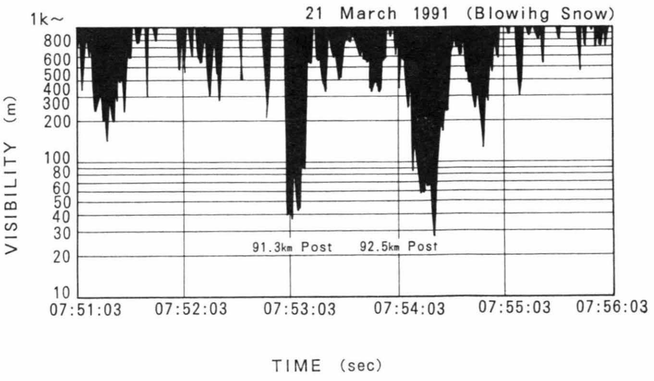

FIGURE 8 Example of variation in visibility measured by sensor traveling at a speed of 80 km/hr along expressway in blowing snow. Two locations where visibility fell below 100 m were measured where conditions changed from forest-covered cuts to bare embankments.

DISCUSSION OF RESULTS AND CONCLUSION

The vehicle-mountable visibility sensor was developed to measure continuously the visibility at motorist eye level while traveling along highways. Several runs of experimental mea-

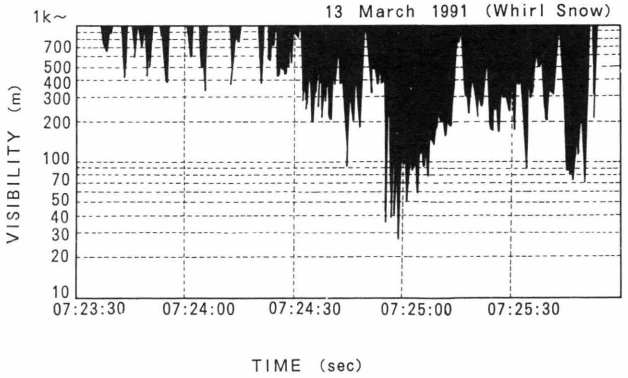

FIGURE 9 Example of reduced visibility caused by passing vehicles in fine weather.

surements the along the 98.6-km expressway show that the sensor is good enough for operation in any weather. Observed variations in visibility in blowing snow were caused by changes in surroundings along the expressway. That the observed visibility changed from 1000 m to below 40 m in a short time indicates that there is high potential for traffic accidents at such places. It would be difficult for motorists to react to such sudden changes in visibility, especially in slippery road conditions. It is very important for traffic safety to improve poor visibility by properly located snow-control measures or warning lights. The sensor is useful for quickly detecting hazard zones requiring protection from blowing snow. Both large- and small-scale variations of visibility would cause traffic accidents for vehicles traveling at high speed on slippery snow-covered roads. Although small-scale variations in visibility may not have an observable impact on traffic safety, information on proper speed and spacing provided to motorists could improve highway safety in blowing snow. Installing the sensor on patrol cars will provide motorists such information in the future.

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Visibility Reduction Caused by Snow Clouds on Highways

KEISHI ISHIMOTO, YOSHIFUMI FUKUZAWA, AND MASAO TAKEUCHI

Reduced visibility for drivers due to snow and its relationship to safe highway operations have been major concerns of road authorities. Visibility even in calm weather is reduced by airborne snow in clouds created by moving vehicles. A study was conducted using a reflector-type visibility sensor placed on a road median to observe the reduction of visibility. A snow-particle counter was mounted on the roof of a vehicle to measure the size of entrained airborne snow particles while driving through a snow cloud. As the temperature drops, cohesion of snow particles decreases and they are easily blown up from the road surface. Visual range was found to change from hundreds to tens of meters in a short time when a snow cloud formed. Collector snow fences reduce the dissipation of vehicle-generated snow clouds on highways. Poor visibility continued longer in sections with snow fences than in areas with no fences. The number of small snow particles is greater in a vehicle-generated snow cloud than in wind-blown snow. Large vehicles cause large snow clouds, and the extent of a snow cloud depends on vehicle size. Snow particles in a vehicle wake are lifted about to the level of the vehicle's roof. In contrast, average visibility is improved and fluctuation of visibility on a highway is mitigated with collector snow fences in blowing snow conditions. However, a snow fence leads to decreased visibility in snow clouds generated by vehicles. The characteristics of visibility in blowing snow and in vehicle-generated snow clouds on highways are presented.

As the speed at which one drives a vehicle increases, more visual information is needed. However, dynamic visual acuity decreases as speed increases, causing severe problems of poor visibility. Dynamic visual acuity—the ability to recognize moving objects—also declines with age. With an increase in the population of elderly drivers, it is important to ensure that enough visual range is available.

Powdery snow on a highway is blown up in the wake of vehicles driving at high speeds even when the weather is calm and the sky is clear. Studies of the characteristics of visibility due to blowing snow have been carried out in the past. Snow break forests, snow fences, and drift-free road design are countermeasures against blowing snow. However, visibility in snow clouds of vehicles has not previously been studied. In this research, visibility reduced by vehicle-generated snow clouds was observed on in-service highways, and the height and duration of snow clouds leading to poor visibility were analyzed with regard to vehicle size, speed, and highway design. Threshold levels of snow entrainment in the wake of vehicles were studied at different air temperatures and precipitation rates.

INSTRUMENTATION

In this paper, the term "large vehicles" refers to trucks weighing 8000 kg and buses with passenger capacity of 11 or more. All other vehicles are considered small. The driver's eye level of a small vehicle is 1.2 m above the road surface. Visibility was observed using a reflector-type visibility sensor set on the median of a highway [National Highway Route (NHR) 12]. The visibility sensor was 1.2 m above the highway surface.

The transmissometer-type visibility sensor has a well-established theoretical background (*1*). A comparison of calculated visibility with visual range as sensed by the human eye shows that the transmissometer sensors can be used to measure visibility in blowing snow. The output voltage (V_O) from a reflector-type visibility sensor was compared with the visibility measured with a transmissometer-type visibility sensor (Figure 1) (*2*). Visual range (V) is calculated by Equation 1:

$$V = 26.33\, V_O^{-0.87} \quad (1)$$

THRESHOLD OF SNOW IN WAKE OF VEHICLES ON HIGHWAYS

The cohesion of snow particles on a road surface is destroyed by the mechanical action of vehicle tires and the shear stress exerted in the wake by moving vehicles. Figure 2 shows the threshold condition of blowing snow with precipitation (*3*). Bonding of snow particles tends to increase with temperature. Figure 3 shows the reduction of visibility by vehicle-generated snow clouds in relation to temperature and precipitation. Precipitation increases visibility attenuation in the wake of moving vehicles. As the temperature drops, the cohesion of snow particles decreases, causing them to be blown up from the road surface more readily. A snow cloud generated by a large truck in the passing lane is shown in Figure 4. In this case, the wind was calm soon after precipitation ended, the sky was clear, and the air temperature was −4°C. Although the road had been plowed and the travel lane was mostly bare, a little snow still remained on the passing lane.

The monthly mean air temperature in Hokkaido from December 1 to April 1 typically ranges between −10 and 0°C. The threshold of snow in the wake of vehicles depends on air temperature. Besides real-time meteorological data, forecasts for precipitation and air temperature are available from online meteorological services. If one knows how the threshold for snow entrainment in vehicle wakes varies with air tem-

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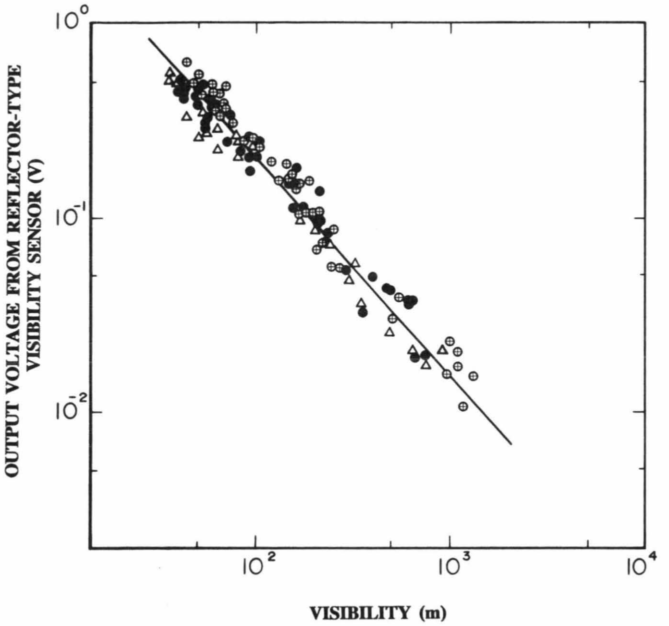

FIGURE 1 Comparison of transmissometer-type visibility output to voltage of reflector-type visibility sensor; $N = 109$, $R = .974$.

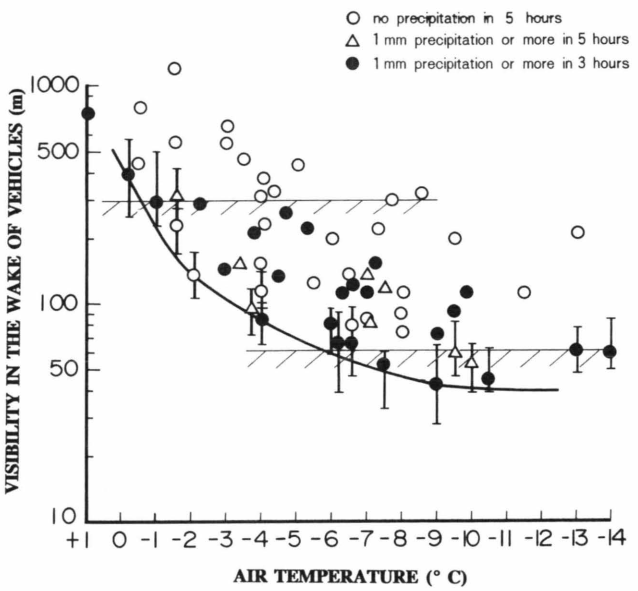

FIGURE 3 Threshold for reduced visibility caused by snow in vehicle wake as a function of temperatures and precipitation rates.

perature and precipitation, it is possible to provide the motoring public with information on adverse conditions caused by vehicle-generated snow clouds.

CHARACTERISTICS OF VISIBILITY ATTENUATION CAUSED BY VEHICLE-GENERATED SNOW CLOUDS

Visual information is indispensable for drivers and becomes more critical as vehicle speed increases. Blowing snow and fog have long been considered the greatest causes of reduced visibility. However, vehicle-generated snow clouds are another important cause of poor visibility. Clouds touching the ground is one type of fog; it causes poor visibility on highways in mountainous areas. The degree of visibility fluctuation due to fog is less than that caused by blowing snow. Figure 5 shows the visibility under foggy conditions observed on a Nakayama mountain pass on NHR 230. Figure 6 shows an observation of reduced visibility due to snow in the wake of a vehicle. Visibility was reduced instantly from more than 1000 to fewer than 100 m. After a vehicle passed the observation point, visibility improved in tens of seconds. Figure 7 shows an observation of blowing snow in Ebetubuto, on NHR 12, where visibility and wind speed changed rapidly.

Visibility is reduced by dispersed snow in the wake of vehicles, not only in blowing snow but also in clear and calm weather. Figure 8 shows the distribution of snow particle sizes on a highway in blowing snow (*left* and *middle*) and vehicle-

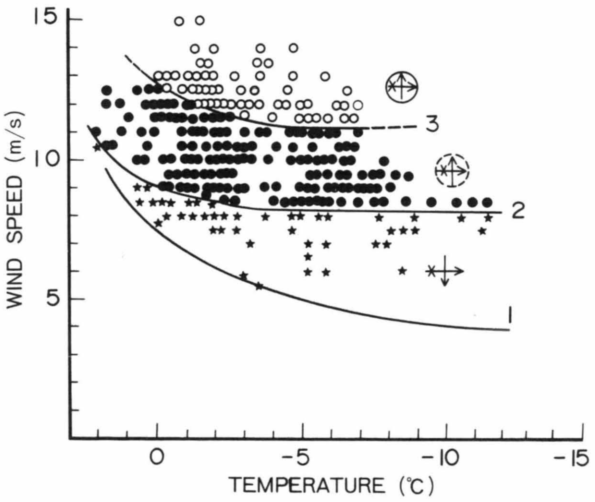

FIGURE 2 Threshold wind speed for blowing snow in relation to temperature.

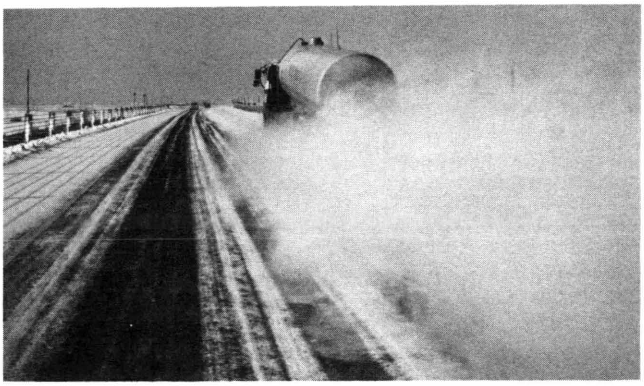

FIGURE 4 Snow cloud generated by large truck on a highway.

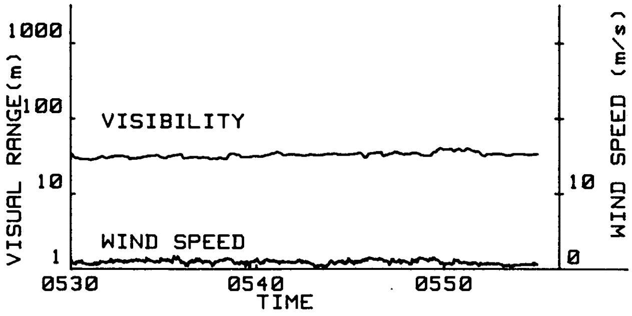

FIGURE 5 Visibility in fog on NHR 230 (Nakayama mountain pass), March 24, 1989.

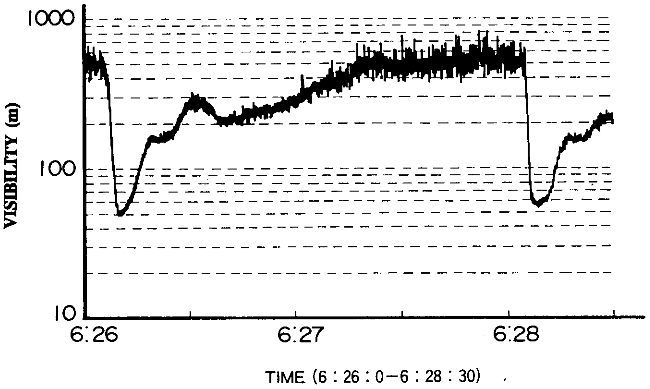

FIGURE 6 Visibility in snow cloud in wake of large vehicle on NHR 12 (Ebetubuto), February 6, 1991.

generated snow clouds (*right*) (*4*). In the vehicle-generated snow clouds, the number of smaller snow particles was greater than that for blowing snow. No particle larger than 250 μm was found.

The wake of a moving vehicle in still air was investigated by Eskridge et al. to predict the dispersion of air pollution along the highway (*5*). They reported the velocity deficit and turbulent energy fluctuation when the wind speed was much less than vehicle speed. The height of the wake (h) behind a vehicle can be derived as

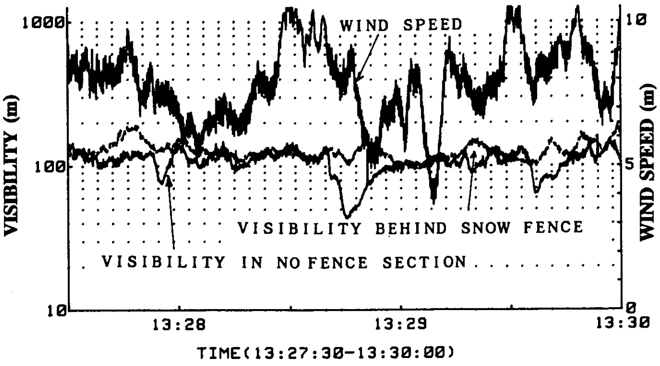

FIGURE 7 Visibility in blowing snow on NHR 12 (Ebetubuto), showing effect of snow fences, February 16, 1991.

$$h = \alpha \gamma Ah(Xh)^{1/4} \qquad (2)$$

Suppose a vehicle moves in the X-direction, where A is the cross section of a vehicle, h is the height of a vehicle, and γ is a constant approximately equal to von Karman's constant. Equation 2 is derived theoretically. Snow particles are heavier than the gas used as tracer, and the dispersed area of snow in the wake of a moving vehicle is supposed to be within h.

INFLUENCE OF ROAD STRUCTURES AND VEHICLE TYPES TO SNOW CLOUDS

The diffusion of snow in the wake of vehicles is affected by the geometry of the road and nearby structures. The duration of snow in the wake of vehicles is defined as the period from the time when visibility is reduced below 300 m to the time when visibility recovers to 300 m. Visibility changed by snow in the wake of a large truck showed a duration longer than 60 sec on NHR 12 at a location along a river embankment with a 5-m-high snow fence 10 m upwind. At this location, the embankment and snow fence delayed the diffusion of snow in the wake. For comparison, the visibility measured by a

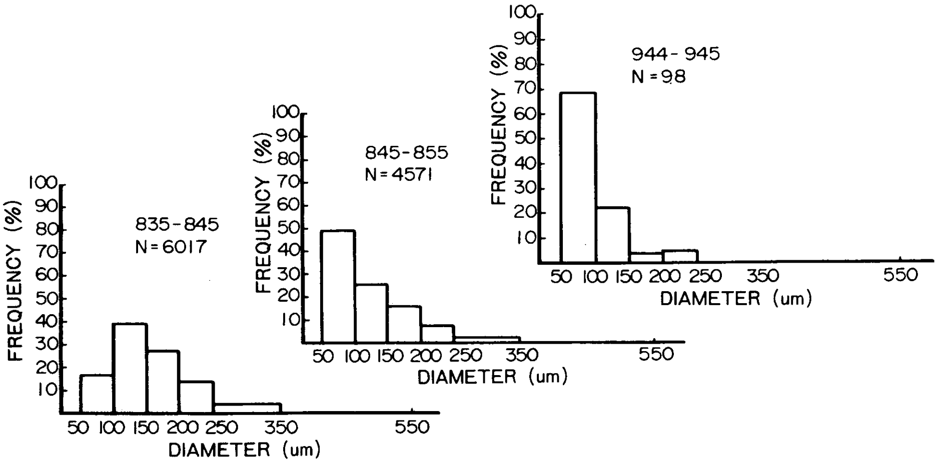

FIGURE 8 Snow particle size distribution on a highway in blowing snow (*left* and *middle*) and in snow cloud (*right*).

reflector-type sensor on the median on NHR 40 shows the duration of reduced visibility to be only about 10 sec (Figure 9). At this location, snow particles in vehicle-generated snow clouds are dispersed more quickly. Figure 10 shows the cross sections of NHRs 12 and 40. During both observations the air temperature was −9.2°C and the wind velocity was below 1 m/sec.

Visibility reduced by snow in the wake of small vehicles was observed on NHR 40 at the same time as the measurements shown in Figure 11 (air temperature of −9.6°C and mean wind speed of 1.1 m/sec). The duration of snow clouds was about 5 sec at the observation point. Minimum visibility was 40 percent greater than that associated with the snow cloud generated by a large vehicle. The larger wakes formed by larger vehicles cause poorer visibility for a longer time than those formed by smaller vehicles.

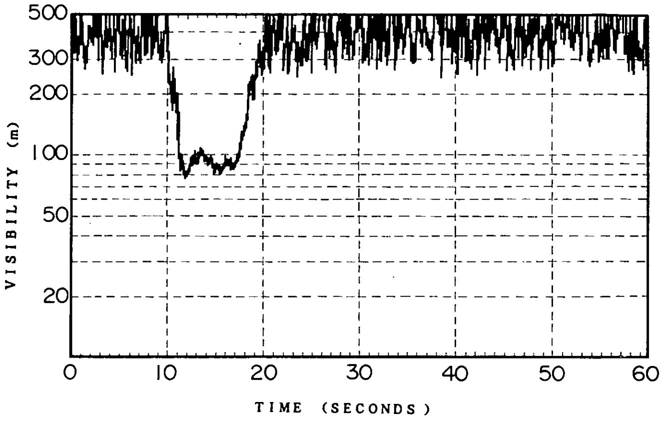

FIGURE 9 Visibility in the wake of large vehicle on NHR 40 (Kaigen).

CONCLUSION

Snow problems such as road closures due to blowing snow have decreased. We can drive at relatively high speeds even during the snow season today. However, traffic accidents during the snow season tend to involve many vehicles. The major cause of such accidents is the diminished visibility due to blowing snow or vehicle-generated snow clouds. Dynamic visual acuity decreases at high speeds and with age. Improvement of visibility in snow conditions is becoming more important with the growing number and proportion of elderly drivers.

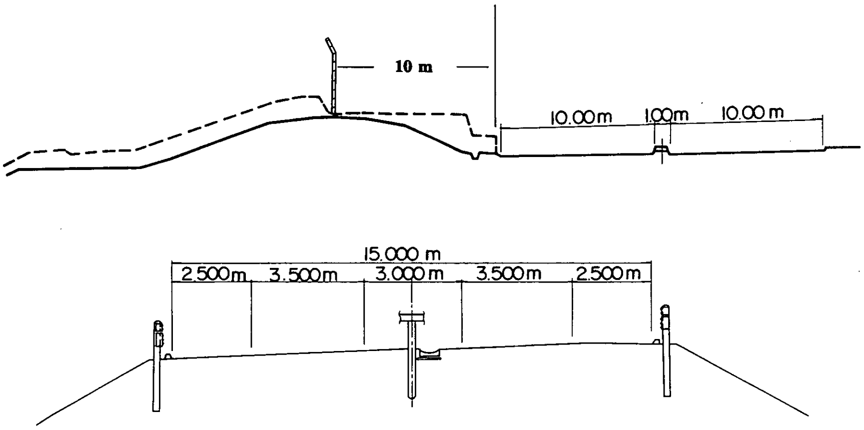

FIGURE 10 Cross sections of NHRs 12 (*top*) and 40 (*bottom*).

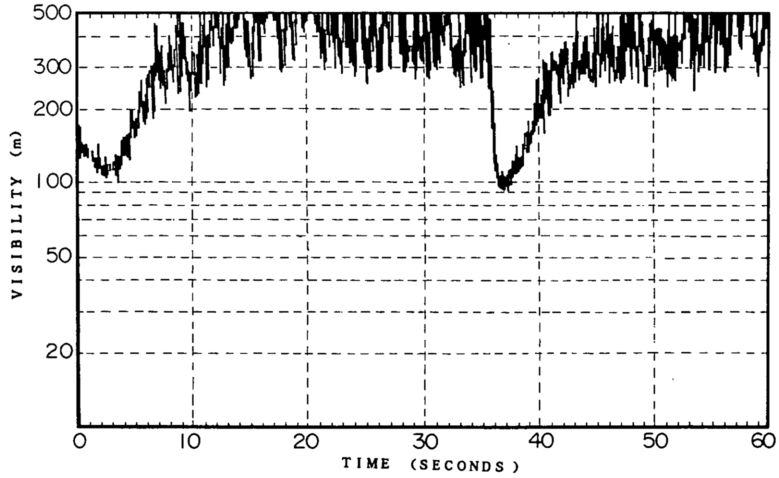

FIGURE 11 Visibility in wake of small vehicle on NHR 40 (Kaigen).

Countermeasures against blowing snow can aggravate the visibility problem caused by vehicle-generated snow clouds. Further studies are under way to determine ways to reduce the visibility problems caused by moving vehicles.

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PART 9

Road Weather Systems

Cost-Effective Snow and Ice Control for the 1990s

JOHN E. THORNES

Road weather information systems (RWISs) are now widely used operationally by road masters to determine when to use deicing chemicals on roads. Data from such systems can also be used to assess the cost-effectiveness of RWISs. To account for the variation in winter weather from year to year (temporal) and across an area (spatial), three winter severity indexes are examined that can be compared with winter maintenance expenditures.

The worldwide introduction and use of road weather information systems (RWISs) has continued unabated since the last Standing International Road Weather Commission conference in Tromsö, Norway, in 1990. Many systems are also coming to the end of their 10-year design lives and are being upgraded or replaced. Table 1 shows the latest estimated state of play in the number of outstations in each country, the amount of thermal mapping conducted, and whether there is a computer link to weather services.

This paper will attempt to assess whether the cost-effectiveness of snow and ice control has increased for those authorities that have introduced RWIS, and whether the situation is likely to change in the 1990s.

The decision to install an RWIS will not be discussed in detail here; it is assumed that most highway authorities will have installed systems by the year 2000. The COST 309 Final Report concludes that "despite relatively high installation costs the implementation of a road weather system will soon reap benefits in terms of better safety, long term cost savings, optimum response to critical weather situations and minimising of environmental damage" (*1*,p.145). The draft SHRP H207 final report concludes that

> every SHA (State Highway Authority) which spends more than $1 million annually for snow and ice control should consider acquiring RWIS to assist in snow and ice control.
>
> An RWIS which blends data inputs from sensors and road thermography into detailed (road weather) forecasts tailored to the needs of a snow and ice control manager offers the opportunity for a significant return on the investment at [benefit/cost ratio] close to 5, yet with significantly improved level of service on the roads and greatly decreased frequency of decision errors. (*2*)

This cost-benefit ratio is identical to that found in Finland as reported in the COST 309 report: "So the cost/benefit ratio is about 1/5 on Kymi road district. In respect of the climate and traffic the Kymi road district represents typical road district in Finland" (*1*,p.90).

RWIS can be used in two main ways: to aid operational decisions on a night-by-night basis and to help management appraisal of overall effectiveness at the end of winter. Most RWISs are installed for operational purposes, and little attention has been paid to management appraisal of their effectiveness. Sophisticated software for operational purposes is available with all systems, but little software has been developed for management; most RWISs have archive facilities, but all too often these facilities are not used properly and data are just filed away on disk. This paper examines what climatological information produced by RWIS is likely to be useful for assessing the severity of a winter, the cost-effectiveness of an RWIS, and the accuracy and effectiveness of an RWIS weather-forecasting service.

WINTER SEVERITY INDEX

Climate variability means that no two winters are ever the same. The main weather parameters that affect winter maintenance are road-surface temperature (below 0°C), precipitation (especially snow), and humidity (frost formation). In an ideal world these parameters could be used to assess the severity of a winter. Unfortunately, road-surface temperatures have been measured only in recent years and climatologists like to have a 30-year average with which to compare a given winter. Air temperature therefore must be used if a long-term average is required, such as 1961–1990. Humidity is not measured reliably at many sites, and data are not readily available in most countries. Data on depth of snowfalls and the number of days with snow cover are available in most countries.

The following winter indexes have been used for the management of snow and ice control. All of them normally consider the period of November 1 to March 31 (151 days, or 152 in a leap year) as winter.

Hulme Index

The Hulme index (*3*) has been modified by Thornes (*4*) to show the variations in winter index about the average, which is set at zero. Thus negative scores represent a colder-than-average winter, and positive scores, a warmer-than-average winter. This is designed to be simple for engineers and politicians to understand. The index is calculated using the following formulae:

$$WI = (10 * T) - F - (18.5 * S)^{0.33} \pm C \qquad (1)$$

---

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TABLE 1 Worldwide RWIS Installation

Country	Thermal Mapping Km	Road Weather Stations No.	Computer Weather Network
Europe			
Austria	0	280	none
Belgium	0	0	none
Denmark	4000	220	yes
Finland	500	150	yes
France	750	200	yes
Germany	200	160	yes
Holland	3000	153	yes
Italy	0	30	none
Luxembourg	200	20	none
Norway	3500	50	yes
Spain	0	0	none
Sweden	12,000	550	yes
Switzerland	100	200	yes
United Kingdom	38,000	520	yes
North America			
U S A	1000	350	yes
Canada	400	10	yes
Others			
Japan	70	2	none
TOTALS	------ 63,720	----- 2,895	

where

T = mean maximum air temperature for period considered,
F = total number of ground frosts (grass minimum temperature below 0°C),
S = total number of days with snow cover at 9:00 a.m., and
C = constant such that the climate averaged WI is zero.

Figures 1 through 4 show the index and its parts for Manchester airport in England. It can be seen that four of the past five winters have been warmer than average for the 1961–1990 period.

Figure 5 shows how Manchester's winter index correlates well with estimates of rock salt use in Great Britain during 1975–1991. One might envisage that if RWISs are effective, there should be a detectable shift to the left of this line of best fit. More cold winters are required before any hypothesis can be tested. Figure 6 shows such a shift in the county of Cheshire, England. Salt use is plotted against the Manchester winter index for 5 years before and 5 years after an RWIS

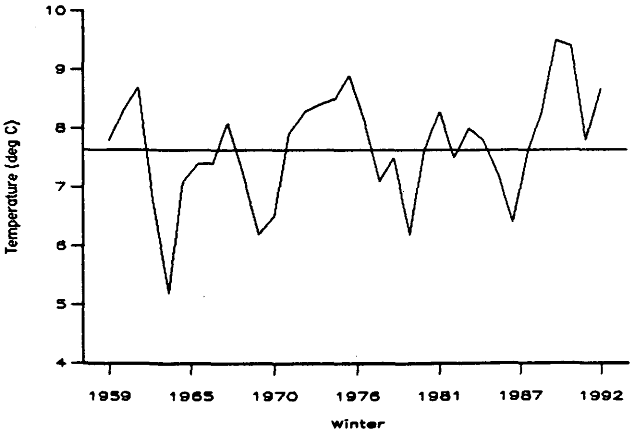

FIGURE 1 Mean maximum temperature, November 1 to March 31, Manchester airport.

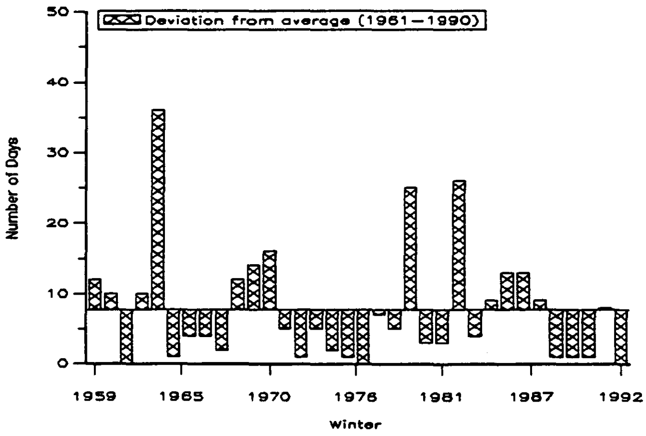

FIGURE 2 Number of days of snow cover at 9:00 a.m., Manchester airport.

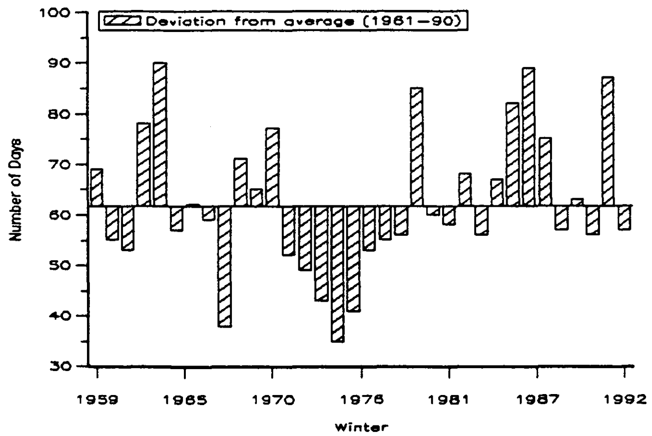

FIGURE 3 Number of ground frosts, Manchester airport.

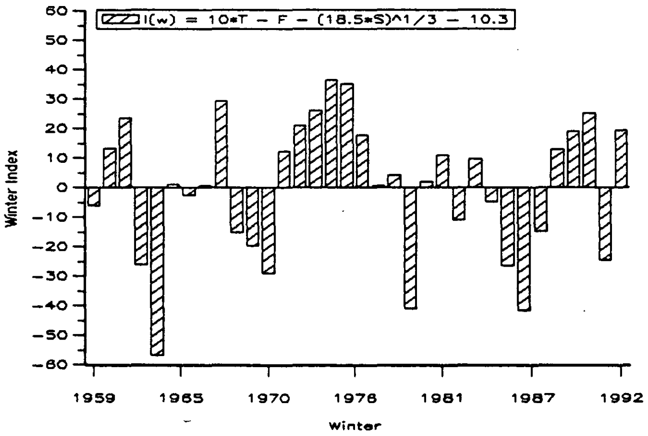

FIGURE 4 Standardized Hulme winter index, Manchester airport.

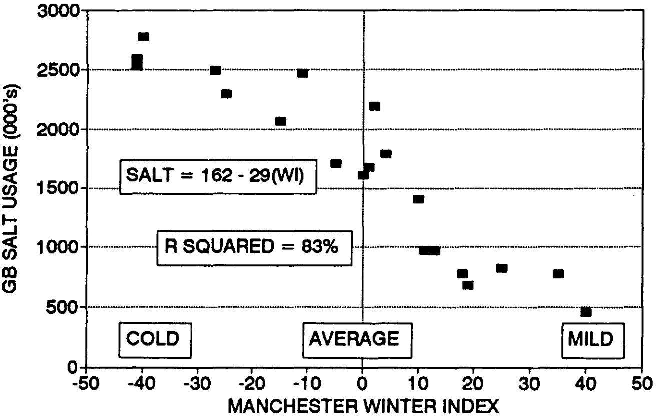

FIGURE 5 Great Britain rock salt use versus Manchester winter index, 1975–1991.

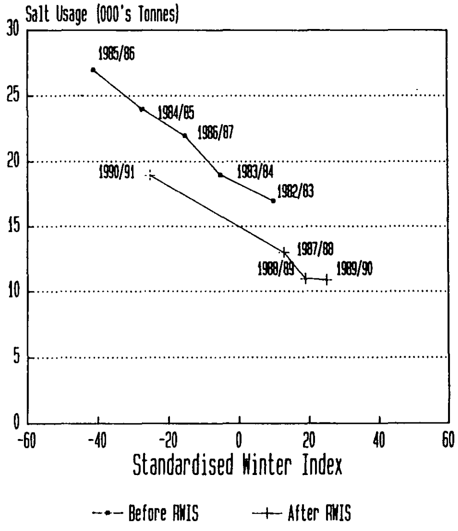

FIGURE 6 Reduction in salt use using RWIS, Cheshire County Council.

was installed. An approximate 20 percent saving in salt use can be seen for a given winter severity (*5*).

SHRP Winter Index

A new winter index has been developed by the University of Birmingham for the SHRP H-207 research program (*2*). It was designed to be a simple objective indication of winter severity with a value ranging from –50 (most severe) through 0 (not too severe and mean level of maintenance) to +50 (warm and no need of maintenance). It has general applicability for other countries. Thus the new winter index is considered to be based on the following parameters for the period from November 1 to March 31:

- Temperature index (TI) is 0 if minimum air temperature is above 0°C, 1 if maximum air temperature is above 0°C and minimum air temperature is at or below 0°C, and 2 if maximum air temperature is at or below 0°C. The average daily value is calculated for the period considered.
- Snowfall (S) is the mean daily value in millimeters.
- Number of air frosts (N) is the mean daily values of number of days with minimum air temperature at or below 0°C ($1 \leq N \leq 0$).
- Temperature range (R) is the value of mean monthly maximum air temperature minus mean monthly minimum air temperature in degrees Celsius.

These four parameters are summed from daily records and then averaged for each month to eliminate the influence of month length (number of days). The new winter index is thus expressed as

$$\mathrm{WI} = a(\mathrm{TI})^{0.5} + b \ln (S/10 + 1) + c[N/(R + 10)]^{0.5} + d \qquad (2)$$

In Equation 2, the terms including the temperature index and snowfall are expected to make the greatest contribution to the winter index. Temperature range has a similar but inverse distribution to relative humidity (*6*), and in the index it is used as an effective indication of atmospheric humidity. Therefore, the third term in Equation 2 is considered to be an expression of frost likelihood.

There are different ways to determine the coefficients of such a winter index formula. The easiest, most common way is to assign appropriate weights to each term, for example,

1. Term: weight
2. TI: 35 percent
3. Snowfall: 35 percent
4. Frost: 30 percent

The nonequal weight on the third term means that the term is considered to be of slightly less significance to maintenance costs. These weights can be adjusted to suit a particular climate.

The absolute contribution of each term to the winter index is minimum when the temperature index, snowfall, and frost are of minimum value: that is, WI = 50 when TI, S, and N are zero (therefore $d = 50$). It is maximum when the temperature index, snowfall, or frost reaches its maximum. Referring to the U.S. climate data (*5*) and considering potential application of the index in cost analysis, the coefficients of Equation 2 are derived by taking into account the critically significant level of each parameter to winter maintenance cost: WI = −50 when TI = 1.87, $S = 16.5$, $N = 1$, and $R = 1$, solving a set of simple equations such that

$$-50 = -35 - 35 - 30 + 50$$

Thus

$-35 = a(\mathrm{TI})^{0.5}$, so when TI = 1.87, $a = -25.58$;

$-35 = b \ln (S/10 + 1)$, so when $S = 16.5$, $b = -35.68$; and

$-30 = c[N/(R + 10)]^{0.5}$, so when $N = 1$ and $R = 1$, $c = -99.5$.

Equation 2 is therefore written as

$$\mathrm{WI} = -25.58(\mathrm{TI})^{0.5} - 35.68 \ln (S/10 + 1) - 99.5\,[N/(R + 10)]^{0.5} + 50 \qquad (3)$$

Figure 7 shows the spatial distribution of the SHRP index averaged over 1950–1951 to 1985–1986. The index ranges from +40 in Florida, South Texas, and coastal California to −40 in the far Northeast. A full discussion of the spatial and temporal values of the index is given in the SHRP final report (*2*).

If the index is to be of use to road masters, it must be compared with the variation in costs of snow and ice control. Figure 8 shows how cost, in dollars per centerline mile, correlates with the index for each state (data were available for only 40 states). It can be seen that there is an inverse relationship (when cost is logged) and that the state with the highest costs and lowest index is Alaska. Colorado, Minnesota, and Washington have similar costs but very different winter indexes. This difference is due to many factors such as maintenance policy, traffic density, and topography. Population density can be used to explain more of the variance: the roads in a densely populated state have a greater traffic

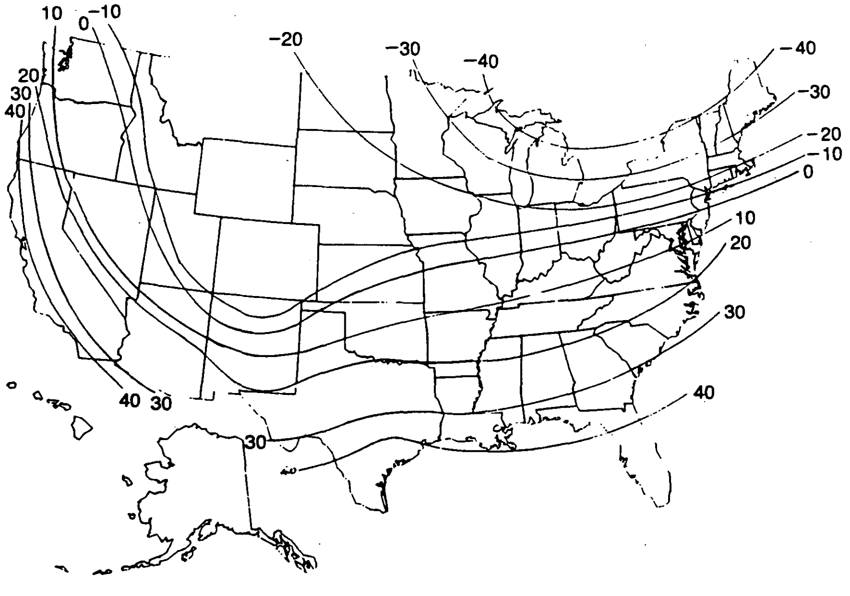

FIGURE 7 Distribution of SHRP winter index across United States, averaged over 1950–1951 to 1985–1986.

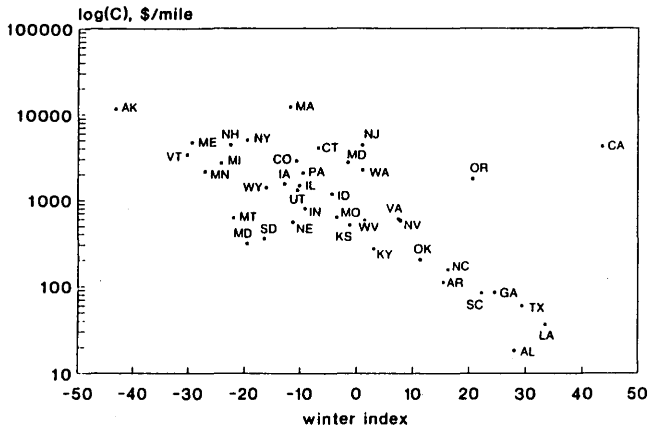

FIGURE 8 Correlation of cost of snow and ice control in each state ($/centerline-mi) with SHRP winter index.

flow and often more priority is given to snow and ice control. Using stepwise regression, the following equation is obtained:

$$C = 632.3 + [7.3 * P * \exp(-0.09 * \mathrm{WI})] - [(0.19 * \mathrm{WI})^3/(1 + P)] \quad (4)$$

where P is the population density in persons per square kilometer. This equation explains 84 percent of the variation in maintenance costs. Thus if a state is spending significantly more than predicted by Equation 4, cost savings are likely. The winter index could be used to see if the introduction of a RWIS is reducing costs below those predicted by Equation 4.

The winter index can also be used at the district level to monitor costs and salt and sand consumption. For instance, in the metropolitan area of Minnesota near Duluth, the following relationships were found between the winter index and salt and sand use (in tons per lane mile):

$$\mathrm{sand} = 571 + 12 * \mathrm{WI} - 0.347(\mathrm{WI} + 50)^2 \qquad R^2 = .977 \quad (5)$$

$$\mathrm{salt} = 83 + 1.25 * \mathrm{WI} - 0.054(\mathrm{WI} + 50)^2 \qquad R^2 = .96 \quad (6)$$

It is too early in the United States to determine if RWISs are having the same impact in reducing the costs of snow and ice control. The SHRP winter index should allow estimates to be made.

COST 309 Winter Index

Denmark has developed a winter index for COST 309 that uses RWIS data at a county level (*1,7*). The index is given as

WI = sum of $W(\mathrm{day})$ from October 15 to April 15

where

$W(\mathrm{day}) = a * (b + c + d + e) + a$;

a = 1, if road temperature is less than 0.5°C at any moment within a 24-hr period; otherwise $a = 0$;

b = number of times road temperature is below 0°C at same time that road temperature is lower than air dewpoint, and this for at least 3 hr within an interval of at least 12 hr; thus maximum value for $b = 2$;

c = number of times road temperature declines below 0°C (from at least 0.5°C to −0.5°C) within a 24-hr period;

d = 1, if snowfall of at least 1 cm is reported within a 24-hr period; otherwise $d = 0$; and

e = if noteworthy snowdrift has occurred; otherwise $e = 0$.

The values for a, b, and c are averaged from the total number of RWIS outstations in a county. The index is then compared to what they have described as an activity level, which is defined as

activity level = $N1 + N2$

where $N1$ is the number of routes salted divided by the number of routes and $N2$ is the number of snow routes cleared divided by the number of snow routes.

The study shows a clear linear relationship between salt use for the whole of Denmark and the winter index averaged for all counties over three winters (*1*). The ratio of winter activity to winter index for each county is calculated, and the lower the ratio, the more efficient the county must be. In 1989–1990, 8 of the 11 counties were very similar with a ratio near 0.5, whereas 3 of the counties had ratios of less than 0.4.

CONCLUSIONS

The Danish index must be calculated in real time on a daily basis. The full index could not be calculated automatically by the RWIS, but some of the elements (a, b, c, and d) could be stored for the road master to make the calculation easier. Elements e, $N1$, and $N2$ would have to be entered by the road master. This daily interaction with the RWIS to summarize the day's activities is to be encouraged, and software could easily be designed to make the task as simple as possible and to display the results for the winter so far. Unfortunately, using actual road-surface temperatures means that the current winter cannot be compared easily with winters before the RWIS was installed.

Therefore, to assess the impact of the RWIS on the costs of snow and ice control, an index based on air temperatures is required. Once an RWIS has been installed, however, another winter index based on road temperatures could be calculated alongside the first index to assess efficiency spatially across a region.

It is important to archive the RWIS data and activity data if the efficiency of snow and ice control is to be properly assessed. Better software is required within the RWIS to make this task easier. For now road masters must judge which is the best winter index for their own circumstances and archive the required information themselves.

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The views expressed in this paper are the author's and not necessarily those of members of SHRP.

Road Weather Information Systems: What Are They and What Can They Do for You?

S. EDWARD BOSELLY III

Road weather information systems (RWISs) have been implemented operationally or tested in many states, counties, and cities, both in the United States and internationally. Research conducted for the Strategic Highway Research Program determined that RWISs can help highway agencies to optimize the resources allocated for snow and ice control. Questionnaires were sent to all of the states and the provinces of Canada; interviews of snow and ice control managers were conducted in 11 states and one Canadian province; and field tests were conducted in Colorado, Massachusetts, Michigan, Minnesota, Missouri, New Jersey, and Washington. The various RWIS technologies are described: meteorological and pavement sensor systems installed in the road environment; road thermography, which involves constructing thermal profiles of road segments using vehicle-mounted infrared thermometers; and detailed, site-specific weather forecasts provided through interaction with meteorological service providers and information tailored to the highway agencies' needs. In addition, the communications aspects of providing information effectively to highway agencies are discussed. Experiences, primarily in Colorado, Minnesota, and Washington, are highlighted, including anecdotal information gathered from other state agencies through interviews and field tests. Successful interagency cooperative efforts are also described because of their ability to reduce the costs of acquiring RWIS hardware for each agency through cost sharing. Finally, cost analysis results of the research are highlighted to point out the potential cost reductions for highway agencies that implement RWIS technologies.

Road weather information system (RWIS) is a term that encompasses the sensing and collecting of on-site weather and road condition information, the processing and dissemination of the information, and the creation and dissemination of forecasts of road and weather conditions. It also refers to people. Some of these people are the meteorologists who issue forecasts and interact with highway agency customers. RWISs are currently installed for use by many states and other agencies to assist in the management of snow and ice control.

In 1988 the Strategic Highway Research Program (SHRP) initiated Study H207 (Storm Monitoring/Communications) to investigate the uses and cost-effectiveness of RWIS technologies. The research team members included the Matrix Management Group, Seattle, Washington; the Washington Transportation Center at the University of Washington, Seattle; and the University of Birmingham in England.

Information gathered in the project showed that more than $2 billion is spent each year in the United States and Canada on snow and ice control. It is believed that some of this money can be saved by using RWISs. This paper briefly describes the H207 research project, identifies different RWIS technologies, and describes some of their uses. Finally, it presents the results of the research.

RESEARCH

The H207 project can best be described in phases: initial information gathering, field testing, and analysis. Gathering information involved sending questionnaires to all of the states and to the provinces of Canada to ascertain the extent of use of weather information and equipment in support of snow and ice control. Questionnaires were also sent to manufacturers of meteorological equipment to define the state of the art in sensing weather and pavement conditions, and to meteorological service providers to determine the types of services available and level of support being provided to highway agencies.

In addition to the questionnaires, the research team conducted interviews in 11 states and one Canadian province. The purpose of the interviews was to determine the types of snow and ice control activities being conducted, the types of weather or road condition information that could assist decision makers, the types of management systems in use for allocating snow and ice control resources, and the types of resources—labor, equipment, and materials—used in snow and ice control.

A literature search was conducted to define the body of knowledge related to RWISs, especially to snow and ice control support. Although initially little published information was produced in the United States, a great deal of information was available from Europe through European cooperative research efforts with support from governments and manufacturers of RWIS technologies. The results of the search are presented in a large bibliography in the H207 final report.

Field testing was conducted to evaluate the use of RWIS technologies in different climates and for different maintenance practices, and to assist in establishing the cost-effectiveness of RWISs in support of snow and ice control maintenance. Initially, tests were to be conducted in Colorado, Minnesota, and Washington. Because of the potential of having few winter weather events in only three states for one winter, four more states were enlisted: Massachusetts, Michigan, Missouri, and New Jersey. Even so, for reasons ranging from broken RWIS equipment to few winter weather events, only

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75 winter weather events, and comments about the RWIS use in support of snow and ice control operations, were reported from the seven states.

Finally, a cost analysis was conducted to evaluate the cost-effectiveness of RWIS technologies in support of snow and ice control. The team developed a computer simulation model that produced ratios of reduced costs in snow and ice control compared with the costs of various weather information sources. The model used statistical techniques to assess the cost reductions in snow and ice control, the ability of weather information to reduce decision errors, and the ability to improve the service level of snow and ice control to the roads.

Only direct benefits—the reduced costs of labor, equipment, and materials—were considered in the analysis. It is believed that the indirect benefits, such as reduced accidents, fuel consumption, insurance premiums, and losses to commerce, will increase the reductions in cost, or benefit-cost ratio, resulting from using RWIS data.

RWIS TECHNOLOGIES

Pavement sensors are probably the most recognizable technology because of usual references to such devices when referring to RWISs. In fact, the terminology of pavement sensors and RWISs appears almost interchangeable to some. But even though a pavement sensor is an extremely important component of an RWIS, it is only one of several.

Pavement sensors typically measure pavement temperature, the condition of the pavement surface (e.g., wet, dry, ice- or snow-covered), and the concentration of deicing chemical on the pavement. Passive sensors use resistance measurements for temperature, and combinations of surface conductivity and field capacitance for the other determinations. Not evaluated during this project is a more recent technology that uses an active sensor to determine the temperature at which the (wet) pavement surface would freeze.

Pavement sensors can be located in the roadway surface for either detection or forecasting of pavement temperature and conditions. It is suggested that predictive siting be the primary purpose for siting sensors since predictive information is most useful in making decisions to assign snow and ice control resources in a timely and effective manner. If sensors are installed for prediction, a subsurface sensor is required to measure the temperature, usually about 0.5 m (20 in.) below the pavement surface in order to determine if heat is flowing toward or away from the pavement surface.

Pavement sensors have many uses for snow and ice control. The pavement temperature can be used to validate pavement temperature forecasts, to determine whether ice formation or bonding can take place, and in turn whether deicing or plowing may be necessary. However, these decisions are best made by using forecasts of pavement temperature and being ready for action, rather than by waiting for conditions to occur. Changes in pavement condition, such as from dry to wet and from wet to ice-covered, are important thresholds for alerting managers that action is required. The chemical concentration of deicing chemicals is a key indicator of whether an application of deicing material will be required or not. If a concentration is above a certain threshold (material dependent), a manager may elect to forgo an application even with a pavement temperature below 0°C (32°F) and wet pavement. The chemical factor can also be used to determine if and when maintenance has made an application of the road where the sensor is located.

Atmospheric sensors and pavement sensors should be collocated. The atmospheric sensors provide additional important information for making decisions and for forecasting weather and pavement conditions. The combination of sensors, their installation, and power and communications hookups are usually referred to as remote processing unit (RPU) stations, RPUs, or outstations (in Europe).

A typical set of meteorological instrumentation at an RPU station would include an anemometer for wind speed and direction, a thermometer and hygrometer for air temperature and dewpoint, and a precipitation detector. Additional sensors can provide information on visibility, amount and type of precipitation, incident and net radiation, and water level if stream gauges are installed. In the future, it is possible that more sensors, such as air-quality monitors (perhaps in transportation nonattainment areas), soil moisture probes (to assist with frost heave analysis), and snow-depth detectors, will be a part of RWIS installations.

Like that of pavement sensors, the most important use of atmospheric sensors is to assist in the prediction of weather and pavement conditions. Data from the sensors are introduced into forecasting models or are used as a basis for initiating forecasts. Data are also useful in helping make decisions about snow and ice control. Examples of data use include wind direction and speed for drifting snow and "freeze drying" of roads (relates to the need to plow), sunlight to melt snow (for making chemical applications), and falling temperatures and dewpoints in conjunction with pavement temperature (to worry about frost).

Road thermography, a technique developed in Europe, involves driving an instrumented vehicle over roads, measuring the pavement temperature with an infrared radiometer, creating profiles of pavement temperatures related to distance along a road, and noting important road and terrain features. The profiles are usually constructed under different atmospheric conditions, because of the different radiational responses of pavement under cloud cover or clear skies, and different precipitation and wind conditions. During the H207 investigation, thermography was accomplished using a handheld radiometer. Although the measurements of pavement temperature in either case may not accurately measure pavement temperature, they do represent relative temperature differences, which are what is important.

Very little thermography has been conducted in the United States, and little use has been made of what is available. In Europe, thermography has been used to assist in selecting RPU station locations, developing forecasts for pavement temperature over a road network by using the profiles to fill in the gaps between sensors, and establishing staged response to snow and ice needs on the roads. For instance, if the forecast calls for only a small portion of roads to be below 0°C (32°F), then a manager may need to call out only a small crew. In Vancouver, British Columbia, the route priorities of snow and ice plows were changed on the basis of the profiles to ensure that the coldest road segments are plowed first, the warmest last.

Meteorological data are another component of RWIS technologies. Examples include weather radar or satellite data, weather observations and forecasts, and maps of meteorological parameters that can be provided to decision makers, especially the data due to be provided by the Next Generation Weather Radar (NEXRAD) currently being installed by federal weather agencies. NEXRAD will have the capability to create maps of projections of precipitation patterns and accumulations overlaid onto maps with road networks and geopolitical references. It is expected that these products will be extremely useful for meteorologists and highway maintenance people alike.

Communications is a major and vital component of an RWIS. Communications are required to disseminate sensor and forecast information to managers and meteorologists. The major components of communications include

- Sensors to RPU, usually hard-wired with cable;
- RPU to a central processing unit (CPU), either via telephone or radio;
- CPU to snow and ice control decision makers and managers, through a collocated or remotely located computer work station or portable computer;
- CPU to meteorologists via remote computer connections;
- Meteorologists to snow and ice control decision makers, employing many means, but normally computer-to-computer connections, telephone facsimile, or direct voice contact via telephone; and
- Perhaps some method of communicating road information from an RPU to the traveling public, such as variable message signs, but this is rarely done in the United States.

Sometimes considered a part of communications, RWIS data processing is an important component of a system. The processing involves formatting raw sensor data into usable information for decision makers or meteorologists and graphical displays of data for decision makers. The way that information is presented can directly affect its utility or use. In some cases, data are formatted for use in forecasting models.

Data should also be archived in some form. Archived data can be used for monitoring trends, creating historical files for maintenance record purposes, expanding climatological data records, and developing local area forecast studies.

Forecasting of weather and pavement conditions may be considered the most important part of RWISs. Although not always a component, forecasts provide the capability to make the decisions to get the right resources to the right place at the right time.

Typical sources of forecasts include the public media, the National Weather Service (NWS), and value-added meteorological services (VAMSs). For the types of decisions snow and ice control requires, forecasts from a VAMS are usually necessary since the most valuable information is that which is tailored to the needs of the highway agency. These forecasts are usually beyond the responsibility of the NWS. In addition, pavement temperature and pavement condition forecasts typically require a VAMS.

The final component of an RWIS is the establishment of a consultancy arrangement between a meteorologist and the highway agency. This arrangement is crucial so that each understands the needs and capabilities of the other. Such a role can be filled by a consultant, a VAMS, an RWIS vendor, or a member of the agency staff.

RESULTS

The following section describes the results of the RWIS cost analysis and the utility of RWISs for snow and ice control. It also presents results obtained from interviews and the project's field trials during the 1990–1991 winter. Fewer data than desired were obtained from the field trials because of the mild winter weather. In the event that quantitative data were not available, additional interviews with state highway agency personnel were used to document at least qualitative results.

Cost Analysis

The research team developed a computer model in order to determine the cost-effectiveness of RWISs. The model, described by Boselly (*1*), computes the cost reduction in snow and ice control when decision makers use different RWIS technologies. The cost analysis showed that when decision makers use weather information to their advantage rather than react to conditions, they can make more timely and efficient use of resources. In general, the model showed that

- RWISs are cost-effective. A system that includes all of the RWIS components can reduce the costs of snow and ice control at a ratio of up to 5 to 1 over the cost of the RWIS. If many sensors are installed in an area, though, the ratio is reduced.
- The largest return on the investment results from using detailed, site-specific forecasts of weather and road conditions, because forecasts are relatively inexpensive when compared with the costs of snow and ice control. Practically any reduction in maintenance costs quickly exceeds the costs of forecasts.
- The model also looked at the service level to the roads for snow and ice control. Using RWISs can improve the service level, mainly by allowing decision makers to get the proper resources where they need to be when they need to be there, rather than after the fact.
- RWISs also help reduce decision errors, both by reducing the number of costly errors (Type II: a condition that is forecast does not occur, but resources have been assigned) and the number of dangerous errors (Type I: a condition occurs that is not forecast, and no resources are assigned to treat it).

Decision Assistance Through RWISs

One of the most cost-effective uses of RWISs is to reduce the need for night or safety patrols. Such patrols have been used in some areas for years to look for snow and ice problems. When problems are encountered, maintenance forces are called out. This is a reactive process, and often when the forces are finally on the road, they are behind in treating conditions. Forecasts of pavement conditions requiring treatment offer the opportunity to call out forces when and where they are needed. The (high) costs of patrols are avoided, and the costs of treatment are reduced.

The critical information needed is what the pavement temperature is going to be with respect to expected atmospheric conditions. Research has shown that pavement temperatures can be forecast within 1°C (2°F) 90 percent of the time (*2*) and that site-specific forecasts are better than 80 percent accurate.

Such forecasts, in conjunction with the sensors that provide validation information related to the forecasts and detect road and weather conditions, allow managers to make other important decisions:

- Appropriate deicing chemical mixes can be selected. In the past, managers relied on air temperature to make mix decisions. Deicing is related to pavement temperature, and forecasts of pavement temperature let managers select the proper mixes ahead of time.
- Proper chemical application rates can also be selected ahead of time on the basis of forecasts of pavement temperature; they can also be adjusted on the basis of current sensor readings.
- If chemical treatment is part of snow removal plans, the decision to make an application can be based on the forecast of pavement temperature.
- Sensors and forecasts also help managers make the most cost-effective decision: to do nothing. Except for perhaps continual overhead costs, doing nothing costs nothing. If a forecast says pavement temperatures will be high enough that a road surface will not freeze, no maintenance action is required.
- Forecasts for the onset of winter weather and road conditions help managers mobilize forces to be ready to go when needed. Frequently, when in a reactive mode, managers find their forces behind the curve when applying chemicals or plowing snow. This can require more materials and time to achieve the desired road conditions.
- Similarly, knowing when a storm or conditions will abate helps managers stop snow and ice control activities when appropriate rather than, for example, waiting for the end of a shift.

Interagency Cooperation

Buying RWIS technologies can be expensive for highway agencies. Even though the responsibility for snow and ice control often ends at a political boundary, weather and road conditions do not. One measure that minimizes cost and maximizes information is for agencies to work together to implement RWISs.

- Within a highway agency, sharing data between maintenance districts or areas can reduce RWIS implementation costs. Where one district may require four or five RPU stations, and a neighboring area the same number, together the two districts may need sensors at only six or seven locations. Sharing information may also make forecasts less expensive, especially if the areas are similar climatologically.
- Interstate cooperation can help reduce costs. If sensor data from a maintenance office in one state can be used by a neighboring state, perhaps they can share the costs of the RWIS. Examples include Missouri using data from Kansas, or Wisconsin using data from Minnesota.
- Some of the most cost-effective cooperative efforts involve interagency cooperation. This can be accomplished when municipal, county, and state highway agencies get together to define their needs, find locations for sensors that can satisfy requirements for each or more than one agency, and share in the costs, perhaps on a pro rata basis. One example is in the Spokane, Washington, area where an airport authority, the state department of transportation, the city street department, and a solid waste utility with special weather information needs share information from RPU stations and use a common CPU for data access. They share the costs of the sensors and compute system maintenance costs on a pro rata basis.

Problems Noted

Cost savings, improved maintenance, and reduced decision errors are all positive results possible from using RWISs for snow and ice control. However, the research team identified some problems with implementing the technologies and with the technologies themselves. These implementation problems are referred to as "barriers": they can be philosophical, psychological, or institutional. Some of the barriers identified include

- Lack of buy-in at the maintenance operations level because of perceptions that the technology is directed from the top down. Many of the successful implementations have occurred when a maintenance foreman or supervisor has decided to go to management with a request for RWISs, rather than the other way around.
- No ownership at the operations level. This results when the person who initiates the implementation leaves the job and his or her replacement does not share the same philosophy or vision.
- Perception that the RWIS is a technological toy and certainly cannot help the maintenance forces perform their snow and ice control mission. Many of the decision makers have been working at snow and ice control for decades, and they believe that they know how to do it right.
- Reluctance to buy into a process at the operator level. This can result from operators perceiving a threat to their pocketbook. Many of the operators look forward to overtime paychecks from the winter activities. RWISs provide an opportunity to reduce overtime pay through more effective decision making.

Accuracy of data from the instruments can also be a problem. Pavement sensors can report temperatures not representative of the pavement temperature under sunlit conditions. Sensors, in general, can report erroneous readings when they are not calibrated routinely.

Another problem surfaces when sensors do not provide data that are representative of an area, which is the result of poor site selection or sensor location. Poor siting can result from decisions to locate RPU stations close to power or communications and consequently neglect sound meteorological and pavement siting practices. It is also possible that sites are selected solely because the operators perceive that a site is needed rather than consider overall RWIS data needs.

Communications can also be a problem. Frequently telephone lines are unreliable, and costs can be high if long-distance phone service is required to obtain data. RWISs from different vendors cannot exchange data because of incompatible communications protocols and data formats. The inability to exchange data can inhibit interagency cooperation.

Contracting procedures for RWIS technologies sometimes lead to undesirable effects. Forecasting services should be treated and acquired as professional services in a process that considers technical meteorological qualifications, not just cost. In addition, no hardware performance standards exist, and highway agencies tend to specify vendor-specific systems.

RECOMMENDATIONS

After the completion of the field trial and cost analysis and the evaluation of the information at hand, the following are the most important recommendations:

- On the basis of the cost analysis and the evaluation of the use of RWISs, all agencies that conduct snow and ice control maintenance should consider acquiring RWIS technologies.
- Training programs should be developed to help highway agencies implement RWISs. A properly designed training program can help personnel overcome the barriers to RWIS use. It is also often required to help managers integrate RWIS data into the decision process for snow and ice control.
- Agencies with RWISs in place should institute, at a minimum, an annual preventive maintenance program that includes semiannual calibrations of pavement and atmospheric sensors.
- Agencies contracting for RWISs should use a two-step acquisition process similar to contracting for other professional services when acquiring forecasting services. Performance specifications should be considered for adoption and used for buying RWIS hardware.
- Standard RWIS communication protocols should be adopted for CPU-to-CPU connectivity between RWISs. A standard data format should also be adopted in order to exchange RWIS data.
- Additional research will be required to
  - Determine the avenues for which interfacing or integrating RWIS information would be desirable (and, if possible, what it would take) as measured by criteria to be established. Possible interfaces include intelligent vehicle-highway systems.
  - Determine the utility of expanding RWISs to include new technologies such as present-weather sensors, radiometers, and visibility and air quality sensors to increase the cost-effectiveness of RWIS installations with more-detailed year-round support.
  - Establish motorist needs for RWIS information through studying human factors and behavioral science in order to provide information to effect behavioral change in drivers.
  - Develop standard calibration techniques for agencies to use for periodic pavement sensor calibration.
  - Determine the ability of data from on-board vehicle sensors to include infrared radiometers for pavement temperature, thermometers, and hygrometers, to enhance RWIS real-time information, to assist in developing historical data bases, and to provide thermal profiles of pavement temperature.
  - Evaluate the use of thermographic profiles in pavement temperature forecasting and the utility of using thermography for snow and ice control resource allocation staging or phasing by conducting road thermal analysis in at least three different climates.
  - Determine the utility of integrating RWIS (or other) in situ measurements into small-area, detailed forecasting models, perhaps as developed or in development through the Office of Atmospheric Research/Forecasting Support Laboratory of the National Oceanic and Atmospheric Administration, in order to improve decision support for transportation systems.
  - Evaluate the benefits to the meteorological community and to transportation for archiving RWIS data for climatological purposes, either with state climatologists or the National Climatic Data Center.
  - Determine the optimum role of the federal government in supporting surface transportation meteorological needs.

CONCLUSION

The SHRP H207 research has shown that RWIS can be a useful tool to improve the maintenance and reduce the costs of snow and ice control. Implementing the technologies requires that agencies develop a sound acquisition process and training programs to ensure the effective use of the data. Ongoing success will depend on how well the information is integrated into an agency's snow and ice control decision processes.

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Road Weather Service System in Finland and Savings in Driving Costs

YRJÖ PILLI-SIHVOLA, KIMMO TOIVONEN, AND JOUKO KANTONEN

The Finnish National Road Administration has developed a road weather service system that produces weather information for both road maintenance personnel and road users. The measuring data of road weather stations and the service of the Meteorological Institute (forecasts and radar and satellite pictures) are transmitted to users' workstations in real time. All the data are combined and shown in visual form. The real-time system also includes an alarm call system for when the weather development exceeds the determined limits at certain road weather station. The service system enables communication between two workstations or a workstation and a central station for real-time information transmission concerning salting operations and such. In the first phase, the system was built mainly with the needs of maintenance personnel in mind. The objective is to improve the monitoring of road weather conditions so that winter maintenance can be carried out systematically and at the right time. The main benefit is the possibility to anticipate the road surface freezing and thus eliminate accidents caused by slipperiness. The road weather information can also act as an impulse for the traffic signs to change according to the weather. The benefits of driving costs consist of the savings in accident costs, vehicle costs, and time costs. The service system gives good real-time information and forecasts of the road condition, so the time that the roads are slippery can be shortened and accidents eliminated. Prompter salting or plowing will improve the trafficability, and driving time will be shorter than it would be without the road weather system. Plowing at the right time affects the thickness of snow and slush on the road. The duration of slippery road condition has been estimated to shorten 10 to 30 min per deicing activity in Finland. Each of these effects results in savings in driving costs.

The Finnish road weather service system is an automated information system that sends actual and forecast weather and road surface information to those responsible for road maintenance. The road weather observation network provides information about weather and surface conditions on all the main roads (Figure 1). At given time intervals, weather forecasts and radar and satellite pictures are received from the Finnish Meteorological Institute. Plain-language observations of surface conditions can also be collated and sent to various users. The data are shown on a versatile screen display that users can easily manipulate to suit themselves. The system also contains a warning facility that produces an alarm whenever given critical weather threshold values are crossed. The alarm is automatically communicated to selected paging devices or telephone numbers. All users of the system are in direct contact with each other by electronic mail. Reports of weather and road conditions are easily communicated to external systems, such as those serving road users.

ROAD WEATHER SERVICE SYSTEM IN FINLAND

The road weather service system in Finland consists of 11 central stations, about 200 workstations, and about 150 observation stations. The workstations and the observation stations form a network covering all of Finland (Figure 1). The system has also a connection to the computer system of the Meteorological Institute, which supplies the system with weather radar and satellite images and weather forecasts. The system sends back information based on the observation station measurements.

The maintenance of the road network on Finland is organized in districts, and each district is responsible for the roads in its area. The district central stations collect information from the observation stations in that district. The information from the observation stations is shared among the central stations. The radar and satellite images are spread to all central stations and thus are available to all workstations in the system (Figure 2).

FUNCTIONS OF ROAD WEATHER SYSTEM

The functions of the central station are configuration, information gathering, communication between the workstations and the central station, and alarm handling (Figure 3).

Configuration

The operation of the system is based on the parameter settings in the central stations. The configuration application is used to determine and update the system parameters. The application is menu-driven, and data are updated in an easy-to-use form. The configuration parameters are the connected observation stations, the connected workstations, the alarm set, the alarm threshold values, the alarm warning addresses, and the active sets of sensors in each connected observation station. The system also includes configuration files that contain information on direct data lines, X25 and telephone lines, and information on other connected computer systems. Every file has a menu option to start the editing.

The parameters identifying a central station include a code number, name, and location. The parameters identifying a workstation include a code number, name, security classification, and type of connection channel. Other information can also be added. The parameters identifying an observation station include a code number, name, security classification,

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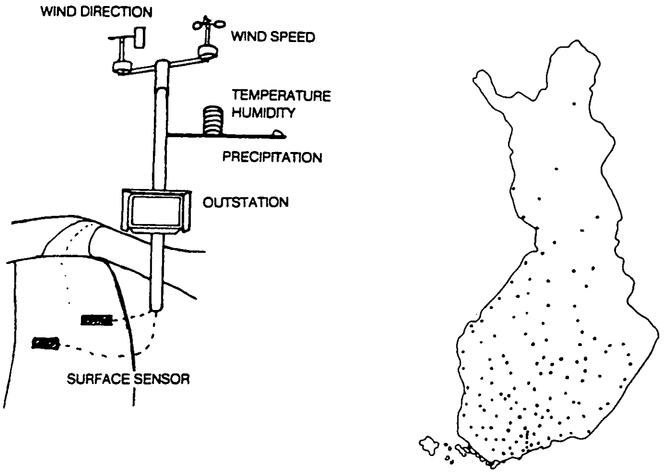

FIGURE 1 **Observation station and network.**

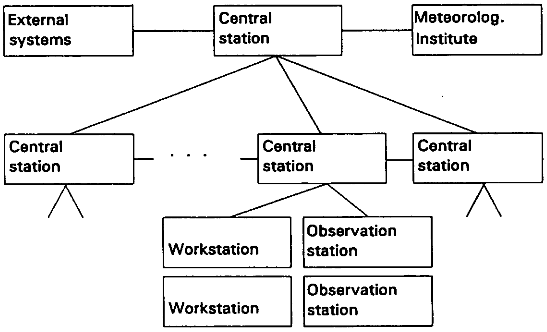

FIGURE 2 **System overview.**

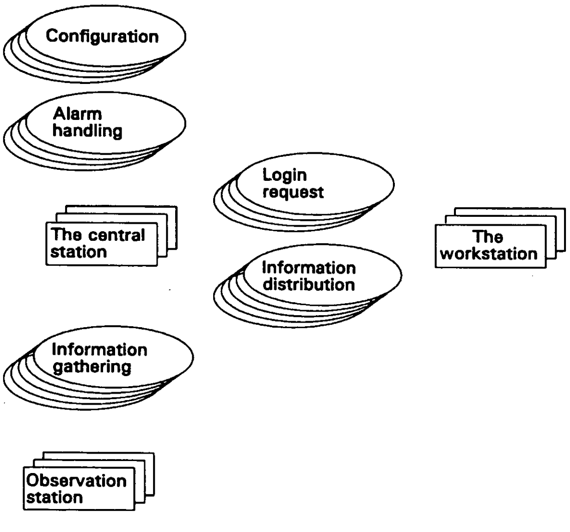

FIGURE 3 **System functions.**

type of connection channel, data-requesting interval, active sensor information, and location coordinates.

The parameters connected to a sensor include a code number, name, security classification, and eventual additional information. An arbitrary filtering function can be attached to each sensor. The functions can also refer to raw or filtered data of the other sensors. The user can define textform definitions corresponding to numerical sensor value domains.

The parameters that determine the structure of the records sent to workstations include codes of the sensors and the destination workstation. In one record, values of a maximum of 20 sensors can be included. A record can consist of either observation data or forecast data, but not both.

For every alarm, the following parameters are specified: alarm identifier, alarm level, alarm address, alarm triggering, and time period within which the alarm limit is being evaluated—for example, icing alarms can be set off during summertime. The observation stations for which the alarm is active are also specified. The alarms are classified by alarm level. For each level a different alarm address can be specified.

The configuration application also includes other system support functions, such as archives and backup utilities, startup and shutdown programs, communication, and overall operation monitoring applications.

Information Gathering

Information gathering is a continuously running background process that sends the data requests to the observation stations at time intervals specified in the system parameters. The time intervals may change as alarm threshold values have been exceeded.

When data from an observation station have successfully been received, the process evaluates possible filtering and alarm triggering functions and forms the records to be sent to the workstations. When an alarm is triggered, the process sends an alarm message to the alarm address according to the alarm level through the alarm handling application.

Communication Between Workstation and Central Stations

The information distribution application sends the formed data records to the workstations at time intervals specified in the system parameters. When the central station contacts a workstation, the workstation requests data records needed for its end user applications. The transfer application checks the security classification of the requested data and sends the permitted records to the workstation. Only the newest lacking information is transferred. The data transferred to workstations consist of sensors data records, radar and satellite images, forecasts, text weather reports, alarms, and electronic mail.

A workstation connects itself to a central station by sending a log-in request to one of the log-in lines of the central station, which are continuously polled by a log-in background process. During the next data distribution cycle the central station contacts all the active workstations. This connection principle ensures that unauthorized users of workstations are not able to break into the central station.

Alarm Handling

The alarm-handling application sends the triggered alarms to corresponding addresses. An address can be a workstation code or a telephone number of a pager.

SOFTWARE ARCHITECTURE

Application Modules

The central station software is written in C-language in the UNIX operating system environment. The information is stored in an Oracle data base. The central station system consists of several program modules. Each module independently performs a specified task. Three types of modules exist: continuously running background processes, modules started up by other modules, and modules initialized with user menus.

Alarm server is a background process that receives triggered alarms and sends alarm messages to corresponding alarm addresses. Observation station polling is a background process that collects the observation station information at given time intervals. The module also evaluates the filter and alarm functions and activates the alarm server when needed. The process forms the data records to be sent to the workstations. When collecting information from a certain observation station, the polling process starts a collection process depending on the communication channel used for transmitting the data from the observation station. Communication can be made by X25, modem line, or direct line connections. Observation data from other central stations are read with another module. After every successful observation station contact, the polling process starts the calculation process, which performs the defined mathematical functions to the sensor data.

Workstation polling is a background process that controls the workstation communication. The module establishes the connections and transfers data records to active workstations at given time intervals. The actual data transferring is done by subprocesses started by the workstation polling process. The chosen process depends on the communication channel in the same way as described in the previous section (X25, telephone lines, direct lines).

Workstation log-in is a background process that polls the log-in lines for workstation log-in requests. The process sets the workstation, which is requesting the data, in an active state after a successful identification.

Data Base

The data base of the system is implemented with Oracle 6.0 data base software tools. The data base operations are carried out with standard SQL embedded in C-language application programs. The information stored in the data base consists of configuration information and observation station measurements.

When the central station system is started, the configuration information is loaded in the shared memory of the system. The application programs use this shared memory data to make data checks and verifications. The mechanism grants maximum system performance.

The information collection application stores sensor measurements in the data base; information on triggered alarms is also stored. The formed data records to be sent to the workstations are written into files, which are in observation station–specific directories. The ready-made records are stored for a specified period, or at least for 24 hr, so the most recent and most frequently used information is in an easily and quickly obtainable form.

It is possible to access the data base directly with any Oracle data base tool, such as interactive SQL-interface or SQL*Forms.

User Interface in Central Station

The user interface of the central station is developed with the D-Screen user interface toolkit. The system is operated with a menu-based user interface. The system operates normally in the background even when the user interface process is not active. The user interface is used for updating configuration settings and for system maintenance. The menu system has options to start the configuration information forms, file editing options, monitoring screen options, and backup utilities.

Communication Software

The communication between the central stations and other computer systems has been implemented with Internet supporting Transmission Control Protocol/Internet Protocol (TCP/IP)–based services provided by the UNIX operating system. The services include remote execution of programs and the file transfer. The data are transferred through Ethernet and X25 networks.

The communication between the central station and the observation stations and workstations has been implemented with the ICECAST communication protocol developed especially for this purpose. Before the transfer, the data are packed, numbered, and framed with identification information. After receiving a data packet, the receiver unpacks and verifies it. The information in the packets is verified using checksum. If no transfer errors are found, the receiver confirms the transfer. If the confirmation is not received, the packet will be sent again.

SAVINGS IN DRIVING COSTS

Introduction

The main purpose of the road weather system is to improve the management of road and weather conditions so that winter maintenance can be effectuated systematically and at the right moment. When the costs and benefits of the improved road weather service are calculated, losses and gains associated with driving costs, road maintenance, and environmental, social, and psychological effects should be taken into account.

Benefits of Road Weather System

The main benefit of the road weather system is its potential to anticipate the freezing of the road surface and thus eliminate the accidents caused by slipperiness. The duration of slippery road conditions can be shortened. Another safety benefit is that drivers can be warned of poor road conditions via different forms of communications, thus decreasing accidents.

Trafficability will improve because of better road conditions, in turn benefiting driving time, fuel, and the environment. Other, direct benefits can be achieved by better methods of maintenance, including

- Work organization,
- Material amounts,
- Watchover, and
- Systems.

Costs of Road Weather System

The costs can be divided into two parts: the road weather observation and data processing system (includes also radar and satellite data), and the forecasting system and service.

Method To Calculate Benefits

The savings associated with only road maintenance (salt reduction, personnel organization, etc.) can be calculated by comparing the costs of the maintenance activities with a road weather system to those without any special weather service. Environmental, social, and psychological benefits are very difficult to determine, but they are still significant to the public.

In this connection, maintenance savings are not estimated but the headlines are made to estimate the benefits that can be achieved in driving costs. Such benefits can be represented as the benefits of each part of the driving costs:

driving costs = accident costs + vehicle costs + time costs

Savings of Accident Costs

One effect of the road weather service system could be to begin salting 50 percent sooner—for example, if salting normally begins 3 hr after confirmation of the change in road conditions, it would now begin 1.5 hr after confirmation. This kind of improvement in maintenance activities would decrease accidents 3 to 17 percent depending on the district and the winter (*1*). The accidents (fatalities, injury, damage to vehicles) are evaluated differently in every country [e.g., in Finland one fatal accident costs about 8 million Finnish marks (*2*)].

$$S_{\text{acc}} = \sum_{k=1}^{3} (\Delta R_k * \text{UC}_k) * \sum_{i=1}^{n} \left[(F_i * \Delta t) * \sum_{j=1}^{m} (L_{ij} * \text{ADT}_{ij}/1440) \right]$$

where

S_{acc} = savings of accident costs;
ΔR_k = $R(\text{ice}) - R(\text{dry})$ = change in accident risk (scale:number of accidents per kilometer);
UC_k = unit cost of accident (estimated value);
k = type of accident [1 = fatal, 2 = injury (without 1), 3 = all (without 1 and 2)];
F_i = number of deicing and plowing activities per year per maintenance district;
i = maintenance district;
ΔT = decreased time of slippery road conditions due to prompter deicing activities;
L_{ij} = length of road network;
j = road category;
ADT_{ij} = average daily traffic per maintenance district and road category;
1,440 = minutes in 24 hr.

The activities occur randomly during morning and evening hours. Changes in traffic during activities do not cause effects, and the change in road conditions (icy-slush-wet-dry) is simply from icy to dry.

Savings of Time Costs

Quicker salting or plowing will improve the trafficability, and driving time will be *x* minutes shorter than without the effect of the road weather service system—which means savings in driving time.

$$S_{\text{time}} = \sum_{z=p}^{t} \Delta \text{TC}_z * \left\{ \sum_{i=1}^{n} \left[(F_i * \Delta T) * \sum_{j=1}^{m} (L_{ij} * \text{ADT}_{ijz}/1440) \right] \right\}$$

where

S_{time} = saving in time,
ΔTC_z = saving in time costs when speed goes from 80 to 90 km/hr,
p = passenger car,
t = truck,
ADT_{ijz} = ADT_{ij} by type of vehicle, and
z = car (p) or truck (t).

Savings of Vehicle Costs

Plowing at the right time affects the thickness of snow on the road. The thickness of snow from 0 to 8 cm causes a 0 to 10 percent increase to vehicle costs (fuel, etc.). If we can show how much the mean thickness of snow decreases during snowfalls by means of the road weather system, we can calculate the benefits of vehicle costs.

$$S_{\text{veh}} = \sum_{z=p}^{t} \left\{ \sum_{i=1}^{n} \left[(F_{\text{p}i} * \Delta T_{\text{p}}) * \sum_{j=1}^{m} (L_{ij} * \text{ADT}_{ijz}/1440) \right] * \Delta \text{VC}_z \right\}$$

where

S_{veh} = savings of vehicle costs,
F_{pi} = number of snowfalls that cause plowing,
ΔT_p = estimated time savings when starting to plow, and
ΔVC_z = saving in vehicle costs.

Problems

The costs of the road weather system can be calculated exactly, but the benefits are only theoretical approximations. It cannot be found out exactly how much the road weather service will shorten the time of slippery road conditions.

Example of Calculating Benefits in Finland

There are 13 road districts in Finland. The total length of public roads is 76 000 km. There are 7437 km of main roads (first class). About 7 percent of the main road network goes through the Kymi road district.

Costs of Road Weather System

The costs can be divided into investments and yearly costs. The system, software, and hardware are investments. Maintenance of the system, forecasts, and radar pictures and the costs of the communications are yearly costs.

The investments of the system are about $4.3 million for the whole country; if the investments are allocated per 6 years and 13 districts, that is $60,000/year/road district. The yearly costs are about $140,000/district. So, the total costs of the system for the Kymi district in a year are $200,000, and $370/km of main road.

Benefits of Road Weather System

In deicing activities, the road masters estimated the average time saved at 23 min/activity (10 road masters in Kymi district, experience of one winter). The average price of an accident is calculated to be about $60,000 in Finland. The change in the accident risk between icy and dry road conditions is, according to the research in Finland, 5.8 accidents per 1 000 000 km. (The average daily traffic varies from 1,000 to 10,000 on that road network.)

Because of the quicker maintenance with the road weather system, the benefits calculated by the equation in the Kymi district are as follows:

Type of Cost	*Amount Saved ($/year)*
Accident	900,000
Time	60,000
Vehicle	20,000
Total	980,000

Thus the cost-benefit ratio is about 1 to 5 in the Kymi road district, which, with respect to the climate and the traffic, is a typical road district in Finland.

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Coastal Influence on Winter Road-Surface Temperatures in the County of Devon, England

P. J. McLean and N. L. H. Wood

Data from a network of 35 road weather stations across the county of Devon, England, were used to evaluate the north and south coastal influence on road-surface temperature. Two relatively cloud-free airstreams were identified: the northwesterly polar maritime and the easterly polar continental, which show that road-surface temperatures within 10 km of the coast are between 1 and 3°C higher than those measured at inland stations. This effect occurred only for wind speeds below 7.5 m/sec. The microclimate of the immediate environment and the altitude of the station were the controlling factors on road temperatures for calm conditions and wind speeds above 7.5 m/sec, respectively.

Devon has the longest road length (approximately 14 700 km) of any county in Britain. Its varied topography and diverse climatic zones complicate winter maintenance, making one treatment across the county an ineffective response.

The earliest U.K. Meteorological Office forecast gave general warnings of ice on roads during weather bulletins when there was a risk of this occurring. However, this forecast was of little use to the highway engineer and meant that all the roads needed to be salted, wasting money. Thornes suggested that a mathematical model would enable a forecast to be made of the road temperature at a particular location (*1*). In time, road weather stations were located at various points and tests were made to see if the model could accurately predict the road-surface temperature. Eventually Thornes's surface climate model came into being and was used in the United Kingdom to predict where and when ice was likely to form. The performance of this model is described by Thornes, (*2*), and eventually an "open road" network was set up in many parts of the United Kingdom, augmented by thermal mapping. The Meteorological Office also designed a model that Rayer describes (*3*). Gustavsson and Bogren explained that thermal mapping under different weather conditions is useful in interpolating temperature for stretches of road between stations (*4*).

These developments have enabled the highway engineer to determine whether there is a need for salting and where there is a priority, saving money and helping to prevent road accidents due to ice.

IMPORTANCE OF COAST ON ROAD-SURFACE TEMPERATURE

The main influences on road-surface temperature are topography, altitude, and coastal influence, although the urban heat island effect can also have an impact. Tabony described the influence of topography on air temperatures (*5*), and further research by Bogren and Gustavsson has determined how topography in turn affects the road-surface temperature (*6*), but there has been little research into how the coast influences the road-surface temperature. Gustavsson and Bogren showed that there was a 5 to 6°C difference between the coastal strip and inland areas in Sweden (*7*), but in this case altitude and shelter also had an influence. This paper sets out to determine the coastal influence on road-surface temperatures alone.

Onshore winds have a warming effect on the roads near the coast for two reasons. First, the sea, at about 10°C, is often warmer than the land during winter nights. During a relatively clear night the temperature difference between land and sea can be pronounced. Synoptic-scale onshore breezes, therefore, will advect warm air inland and modify the nocturnal boundary layer. Gustavsson showed that there is a strong correlation between road temperature and air temperature (*8*).

Second, the wind is stronger over the sea than over land as frictional effects reduce the wind speed inland. And radiational cooling inland stabilizes the air in the boundary layer, and therefore the wind speed reduces further. This means that an open coastal road will be influenced more by the mixing of air than an inland road will be.

ROAD ICE PREDICTION NETWORK IN DEVON

There are 35 road weather stations in Devon. The Meteorological Office receives data every 15 min, including road-surface temperatures, air temperatures, relative humidity, surface conductivity, and road conditions (e.g., dry or wet). A forecast is made daily at about noon, and it is updated if the expected synoptic conditions change. The forecast data include expected graphs and text and 2- to 5-day general forecasts. The forecast data are used to produce a map that shows the expected temperatures for certain stretches of road, giving different colors for ranges of temperatures. This information is received by Devon County Council, and decisions to use salt on the roads are made accordingly. The data are

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also sent to the Institute of Marine Studies at the University of Plymouth, using a modem that feeds the information into a microcomputer. Here, research is being carried out into improving the road temperature forecasts for the county.

TOPOGRAPHY OF DEVON

Devon is a county in the southwest of England. Its outline and approximate relief are shown in Figure 1. The county's topography features hills and valleys, although there are a few relatively flat areas. The main areas of high ground are Exmoor, in the north, and Dartmoor, which rises to about 600 m in the center of the county.

There are also two coastlines more than 100 km apart. The north coast has high cliffs. It faces the point at which the Bristol Channel meets the Atlantic Ocean and is open to the north and west. The south coast, on the other hand, faces the English Channel and has a more varied topography. Most of the south coast is exposed to the south and east.

AIR MASSES BRINGING ONSHORE WINDS

The climate of Devon in winter is mild because of the influence of the North Atlantic drift, which means sea temperatures are from 11°C in December to 8°C in March. This means frost generally occurs only occasionally. However, in anticyclonic spells in mid-winter, with clear skies and light winds, temperatures usually fall below 0°C in inland parts of Devon. The factors determining the occurrence of clear skies depend on the air mass and wind direction.

Two fairly cloud-free airstreams affect Devon. The first is the polar maritime, which brings a northwesterly airstream, so the north coast experiences onshore winds. The other is the polar continental, which brings easterly or southeasterly winds, which are onshore on the south coast. Both air masses are often associated with cloudless skies during the night, especially in anticyclonic conditions. In winter, when either of these two air masses is present, frost is likely inland under clear skies. Therefore, the two airstreams were used to study the coastal effect on road-surface temperature.

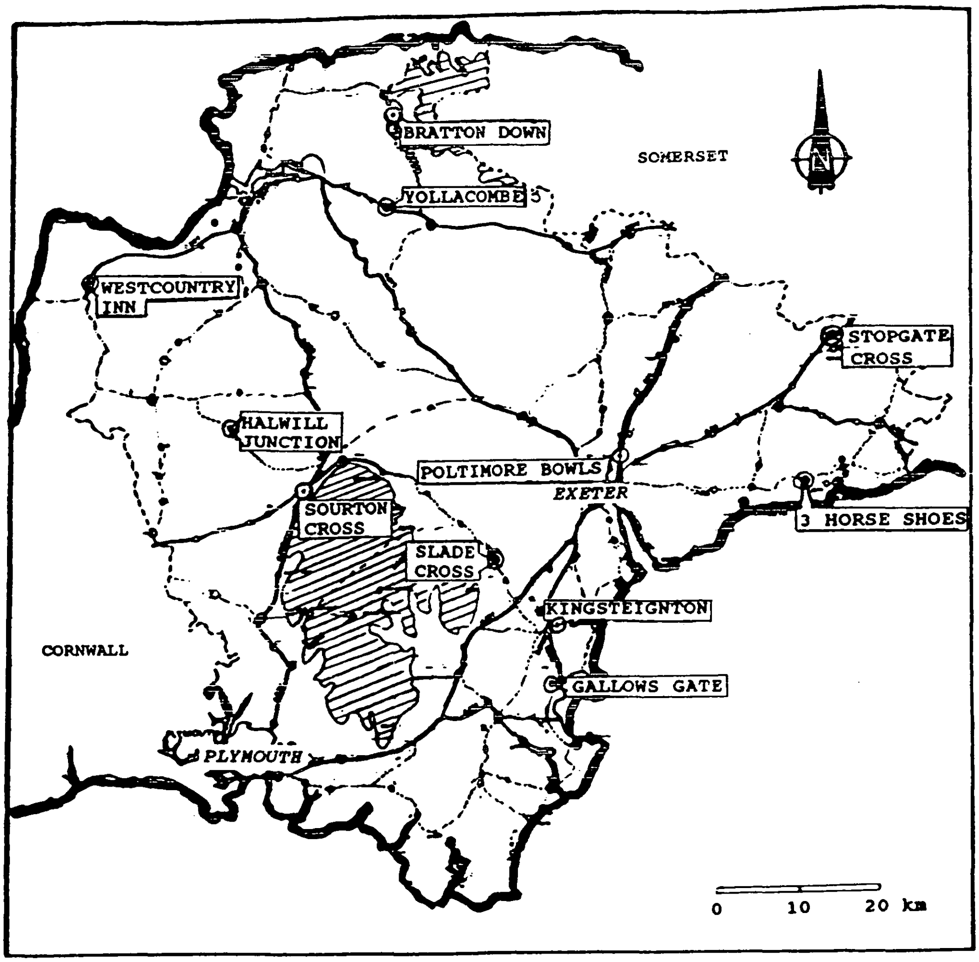

FIGURE 1 County of Devon with locations of road weather stations (areas above 300 m shaded).

OBSERVATIONS

Three coastal road weather stations are situated on the south coast, and two, on the north coast. Table 1 shows the coastal stations used, and Table 2 shows the corresponding inland stations with similar altitude and exposure that were used in comparison. Each of the stations is also shown in Figure 1. The comparisons for each of the stations were made on nights when there was a northwesterly or northerly wind and on nights when there was a southeasterly or easterly wind.

Varying wind speeds for each airstream were used on the appropriate nights so that the influence due to the strength of the wind could be compared.

The data for each station were collected using the Vaisala Road Information Workstation V5.81 package. The data were transmitted by a modem from County Hall, Exeter, to the University of Plymouth. The data that showed readings for each station every 15 min were displayed in graphical and tabular form. However, only the minimum temperatures were noted. These were then analyzed to see if there was a difference between the coastal stations and inland stations when onshore winds occurred.

All the minimum road-surface and air temperatures for each station are shown for each occasion that suitable days occurred: Table 3 presents the observations during easterly airstreams and Table 4 presents the observations for the northerly airstreams. Summaries of the synoptic conditions are given in Table 5 on the easterly occasions and in Table 6, for the northerly occasions. Figures 2 through 5 show inland temperatures plotted against coastal temperatures so that the influence of the coast on the road and air temperature can be estimated, the dashed line representing coastal temperature being equal to inland temperature. Figure 6 shows the effect of the wind speed on the coastal-inland temperature difference.

DISCUSSION OF RESULTS

Referring to Figures 2 through 5, the coastal effect is more marked with easterly winds because skies are clearer on these occasions and air temperatures are lower in the polar continental air mass than in the polar maritime.

The effect of the coastal influence on the roads was found to increase temperatures from 1 to 3°C over those of the inland stations, as shown in Figures 2 through 5. Statistics of the linear regression between inland and coastal minimum temperatures are shown in Table 7. A linear correlation coefficient of better than .81 occurs in all cases except Figure 5. Generally, the coastal warming on the road was similar to the coastal warming on the air temperature. Warmer maritime air at the surface was mixed into the surface boundary layer, reducing the radiation loss on the road surface.

The equation for linear regression for Figure 2 was

$$\text{inland temperature (°C)} = -1.20 + 0.93 \text{ coastal temperature (°C)}$$

The equation for linear regression for Figure 4 was

$$\text{inland temperature (°C)} = -1.21 + 0.98 \text{ coastal temperature (°C)}$$

TABLE 1 Height And Exposure of Inland Stations

Station Number	Name	Height (m)	Exposure	Comparative Inland Station
12	Kingsteignton	24	Open	3
13	3 Horse Shoes	169	Open	20
21	Gallows Gate	150	Open	19
31	West Country Inn	198	Partly closed	29
34	Bratton Down	320	Open	26

TABLE 2 Height And Exposure of Coastal Stations

Station Number	Name	Height (m)	Exposure	Comparative Coastal Station
3	Poltimore Bowls	15	Open	12
19	Slade Cross	137	Partly closed	21
20	Stopgate Cross	253	Open	13
26	Sourton Cross	277	Open	34
29	Halwill Junction	180	Partly closed	31
33	Yollacombe	150	Partly closed	31

TABLE 3 Observations for Easterly Airstreams

		COASTAL			INLAND		
WIND			MIN TEMP.*			MIN TEMP.*	
(m/s)	DATE	STATION	ROAD	AIR	STATION	ROAD	AIR
0-2.5	12/12/91	12	-2.5	-4.0	3	-4.5	-6.5
		13	-4.0	-3.5	20	-5.0	-3.0
		21	-2.0	-2.0	19	-4.0	-5.0
	15/01/91	12	5.5	5.0	3	5.0	4.0
		13	3.5	3.0	20	3.0	2.5
		21	4.5	4.0	19	4.0	3.0
	31/01/92	12	0.5	-0.5	3	-1.0	-2.5
		13	-1.5	-1.5	20	-2.0	-2.5
		21	1.5	1.5	19	-1.0	-1.0
2.5-5	11/12/91	12	0.0	-1.0	3	-1.5	-3.0
		13	-3.5	-3.0	20	-4.0	-3.0
		21	0.5	-1.0	19	-1.0	-2.5
	14/12/91	12	-1.5	-3.5	3	-2.0	-4.0
		13	-2.5	2.5	20	-2.0	3.5
		21	-0.5	2.5	19	-2.5	-0.5
	23/01/92	12	-1.0	-1.5	3	-2.0	-2.5
		13	-3.0	-3.0	20	-4.5	-2.5
		21	-0.5	-0.5	19	-2.5	-1.5
5-7.5	07/02/91	12	-5.5	-5.0	3	-5.5	-5.5
		13	-8.5	-7.0	20	-7.5	-7.5
	08/02/91	12	-6.5	-7.0	3	-8.0	-9.5
		13	-6.0	-4.5	20	-7.5	-5.5

* TEMPERATURES IN °C

TABLE 4 Observations for Northerly Airstreams

		COASTAL			INLAND		
WIND			MIN TEMP.*			MIN TEMP.*	
(m/s)	DATE	STATION	ROAD	AIR	STATION	ROAD	AIR
0-2.5	05/02/91	31	-4.0	-4.0	29	-4.0	-4.0
		34	-4.5	-3.0	26	-3.5	-3.0
	02/02/92	31	3.0	2.0	29	2.0	-0.5
		34	-1.0	-1.5	26	-3.0	-2.5
	09/03/92	31	0.5	0.5	29	0.5	-0.5
		34	0.0	-1.0	26	1.0	3.0
2.5-5	10/02/91	31	-3.5	-2.0	29	-5.0	-3.0
		34	-4.5	-2.0	19	-5.5	-4.0
	09/11/91	31	4.0	6.0	29	2.0	6.0
		34	4.0	4.5	33	2.5	4.5
	27/03/92	31	2.5	2.5	29	1.0	3.5
		34	1.5	1.5	26	1.5	3.0
5-7.5	13/02/91	31	-4.5	-3.5	29	-5.0	-5.0
		34	-5.5	-1.5	26	-6.0	-4.5
	28/03/92	31	2.0	4.5	29	2.0	4.0
		34	2.0	2.5	26	1.0	3.0

* TEMPERATURES IN °C

TABLE 5 Synoptic Conditions for Easterly Occasions

DATE	PRESSURE PATTERN	WIND VELOCITY	WEATHER CONDITION
07/02/91	ANTICYCLONIC	5 m/s NE	MAINLY CLEAR
08/02/91	CYCLONIC	6 m/s NE	CLEAR, SNOW FURTHER EAST
11/12/91	ANTICYCLONIC	4 m/s E-NE	MOSTLY CLEAR
12/12/91	ANTICYCLONIC	1 m/s E	MOSTLY CLEAR
14/12/91	ANTICYCLONIC	4 m/s E	PARTLY CLOUDY
15/01/92	ANTICYCLONIC	2 m/s SE	PARTLY CLOUDY
23/01/92	ANTICYCLONIC	3 m/s SE	PARTLY CLOUDY
31/01/92	ANTICYCLONIC	2 m/s E	MOSTLY CLEAR, MISTY

TABLE 6 Synoptic Conditions for Northerly Occasions

DATE	PRESSURE PATTERN	WIND VELOCITY	WEATHER CONDITION
05/02/91	ANTICYCLONIC	2 m/s N-NE	PARTLY CLOUDY
10/02/91	CYCLONIC	3 m/s N	MOSTLY CLEAR
13/02/91	ANTICYCLONIC	5 m/s N-NE	CLEAR
09/11/91	CYCLONIC	3 m/s NW	PARTLY CLOUDY
02/02/92	ANTICYCLONIC	1 m/s N-NE	MOSTLY CLOUDY, MISTY
09/03/92	ANTICYCLONIC	1 m/s N-NE	PARTLY CLOUDY
27/03/92	ANTICYCLONIC	4 m/s N	PARTLY CLOUDY
28/03/92	ANTICYCLONIC	6 m/s N	PARTLY CLOUDY

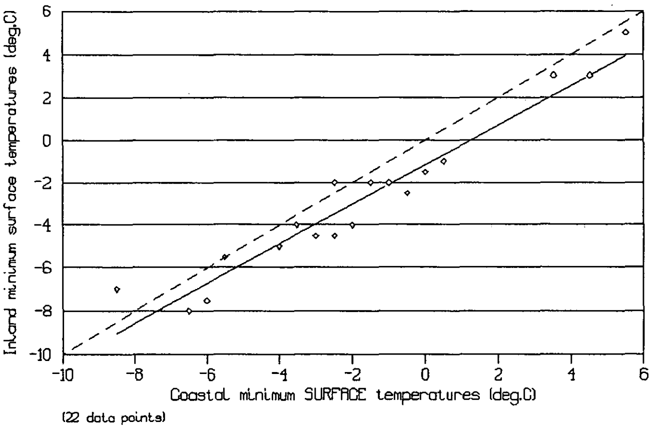

FIGURE 2 Graph showing road-surface temperatures for easterly winds below 7.5 m/sec.

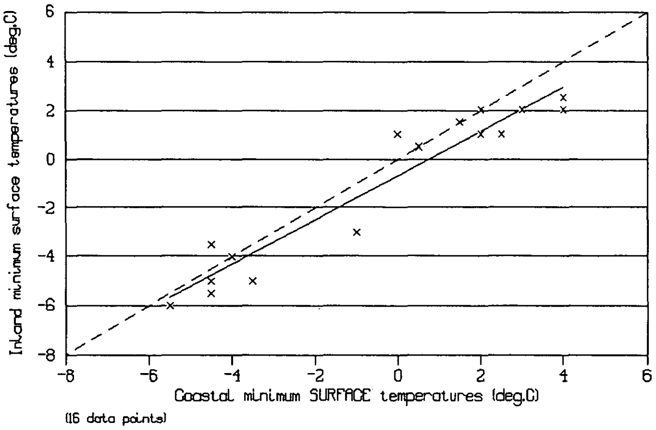

FIGURE 4 Graph showing road-surface temperatures for northerly winds below 7.5 m/sec.

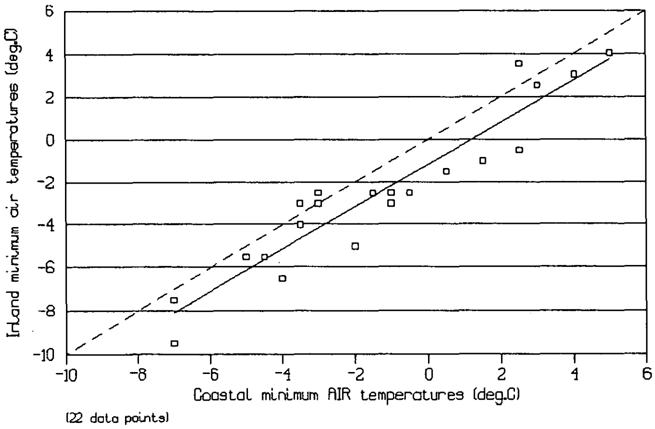

FIGURE 3 Graph showing air temperatures for easterly winds below 7.5 m/sec.

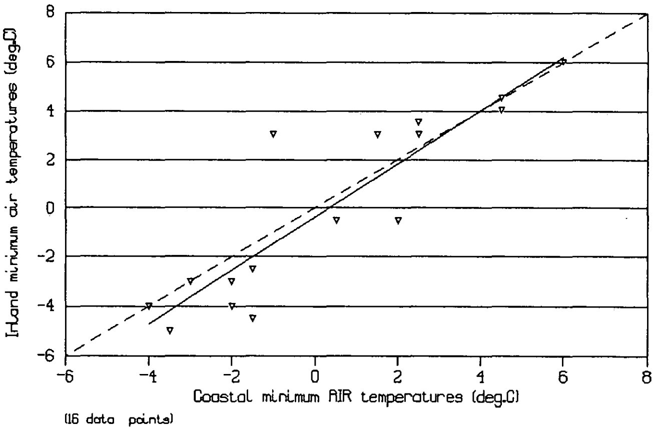

FIGURE 5 Graph showing air temperatures for northerly winds below 7.5 m/sec.

Clouds also played an important part because on occasions they tended to move in from the sea to the more coastal areas whereas inland skies remained relatively clear. These are the occasions in which temperature deficits were 3°C. This is true only for the easterly occasions, because cloud cover tended to be more widespread during the northerly airstream, when cloud cover was more likely to occur. However, when clouds were more widespread, the difference between coastal and inland stations was minimal. There were very few occasions when skies were completely clear across the whole county.

The results for Station 13 were fairly unconvincing. This may be because most of the time that easterly winds occurred, they came from a more northeasterly direction. At these times winds were not directly from the sea at Station 13, so there was no coastal influence.

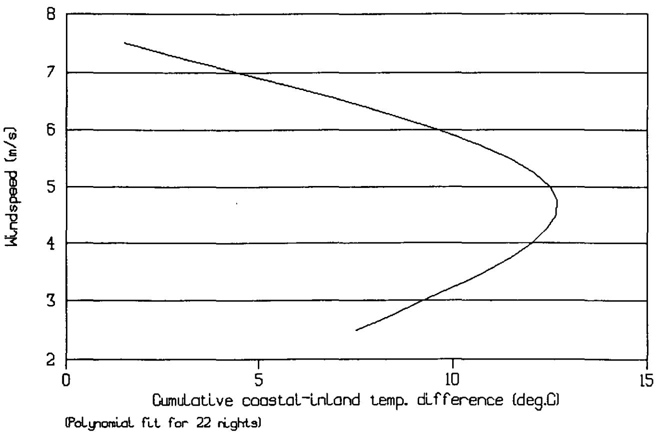

FIGURE 6 Easterly wind speed influence and coastal warming.

Referring to Figure 6, a maximum effect of coastal warming is noted at about 5 m/sec. The microclimate of the immediate environment is more important at low wind speeds. At wind speeds above 5 m/sec, the effect again reduces and the altitude of the station becomes the controlling factor on minimum surface temperature.

The effect of varying wind speed on coastal warming does not occur for northerly winds because the polar maritime was generally more cloudy than the polar continental air mass. The effect of cloud cover reduced the cooling inland; therefore, the warming effect was reduced. The topography of the road weather stations on the north coast also played an important factor, in that the stations are at relatively high altitudes. Therefore, the nocturnal cooling was less intense generally than it would be at lower-altitude stations, reducing the difference between coastal and inland stations.

TABLE 7 Results from Regression Analysis of Each Graph

GRAPH	WIND DIR.	TEMPERATURE	R^2
FIGURE 2	EASTERLY	ROAD	0.93
FIGURE 3	EASTERLY	AIR	0.89
FIGURE 4	NORTHERLY	ROAD	0.92
FIGURE 5	NORTHERLY	AIR	0.81

CONCLUSION

A warming influence was found to exist on the coastal road weather stations when winds were onshore; it was especially noticeable on the south coast when winds were easterly. The warming effect was found to be between 1 to 3°C, and the most noticeable warming occurred when windspeeds were near 5 m/sec. At wind speeds greater than 5 m/sec the altitude was the predominant influence on the temperature, whereas at less than 5 m/sec the local topography was found to be more important.

Although on the north coast a warming influence occurred when winds were northerly, it was less marked than the effect on the south coast—mainly because the stations were at a higher altitude and because the northerly airstreams tended to be more cloudy.

ACKNOWLEDGMENTS

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PART 10

Weather Forecasting

Description of a Local Climatological Model for Improvement of Winter Road Surveys

JÖRGEN BOGREN AND TORBJÖRN GUSTAVSSON

The local climatological model developed at the University of Gothenburg is described. The control measurements are mainly focused on two parts of the model: variation in road surface temperature under different synoptic conditions, and control functions in the model. The temperatures calculated by the model have been evaluated by use of temperature recordings along road stretches during different weather conditions. Both the actual road surface temperatures and the geographical extension have been analyzed, and the results show an overall good agreement between calculated and measured temperatures. Tests of the model were also carried out by use of temperature recordings from stations in the road weather information system. Analyses of temperature recordings from the field stations showed that the control functions included in the model are sufficient to separate the main types of weather conditions. However, it is necessary to develop the functions to take all possible temperature patterns into account. A possible way of developing the control criteria would be to include a comparison with historical temperature distributions before the data are extrapolated to be valid for road stretches.

Since the mid-1970s, research and development with emphasis on road climatology has been carried out at the Department of Physical Geography, University of Gothenburg. In 1985 a project started with the chief aim to develop a local climatological model to help in determining temperature variations along road stretches. The results from this project are reported elsewhere (*1–3*).

The system used today for surveying road slipperiness, the road weather information system (RWIS), consists of field stations at sites that are frequently exposed to slipperiness. The stations are connected to a central computer that enables surveillance of the road net. Lindqvist and Mattsson present the development of this system and a climatological background (*4*).

The idea behind the RWIS is that field stations are located at such sites that an indication of risk of slipperiness is received as early as possible. Since different weather situations give rise to different types of slipperiness, the stations are also located at different topographical sites: in shady areas, in valleys, or on bridges.

A disadvantage of today's RWIS is that only very localized information is received about temperature and risk of slipperiness, that is, long stretches of the road net lack sufficient surveillance. An extrapolation of data from the stations that is valid for road stretches is not possible without some kind of conversion in relation to the local topography. A method of accomplishing such a conversion would be to use a local climatological model of the type developed at the Department of Physical Geography. The model is developed by analysis of recordings from RWIS stations and from thermal mappings along road stretches. The result of this analysis is a number of empirical formulas with whose aid the relationship between local climate, topography, and weather is determined. The model is founded on the basic principle that a certain temperature pattern is repeated under similar weather conditions. Furthermore, the model uses the thermal mappings carried out along the road section in question and data from RWIS stations in the surroundings to determine the temperature variations along a road stretch.

This paper deals with tests of the local climatological model that have been performed within the frame of the project ARENA—TEST SITE WEST SWEDEN. The county of Halland in southwest Sweden was chosen as a test area, since an adaptation and application to this district were carried out during the development of the model (Figure 1). This paper focuses on

1. Control of the model's accuracy in relation to temperature measurements by a thermal mapping vehicle, and
2. Control of the model's function in relation to historical RWIS recordings and weather observations from synoptic weather stations in the area.

The methods used for control of the accuracy and function of the model are based on an analysis of thermal mappings and direct measurement results from the RWIS stations during different weather situations. Data from the two synoptic weather stations at Glommen and Torup were used for determining the amount of clouds and the regional wind velocity, which makes it possible to control the function of the model.

LOCAL CLIMATOLOGICAL MODEL

The use of topoclimatological parameters offers a possibility to establish the temperature variations along a road stretch under different weather conditions. The fundamental topographical parameters used as input for the calculations of these

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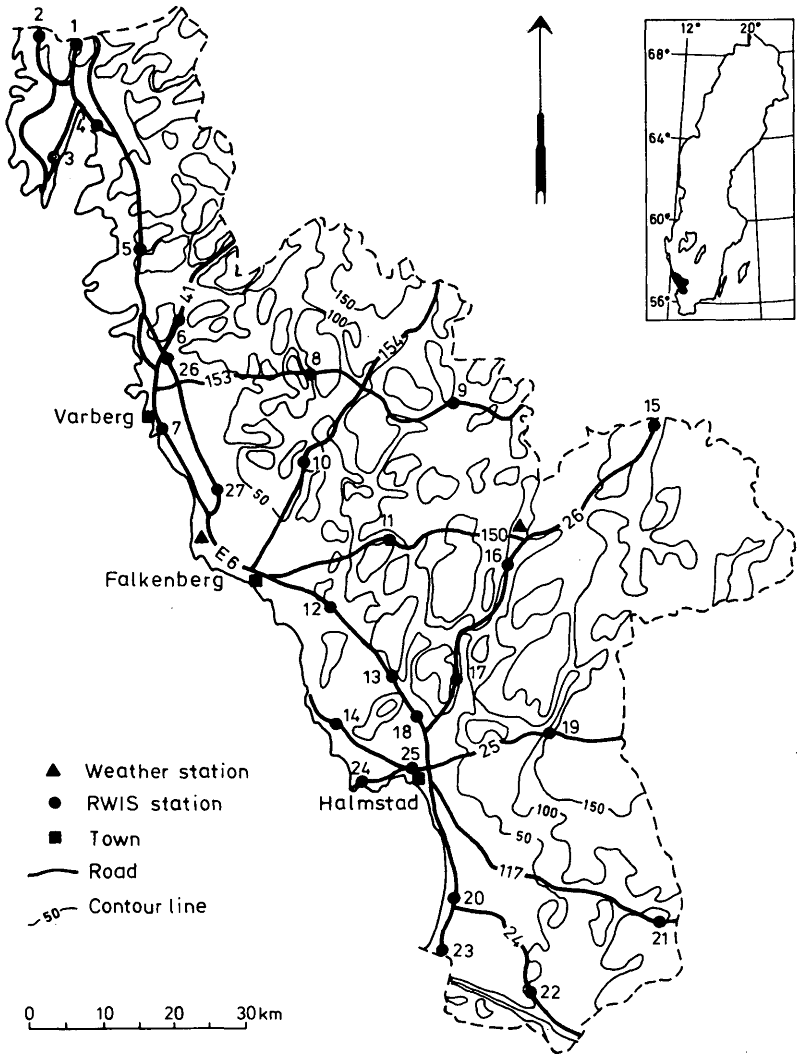

FIGURE 1 Map showing county of Halland with RWIS stations.

variations are

- Valleys: size (width and depth) determine the gathering and pooling of cold air. Exposure to wind is also an important factor for the formation of pooling and stagnation.
- Shaded areas: objects causing shadow can be described by form and size parameters in combination with orientation and distance from the road.
- Altitude: variations in altitude along the road are determined at 50-m intervals.
- Bridges: construction material, length and volume, and type are factors affecting the temperature pattern.

Other factors that must be included when discussing a specific area are proximity to water (large lakes or the sea) and the regional climate of the area.

When applying the model to a specific area, thermal mapping by car for the road sections in question as well as access to historical RWIS data are required. The data obtained from thermal mapping by car, along with analysis of topographical maps, give information of areas exposed to temperature fluctuations. The magnitude of the fluctuations under different weather conditions and between different areas is revealed from this type of data. The measuring trips by car also serve as a basis for division into topoclimatological segments along road stretches. Historical data from RWISs in the area are used to confirm the temperature fluctuations determined from the thermal mappings. These data also form the basis for establishing the temperature variations that can occur within the given area and for separating different types of temperature variations conditioned by the weather.

The different road stretches are classified with the aid of topographical maps but also by field measurements and field controls. The latter are especially important when it comes to establishing the exact orientation of road stretches and the type of objects causing shadow, which, in turn, is entirely decisive for the determination of shadow effects.

The relative extension and location of every type of segment included in the model are determined by integrating the information derived from the analysis of temperature data and information from maps and field controls. From the analysis of thermal mappings and RWISs, the basis is given for the formulas showing the relative temperature difference.

TEST OF LOCAL CLIMATOLOGICAL MODEL

For each section of the road stretches, a separate estimate is made for the prevailing temperature situation. The different temperature situations in question are the temperature patterns for (a) day/clear, (b) night/clear, (c) temperature reduction by altitude, and (d) regional pattern.

Day/Clear

Situations with the temperature pattern day/clear are characterized by large temperature variations occurring within a short stretch. The low temperatures are connected to road rock cuts, dense vegetation, or other objects shedding a dense shadow over the road. The difference in temperature arising on clear days between a screened and a sun-exposed area is determined, except for the shading object's properties, by the position of the sun.

Owing to the seasonal variation of the sun's course, the maximum possible temperature difference between sun-exposed and screened areas varies during winter from about 2°C in early January to as much as 15°C in the end of March. This relation between solar elevation and potential temperature difference is used for the calculation of screening effects during day/clear conditions. By knowing the day of the year the solar elevation is calculated, it is possible through the model to determine the relative temperature pattern formed by the alternating sun-exposed and screened parts along the road stretches. The relation between daily maximum solar elevation and the magnitude of road-surface temperature differences during day/clear conditions is illustrated in Figure 2.

When a road stretch is considered for the clear days, a division into five units is used, S0 through S5, where the index refers to the time of the day at which the road is screened:

- S0 = exposed to sun,
- S1 = screened in the morning,
- S2 = screened during noon,
- S3 = screened in the afternoon,
- S4 = S1 and S2 in combination, and
- S5 = S2 and S3 in combination.

A thermal measurement by car was carried out along Road 153 during February 27, 1991, at noon. The weather was characterized by a clear sky and a light wind. For this situation the road surface temperature is calculated by the model to −1.6°C for the S2 and S4 segments, whereas the S0 segments are calculated to 5.8°C, giving a difference of 7.4°C between screened and sun-exposed segments.

A comparison between calculated and measured values (Table 1) shows that the regions segmented as screened sites have the lowest temperatures. The difference in absolute temperature between calculated and measured values is tolerably small. The largest differences appear at sun-exposed S0 seg-

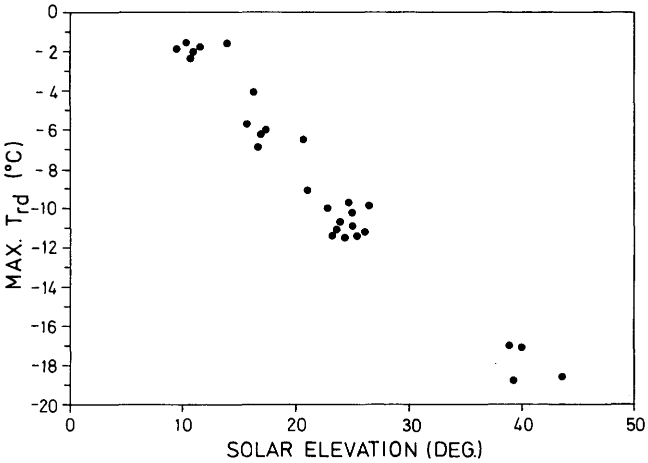

FIGURE 2 Plot of solar elevation versus maximum road-surface temperature difference (MAX.Trd) between sun-exposed and screened areas.

TABLE 1 Control Measurements Along Road 153 on February 27, 1991, at 12:00 p.m.

Distance (km)	Type of segment	Calculated temp. (°C)	Measured temp. (°C)	Difference
0-11.5	S0	5.8	6.4	0.6
11.5-12.5	S2	-1.6	-2.0	0.4
12.5-15.2	S0	5.8	7.7	1.9
15.2-16.5	S4	-1.6	-2.1	0.5
16.5-17.8	S0	5.8	4.1	1.7
17.8-19.3	S4	-1.6	-1.6	0
19.3-22	S0	5.8	6.0	0.2
22-23.5	S4	-1.6	-1.8	0.2
23.5-25	S0	5.8	5.4	0.4

ments, 1.9 and 1.7°C, respectively. This can be explained by the inclination of the road. Most important is that the calculated values for the screened segments differ marginally from the measured ones and also that the error is negative, that is, the calculated value indicates a somewhat lower temperature than the measured value. The error is throughout less than 0.5°C for seven of nine segments, which must be regarded as a good agreement between calculated and measured temperature values.

Night/Clear

The differences in temperature during clear nights are mainly determined by two factors: the possibility of cold air pooling and the exposure of a certain area to wind. Cold air pooling occurs in low-lying parts, such as valleys and small hollows, provided that there are open surfaces that can drain the cold air to the bottom. There is an obvious connection between the depth and width of a valley and the temperature difference arising between the bottom and the top of the valley (*5*). This geometrical dependence makes it possible to calculate the temperature variation caused by different types of valleys.

The presence of valleys and small-sized hollows is generally entirely decisive for the variation in air and surface temperature during clear nights with light winds. As far as the county of Halland is concerned, however, the exposure to wind is the most important factor. This is due to the geographical position, that is, the proximity to the sea, as well as the variation of the forest cover within the county. The regions in which a large cold air pooling could occur are the open areas near the sea. The formation of strong cold air lakes is often prevented, however, since within this area the exposure to wind is so great that the air cannot be stabilized.

When examining historical data from the RWIS stations in the county of Halland and from the measuring trips by car that were carried out as a basis for situating the stations, it was ascertained that the regions with the lowest temperature values during clear nights are the forested areas in the eastern part of the county. However, also within this part variations occur governed by the local topography and the different degrees of forest density.

The fact that the lowest temperatures occur within the forested area complicates the calculation of the variation in surface temperatures considerably. The canyon created on both sides of the road that passes through a dense forest influences the air and the road surface in different ways. The forest canyon causes the wind exposure to be minor, and thereby a stabilization of the air can easily occur. It is comparatively common for the stations in the eastern part to have air temperatures that are 6 to 10°C lower than those of the western stations.

The road surface, however, is not affected in the same way as the air by the surrounding forest. The cooling of the road is reduced considerably because of the back radiation emanating from the nearest trees—that is, the surface radiation is prevented by trees, which causes the temperature drop to be less than would be the case if an equally large difference in air temperature affected the road within an open area.

The largest variation in temperature in the study area occurs between the coastal zone and the eastern forested area, as previously discussed. Because of this, the control measurements have been focused on the roads perpendicular to the coastline and which crosses the forested part of the county.

During the night of November 20–21, 1991, two measurements by car were carried out along Road 153, where Stations 8 and 9 are located. The first measurement trip started at 8:00 p.m. and the second at 5:00 a.m., both at the road crossing E6/153.

Both temperature recordings gave the same result: a general decrease of the air temperature by approximately 5 to 6°C from the coastline toward the county border. However, no such general trend can be found for the road-surface temperature. This can be explained by the matter previously discussed: namely, the reduced drop in surface temperature in the forested part of the count owing to the obstruction of the long-wave radiation caused by the trees close to the road.

The result from the control measurements and the calculated surface temperature values by use of the local climatological model are presented in Table 2. There is a general good agreement between the calculated and measured temperatures: 9 segments out of 11 agree within 1.0°C. However, further studies are planned to deal with the relationship between a specific sky view factor and the surface temperature development. Formulas based on this type of relationship will further increase the readability of the predictions produced by the model.

Temperature Reduction by Altitude

During situations when the sky is overcast and it is windy, the temperature variations caused by local topography are greatly reduced. When wind and clouds cause the air mass of the atmosphere to mix completely, the temperature pattern is determined by the altitude above sea level—that is, the temperature drops by increased altitude above sea level.

As for Halland, the altitude conditions vary from 0 and 200 m above sea level. This implies that temperature differences of 1.5 to 2°C can arise under overcast and windy conditions. Figure 3 exemplifies a situation in which temperature reduction by altitude is prevailing (December 8, 1991, 8:00 p.m.). The surface temperatures at the different RWIS stations in the county are plotted against the altitude. The sky was overcast with winds varying from 2 to 6 m/sec. The lowest air temperature, 2.1°C, was recorded at the highest-situated RWIS station, Station 19. A regression analysis shows a good correlation between altitude above sea level and surface temperature. The regression function

$$\text{RST} = 4.0 - 0.01H$$

where RST is the road-surface temperature and H the altitude above sea level indicates a decrease in temperature by the equivalent of 1°C/100 m. The correlation is .77, which means that the relationship can be considered ensured.

The model tests whether this temperature pattern (temperature reduction by altitude) will be valid with light or strong winds prevailing and whether the criterion day/clear has been eliminated during daytime. A validity test of the pattern implies that the temperature reduction calculated should

TABLE 2 Control Measurements Along Road 153 on February 20–21, 1991, at 8:00 p.m. and 5:00 a.m.

Segment	Calculated temp. (°C) 2000 h	Measured temp. (°C) 2000 h	Calculated temp. (°C) 0500 h	Measured temp. (°C) 0500 h
1	-4.5--5.5	-3.5--4.5	-7.0--8.0	-7.0--8.0
2	-4.5--5.5	-4.5--5.5	-6.0--7.0	-6.0--7.0
3	-3.5--4.5	-2.5--3.5	-5.0--6.0	-5.0--6.0
4	-4.5--5.5	-4.5--5.5	-6.0--7.0	-7.0--8.0
5	-3.5--4.5	-3.5--4.5	-5.0--6.0	-6.0--7.0
6	-4.5--5.5	-4.5--5.5	-8.0--9.0	-8.0--9.0
7	-3.5--4.5	-3.5--4.5	-7.0--8.0	-7.0--8.0
8	-4.5--5.5	-4.5--5.5	-8.0--9.0	-8.0--9.0
9	-3.5--4.5	-3.5--4.5	-7.0--8.0	-7.0--8.0
10	-4.5--5.5	-4.5--5.5	-8.0--9.0	-8.0--9.0
11	-3.5--4.5	-3.5--4.5	-7.0--8.0	-7.0--8.0

be less than 1.5°C/100 m and that the correlation should be high.

The temperature pattern in Figure 4 shows a calculated situation on January 16, 1991, at 11:00 a.m. for part of the northern region in Halland, which results in the temperature reduction by altitude. The thermal map shows the prevailing temperature pattern where the temperature difference is divided into four classes with a class width of 0.5°C (Figure 4). The lowest temperature in the high-lying parts is marked with a cross-ruled screen and is equal to −1.0 to −1.5°C. The highest temperature is marked in white, which is equal to 0.5 to 0°C, which means that the temperature span in this situation is a good degree between the coldest and the warmest parts. In this type of weather situation, the segmentation follows the absolute altitude above sea level along the road, and this temperature pattern is verified by the recorded temperatures at the RWIS stations in the actual area.

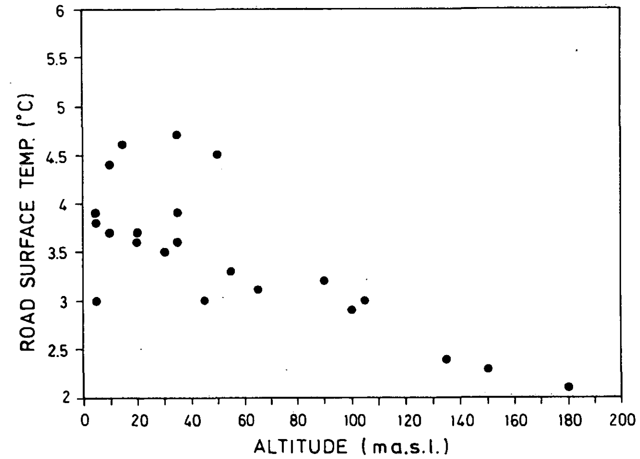

FIGURE 3 Plot of road-surface temperature versus altitude for RWIS stations in county of Halland during cloudy windy situation.

Regional Pattern

Regional pattern is the temperature criterion chosen by the model when day/clear, temperature reduction by altitude, and night/clear are eliminated from earlier calculations in the test algorithm.

The regional pattern is based on the segmentation being performed in such a way that an adaptation to existing RWIS stations can be done by a formula for each segment. An example of the segmentation used for regional pattern is shown in Figure 5. The situation is from January 16, 1991, at 2:00 p.m. The model tests whether there is a temperature reduction by altitude, but in this case the given condition is not fulfilled and the model chooses to work with regional pattern. The temperature distribution at the regional pattern is such that the variation cannot be systematically tied up to specific topographical parameters. In the case of temperature distribution regional pattern, the individual RWIS stations exert a direct importance for the different segments. The segments are placed in such a way that the geometrical distribution of the RWIS stations reflects the segments. The regional temperature distribution is therefore decisive for the determination of the formulas and for the segmentation in this type of situation.

DISCUSSION OF RESULTS

The advantage of using a local climatological model of the kind presented in this paper is not only that a complete temperature surveillance becomes possible but also that a considerably more differentiated picture can be received that can serve as an important aid when giving priority to combatting slipperiness in different areas or on road stretches within a working district. Moreover, the model offers great advantages when combining small surveillance areas into larger ones because, for an effective combatting of slipperiness, there is not the same need for local knowledge of areas exposed to slip-

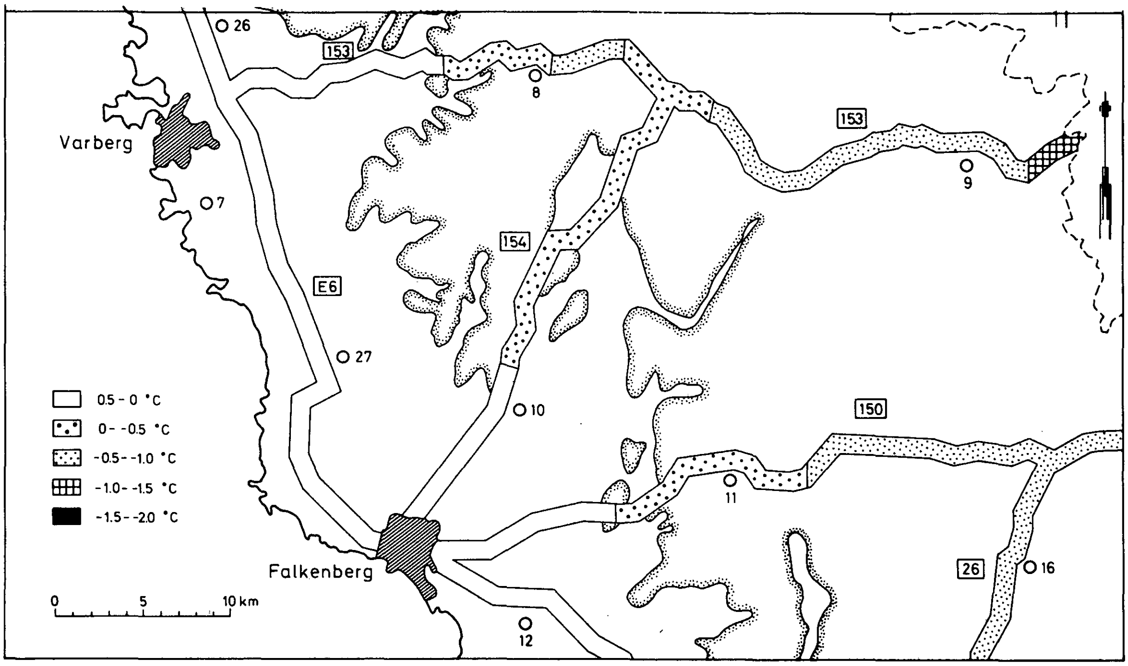

FIGURE 4 Calculated road-surface temperature for January 16 at 11:00 a.m.

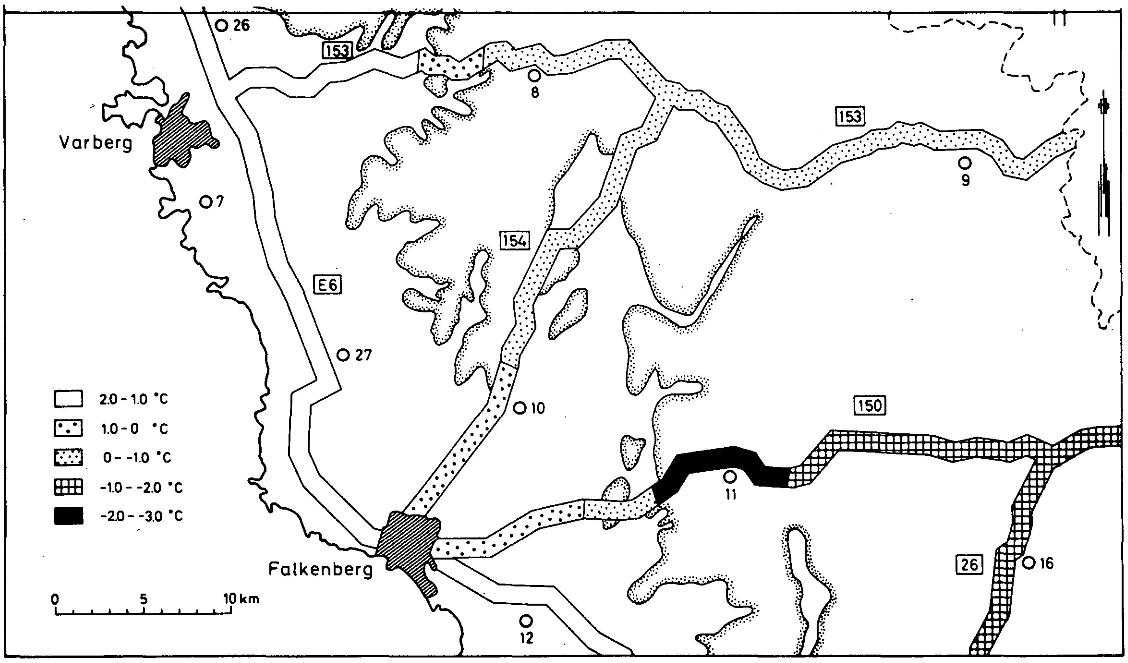

FIGURE 5 Calculated temperature distribution for episode categorized as regional pattern.

periness along certain road stretches. If the combatting of slipperiness can be made more effective, the number of accidents will decrease and the use of devices for eliminating slipperiness can be reduced.

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Description and Verification of a Road Ice Prediction Model

J. SHAO, J. E. THORNES, AND P. J. LISTER

The IceBreak model developed by Vaisala TMI is described in its physical bases. The model is verified and compared with the U.K. Meteorological Office model using roadside inputs of winter 1990–1991 at 11 sites in the United Kingdom. The results show that the IceBreak model has a near-zero bias and about 1°C standard deviation in overall and minimum temperature predictions. It provides improved accuracy in road ice prediction.

Winter road maintenance is a serious problem in Western and Northern Europe, North America, and some other countries. Snow and ice control for highways is very expensive and a difficult cost to control because of winter variability. To allow time for winter maintenance engineers to remove snow and prevent ice or frost formation or snow accumulation (such as by spreading deicing chemicals) in good time, an accurate prediction of road-surface temperature and conditions is necessary. In recent years, three numerical road ice prediction models have been developed in the United Kingdom specifically for this purpose (*1–5*). Some others have also been developed outside the United Kingdom, such as the Swedish (*6*), French (*7*), American SSI (*8*), and Finnish (*9*) models.

The IceBreak model developed by Shao (*5*) is in operational use in Europe and the United States, together with telecommunication display facilities developed by Vaisala TMI Limited (VTMI). Previous publications have described single-site verification and comparisons with the Thornes model and the U.K. Meteorological Office Road Ice Prediction Model (MORIPM) (*5,10*). In this paper, the physical and mathematical bases of the IceBreak model are described and the model is run at 11 sites in England and Scotland, using actual roadside data in winter 1990–1991 as input. These retrospective model runs (under ideal conditions) are then compared with the actual measurements to evaluate model performance, and the results are also compared with the MORIPM. Because of the restriction on availability of other models, the IceBreak model is compared only to the MORIPM. Surface status measurements (dry, wet, and icy) are often influenced by chemicals spread on the road, so only road-surface temperature is compared for the two models in the paper.

MODEL PHYSICS

The IceBreak model is constructed using an unsteady one-dimensional heat conduction equation. It is assumed that the road surface and underlying sublayer are horizontally homogeneous so that heat transfer in lateral directions ("edge effect") is neglected. The model considers a vertical pillar with unit cross-section area that extends from the surface to a depth of 1 m. The depth is considered to be deep enough to eliminate the diurnal oscillation of temperature. The governing equation to describe heat transfer in the sublayer is

$$C_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \tag{1}$$

where

C_m = volumetric heat capacity,
k = thermal conductivity, and
$T(z,t)$ = temperature at any time t at any grid point with depth z in the pillar.

The equation states that the rate of change of heat storage with time in a unit volume of sublayer is equal to the divergence of the vertical heat flux density across that volume. It is possible to construct a full three-dimensional model for heat flow under the road surface, but the resulting equations would be quite complicated and difficult to solve. For this reason, road edge effects are ignored and the temperature is taken to be a function of time and depth only.

Initial and boundary conditions for Equation 1 are required in order to fully pose a physically meaningful problem. The initial condition prescribes the temperature at every point in the pillar at an initial moment. It can be expressed as

$$T(z,0) = I(z) \qquad 0 \le z \le 1\,m,\ t = 0 \tag{2}$$

The boundary conditions are

$$T(z,t) = B(t) \qquad t > 0,\ z = 0 \tag{3a}$$

$$T(z,t) = \text{constant} \qquad t > 0,\ z = 1m \tag{3b}$$

where $I(z)$ and $B(t)$ are continuous functions. $I(z)$ is usually derived by Lagrangian interpolation, and $B(t)$ (the upper boundary condition) is set up using an equation for the road-surface energy balance. The heat fluxes on the road surface

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are described in Figure 1. The energy balance equation is

$$(1 - A_s)S + L'(T_0) - H(T_0) - LE(T_0) + G(T_0) = 0 \qquad (4)$$

where

S = solar irradiance,
A_s = surface albedo,
L' = net long-wave irradiance,
H,LE = sensible and latent heat flux densities,
G = ground conductive heat flux density, and
T_0 = road-surface temperature.

The parameterization of each of these parameters is described in more detail later.

By discretizing Equation 1 and Equations 2 through 4, a set of equations is derived; by solving this set of equations, the road-surface temperature and status are generated step by step forward in time.

PARAMETERIZATION

The aim of parameterization of Equation 4 is to develop a scheme that expresses or calculates the fluxes of heat and moisture in terms of easily measured or predicted meteorological variables such as air temperature, dewpoint temperature, mean wind speed, cloud cover, and cloud type.

Incoming solar radiation is the main heat source of the road sublayer and the "force" that drives changes in the road-surface temperature. It is expressed as

$$S = fS'\cos Z t_R t_g t_w t_p t_c \qquad (5)$$

where

S' = solar constant (1353 $\mathrm{Wm^{-2}}$),
Z = solar zenith angle,
f = factor to account for deviation in mean earth-sun distance,
t = transmission coefficient after: Rayleigh scattering (R), absorption by permanent gases (g), and water vapor (w), absorption and scattering by aerosols (p), and clouds (c).

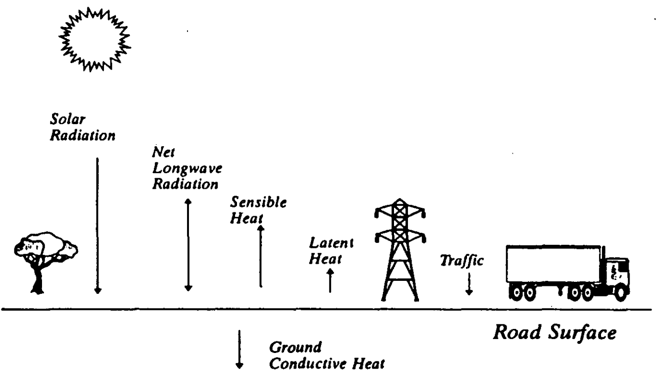

FIGURE 1 Road-surface energy budget.

The distance factor and solar zenith angle are computed from the astronomical equations:

$$f = 1 + 0.034 \cos [2\pi(N - 1)/365] \qquad (6)$$

$$Z = \arccos[\sin (L) \sin (d) + \cos (L) \cos (d) \cos (h)] \qquad (7)$$

where

N = Julian day,
L = latitude,
d = declination angle, and
h = hour angle.

Attenuation by Rayleigh scattering is given by the empirical formula developed by Kondratyev (*11*) and later modified by Atwater and Brown (*12*):

$$t_R t_g = 1.021 - 0.084 \sqrt{m(949p^{-5} + 0.051)} \qquad (8)$$

where p is pressure and m is the optical mass derived from

$$m = 35\sqrt{1224 \cos^2 Z + 1} \qquad (9)$$

Transmission after water vapor absorption is modeled according to an expression given by McDonald (*13*):

$$t_w = 1 - 0.077(wm)^{0.3} \qquad (10)$$

where w is the precipitable water calculated by Smith (*14*):

$$w = \exp[1.3709 - \ln(e + 1) + 0.07074T_d] \qquad (11)$$

where e is a latitudinally dependent constant varying from 1.11 to 3.37 and T_d is the dewpoint temperature.

A simple treatment for aerosol attenuation given by Houghton (*15*) is adopted:

$$t_p = X^m \qquad (12)$$

where X is a constant (0.95). The cloud transmittance function is expressed as

$$t_c = 1 - \sum[1 - C_i(1 - c_i)] \qquad (13)$$

where C_i is the cloud amount and c_i is the cloud transmittance determined by field observations for the ith cloud layer (i = 3).

The net long-wave radiation comprises two components: the upward radiation from the pavement and the downward radiation from the sky. It is expressed as

$$L' = (L^{\downarrow} - L^{\uparrow})SVF \qquad (14)$$

where SVF is the sky view factor (*16*).

For simplicity, and because only limited meteorological observations are available at a typical forecast site, sensible and latent heat fluxes are estimated by the bulk method, which assumes that the transfer process within a well-mixed atmospherical boundary layer is proportional to the local gradient between the surface and the atmosphere multiplied by the wind speed:

$$H = -\rho c_p C_H u(T' - T_0) \tag{15}$$

$$LE = -\rho L C_E u(q' - q_0) \tag{16}$$

where

ρ = air density near surface;
c_p = specific heat of air at constant pressure;
L = latent heat of condensation;
C_H, C_E = bulk transfer coefficients for sensible heat and moisture;
u, T',q' = wind speed, potential temperature, and specific humidity at the height of sensor installation; and
T_0, q_0 = surface values.

In the IceBreak model, the influence of traffic has been considered by simulating a thermal radiative flux (Lv) from the warm vehicles:

$$L_v = \varepsilon C_v(T_a + D_v)^4 \tag{17}$$

where

ε = emissivity of vehicles,
C_v, D_v = traffic coefficients, and
T_a = air temperature.

COMPARISON

The IceBreak model and MORIPM are run on a 24-hr cycle, projecting forward from the measured noon road-surface temperature. The model input comprises six elementary meteorological variables: air temperature, dewpoint, wind speed, total cloud amount, dominant cloud type, and precipitation. For the Meteorological Office model, low-cloud amount is also needed. All these meteorological input variables are in three-hourly intervals.

The sites tested for comparison were chosen on the basis of the road classification: motorways (M), dual and single carriageways (A or B), and bridge decks. The 11 sites are given in Table 1. The actual roadside input data (except cloud and precipitation) were extracted from roadside sensor measurements in the daily files from November 1, 1990, to February 28, 1991. The cloud amount, cloud type, and precipitation were derived from observations of nearby weather centers. If enough site information was not obtained, the site parameters such as transmission coefficients and the height of well-mixed layer and traffic coefficients were taken to be the same as those derived at Chapman's Hill site, at which the IceBreak model was developed. Only road-surface emissivity (0.940 to 0.975), roughness length (0.5 to 3.0 cm), thermal conductivity, and capacity of the road sublayer are allowed to vary from site to site. The conductivity has a value of either 1.3 $\mathrm{Wm^{-1}K^{-1}}$ (asphalt) or 1.5 $\mathrm{Wm^{-1}K^{-1}}$ (concrete and soil). The heat capacity is either $1.3 * 10^6$ $\mathrm{Jm^{-3}K^{-1}}$ (asphalt) or $1.5 * 10^6$ $\mathrm{Jm^{-3}K^{-1}}$ (concrete and soil). The data base of site parameters for the MORIPM was provided by the U.K. Meteorological Office and then improved at the University of Birmingham for the values of emissivity, thermal properties, surface albedo, and roughness length for each site (*17*).

TABLE 1 Test Site Information

Site Name	Site Code	Weather Center	Road Type	Height (m)
Chapman's Hill	WN003	Birmingham	M5/concrete	200
Thurcroft	XM005	Leeds	M1/asphalt	100
Slochd Summit	IN002	Aberdeen	A9/asphalt	380
Tyrebagger	GR003	Aberdeen	A96/asphalt	36
Barton Mills	SF001	Norwich	A11/concrete	10
Siddington	CH007	Manchester	A34/asphalt	30
Windsor Park	BR006	London	A332/asphalt	88
Grange Moor	KB003	Leeds	B6118/asphalt	220
Stubbin Road	RO013	Leeds	B6089/asphalt	60
Ray Hall	WN002	Birmingham	M5/M6/bridge	123
West Linton	BO001	Glasgow	A702/bridge	200

Each model was run at an initial time of 1200UTC and compared with hourly measurements of road-surface temperature. Table 2 shows the overall errors on the basis of an hourly comparison throughout the winter, and the errors in daily minimum and maximum temperature predictions. The errors are quantified by bias, standard deviation (*SD*), and root-mean-square (*RMS*) error. A physically sound numerical model is expected to produce a bias, *SD*, or *RMS* near zero under the ideal conditions for every site. It is seen from the table that the IceBreak model has a nearly zero bias and about 1-degree *SD* or *RMS* error for all of the sites, whereas the bias and *SD* or *RMS* error of the MORIPM vary widely from site to site. The results show that the IceBreak model produces a higher accuracy in the simulation of overall (every hourly simulation on every day) and minimum road-surface temperatures. Generally, the IceBreak model has a smaller bias and a smaller *RMS* error (except site IN002 and KB003) with a narrower band of variation, and the MORIPM has an obvious cold bias and a larger deviation for most of the sites. However, in the prediction of maximum temperature, the MORIPM is slightly better than the IceBreak model.

Minimum temperature prediction is one of the most important aspects for the highway engineer. Figures 2 through 12 show the frequency distribution of the difference between predicted and actual minimum temperatures for the models. On average, 43.6 percent of the IceBreak model's minimum predictions fall within the ±0.5°C tolerance band, as do 39.2 percent of the MORIPM predictions. For the 1-degree tolerance band, the figures are 73.6 percent for the IceBreak model and 68.5 percent for the MORIPM.

For the bridge sites (WN002 and BO001), the IceBreak model is significantly better than the MORIPM, except in the prediction of maximum road-surface temperature at West Linton. This means that the IceBreak model is more useful in road ice prediction for the most potentially dangerous sites.

For different road-surface conditions when actual road-surface temperature is above zero or below zero, the comparison between the two models show the same results as discussed earlier (see Table 3).

All these results demonstrate that the IceBreak model is more applicable than the Meteorological Office model.

CONCLUSION

The IceBreak model is a physically sound numerical road ice prediction model as shown by the comparison of bias, *SD*,

TABLE 2 Comparison of IceBreak and MORIPM Predictions: Winter 1990–1991

Site	No. of	Overall			Minimum		Maximum	
Code	Days	Bias	*SD*	*RMS*	Bias	*RMS*	Bias	*RMS*
WN003	103	-0.22	1.078	1.101	-0.17	0.863	0.10	1.521
	103	-0.77	1.198	1.426	-0.78	1.233	-0.10	1.572
XM005	108	-0.04	0.818	0.819	-0.16	0.869	0.35	0.965
	108	-0.29	0.834	0.884	-0.21	0.750	0.06	0.929
IN002	81	0.09	1.312	1.314	0.09	1.290	0.37	1.327
	81	0.05	1.132	1.132	0.31	1.006	-0.16	1.316
GR003	89	-0.32	1.006	1.054	-0.26	1.084	-0.03	1.132
	89	-0.98	1.073	1.453	-0.97	1.495	-0.52	1.198
SF001	111	-0.24	0.834	0.869	-0.02	0.899	-0.39	1.100
	111	-0.37	0.879	0.952	0.01	0.828	-0.49	1.177
CH007	88	-0.18	0.959	0.976	-0.18	0.958	-0.11	1.240
	88	-0.31	0.987	1.034	-0.19	0.961	-0.19	1.206
BR006	89	-0.19	0.972	0.990	0.08	0.868	-0.10	1.199
	89	-0.56	0.979	1.128	-0.34	0.933	-0.17	1.180
KB003	118	0.17	1.019	1.033	0.39	1.085	0.19	1.290
	118	0.26	0.951	0.986	0.65	1.174	-0.14	1.116
RO013	112	-0.31	0.860	0.914	-0.40	0.985	0.11	0.922
	112	-0.76	0.878	1.161	-0.94	1.215	0.03	0.948
WN002	108	-0.17	0.931	0.947	-0.22	0.814	-0.37	1.442
	108	-0.87	1.106	1.404	-0.90	1.349	-0.34	1.502
BO001	117	0.03	1.105	1.105	-0.09	1.140	0.65	1.303
	117	-0.83	1.216	1.470	-1.15	1.653	0.05	1.052
Mean		-0.12	1.026	1.048	-0.09	0.987	0.07	1.222
		-0.49	1.021	1.185	-0.41	1.145	-0.18	1.200

NOTE: For each site, the first line shows the results of the IceBreak model and the second line, for the MORIPM.

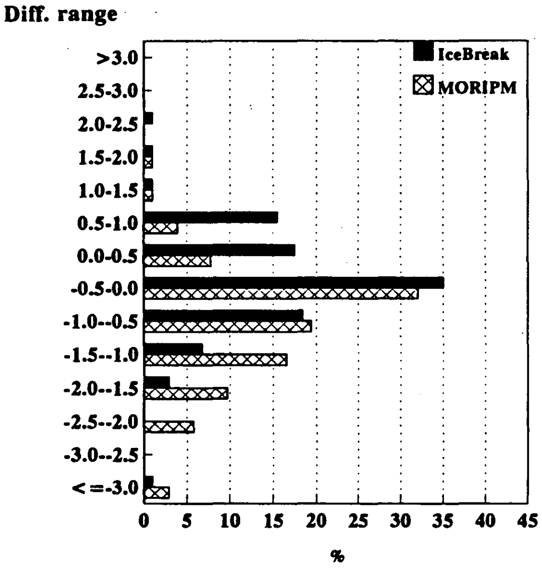

FIGURE 2 Frequency distribution of difference of minimum temperature, Chapman's Hill (WN003).

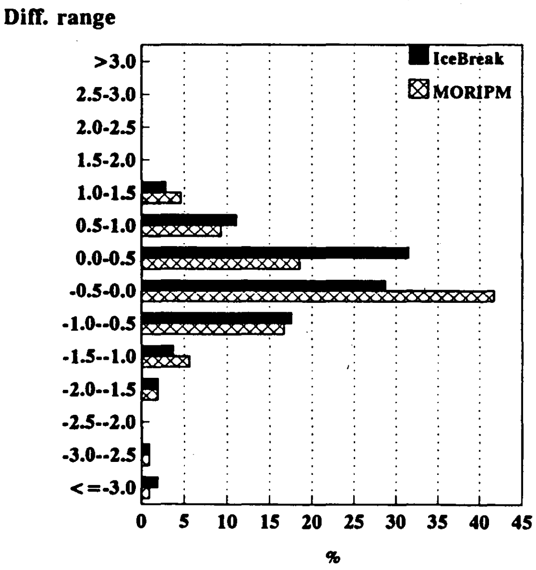

FIGURE 3 Frequency distribution of difference of minimum temperature, Thurcroft (XM005).

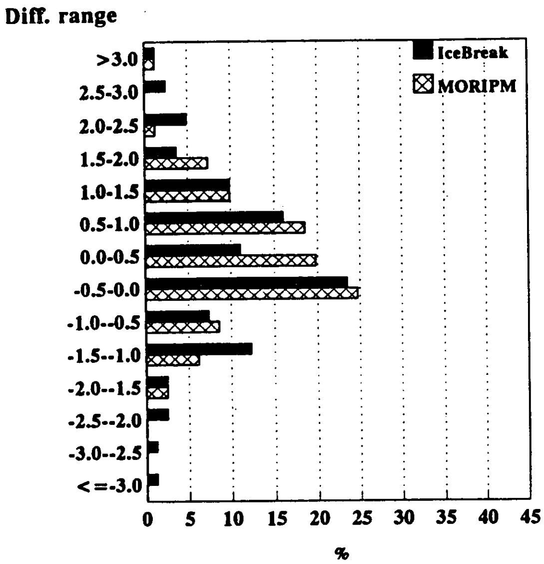

FIGURE 4 Frequency distribution of difference of minimum temperature, Slochd Summit (IN002).

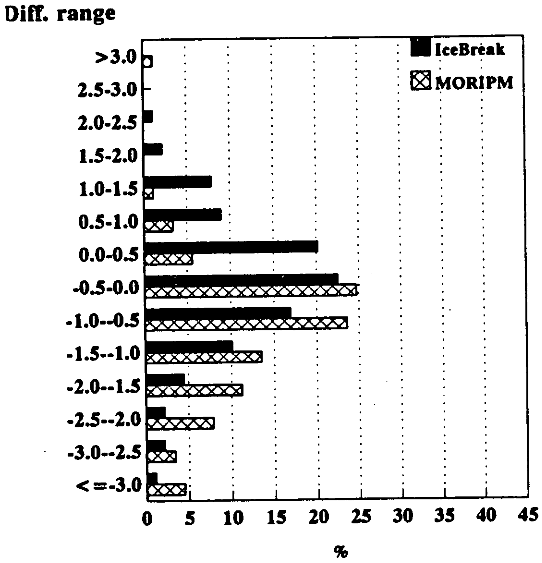

FIGURE 5 Frequency distribution of difference of minimum temperature, Tyrebagger (GR003).

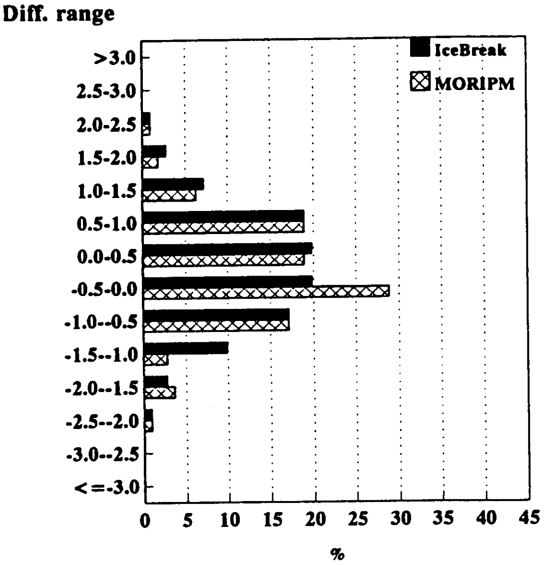

FIGURE 6 Frequency distribution of difference of minimum temperature, Barton Mills (SF001).

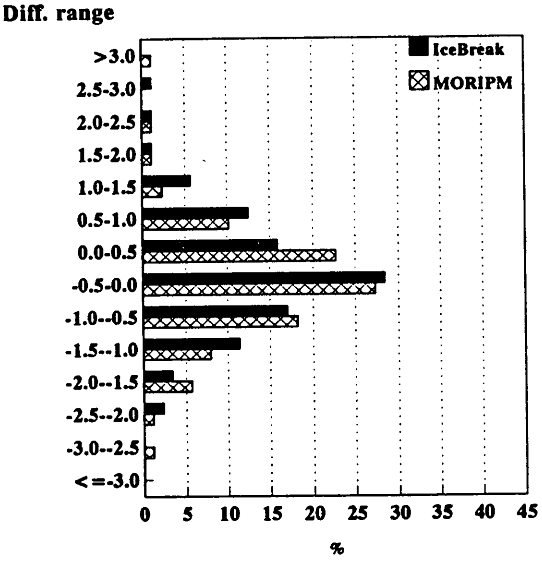

FIGURE 7 Frequency distribution of difference of minimum temperature, Siddington (CH007).

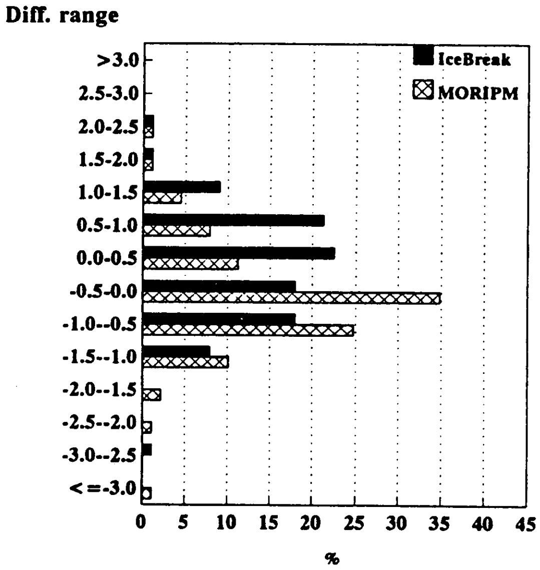

FIGURE 8 Frequency distribution of difference of minimum temperature, Windsor Park (BR006).

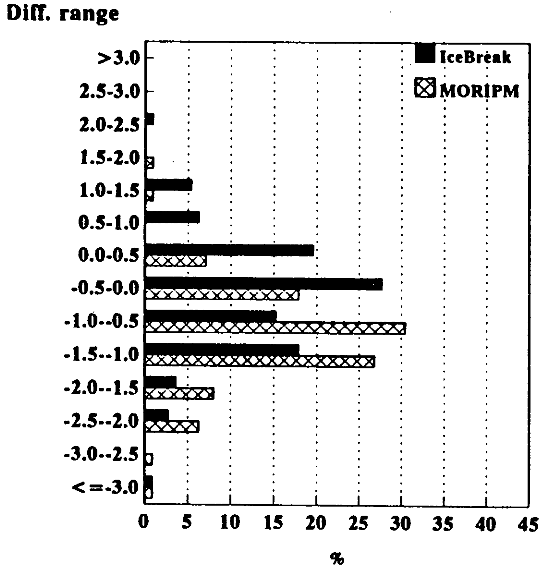

FIGURE 10 Frequency distribution of difference of minimum temperature, Stubbin Road (RO013).

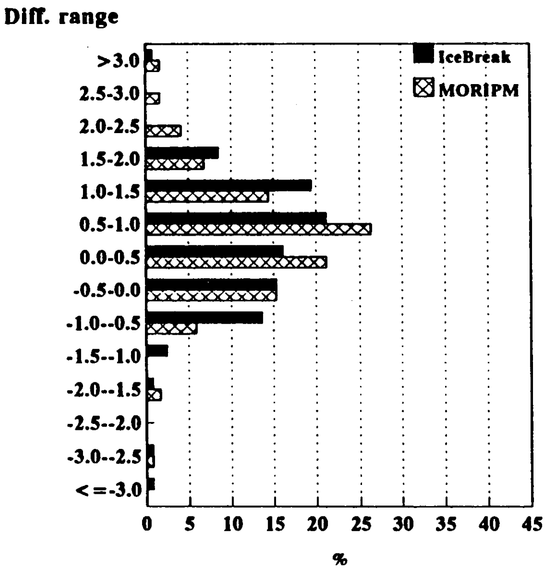

FIGURE 9 Frequency distribution of difference of minimum temperature, Grange Moor (KB003).

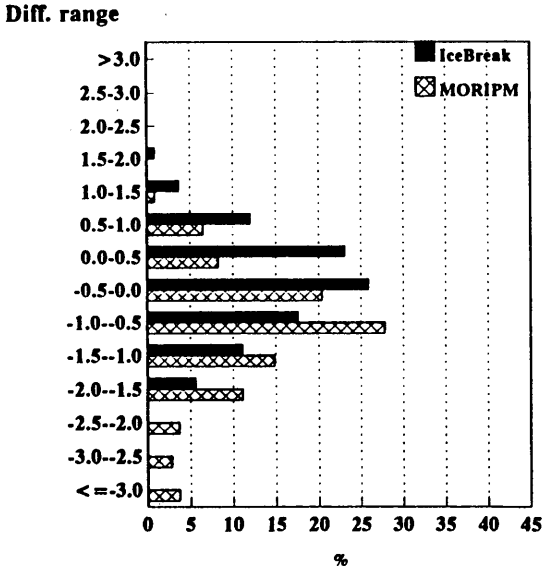

FIGURE 11 Frequency distribution of difference of minimum temperature, Ray Hall (WN002).

TABLE 3 Comparison of Model Forecasts with Actual Road Surface Temperature Above or Below Zero: Winter 1990–1991

Site Code	$T_s > 0°C$ IceBreak		MORIPM		$T_s \leq 0°C$ IceBreak		MORIPM	
	Bias	*RMS*	Bias	*RMS*	Bias	*RMS*	Bias	*RMS*
BO001	-0.16	1.08	-0.77	1.27	0.15	1.11	-0.86	1.58
BR006	-0.24	1.03	-0.60	1.16	-0.21	1.02	-0.50	1.08
CH007	-0.34	0.90	-0.51	0.97	-0.02	1.05	-0.09	1.09
GR003	-0.51	1.07	-1.13	1.60	0.09	1.01	-0.78	1.24
HW010	-0.33	0.99	-0.79	1.34	-0.19	1.55	-0.75	1.53
IN002	-0.06	1.07	-0.20	0.89	0.37	1.40	0.10	1.18
KB003	0.10	1.15	0.06	0.89	0.25	1.15	0.45	1.07
RO013	-0.38	0.90	-0.86	1.16	-0.13	0.96	-0.50	1.18
SF001	-0.25	0.83	-0.48	0.90	-0.23	0.96	-0.06	1.08
WN0022	-0.31	0.91	-0.93	1.37	0.11	1.01	-0.74	1.48
XM005	-0.14	0.83	-0.38	0.87	0.02	0.82	-0.13	0.91

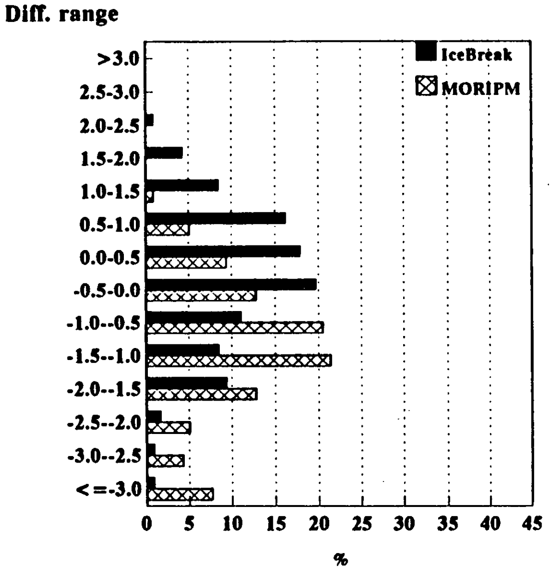

FIGURE 12 Frequency distribution of difference of minimum temperature, West Linton (BO001).

and *RMS* error in a retrospective analysis for 11 sites in England and Scotland. The results of the comparison show that the IceBreak model provides improved accuracy in the prediction of overall and minimum road-surface temperatures over one of the most widely used models in operational use, the MORIPM.

ACKNOWLEDGMENTS

The authors wish to thank P. Buchanan, S. Manstone, and A. Astbury of the U.K. Meteorological Office for their generosity in providing all the data required.

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Detailed Weather Prediction System for Snow and Ice Control

ELMAR R. REITER AND LUIZ TEIXEIRA

A computerized weather prediction system for snowstorms and blizzards was designed and tested extensively during the 1991–1992 winter in Colorado, and installed operationally in January 1993. The system contains several technological innovations. It uses the raw radiosonde and surface observations disseminated via satellite communication links by the National Weather Service. From these data a numerical prediction model generates forecasts at 3-min intervals over a 24-hr period, covering an area the size of the United States, but zooming in over a statewide area (e.g., Colorado) with much greater prediction details. The system runs on a 486 PC and relies on a detailed geographic data base with topographic elevations available in 1- × 1-km horizontal resolution. This data base is used to (a) compute the effects of terrain on weather development and (b) generate graphic displays of terrain and weather. A road network data base is also available for display. Terrain and predicted weather can be shown in several resolution steps, specified by the user, throughout the state, maintenance district, or county. The user can compare predicted weather (precipitation, temperature, winds, humidity) with actual data from sensors or human observers as they become available. If major discrepancies develop, the user can change forecasts locally or regionally by simple point-and-click operations on the computer screen, calling on embedded expert systems.

Highway maintenance operations currently rely on forecasts issued either by the media—which they presumably obtained from the National Weather Service (NWS)—or by vendors that redistribute NWS forecast products. Although the quality of these forecasts has improved steadily over the past few years, it still leaves much to be desired when tough decisions must be made on the basis of the weather. What does one do with a forecast for "30 percent chance for snow between one and five inches along the foothills tonight"? The "30 percent" means that in past history numerical weather forecasts looking similar over the area of concern ("the foothills") produced the predicted results ("one to five inches of snow") in approximately 30 percent of the cases. Meteorologists call this the model output statistics of a numerical prediction model (*1*).

A highway maintenance engineer needs different information, which is not easy to obtain under the current system:

- Is it going to snow or not?
- Where exactly is it going to snow? (The "foothills" in Colorado stretch from the Wyoming to the New Mexico borders and are hardly a precise indicator for individual snow patrols.)
- When is it going to start, and when is it going to end? ("Tonight" leaves too wide a margin for idle "cruising" time.)
- Is it going to come as snow, freezing rain, or rain? (Do we call out the plows, the sanding trucks?)
- If it comes as snow, will it first melt on the pavement, then freeze?
- How much snow can we expect? (1 in. might melt by itself; with 5 in. the plows will be out all night.)
- Will there be enough wind to cause snowdrifts that require plowing even after it stops snowing?
- What if observations show that the forecast is going off track? Can it be corrected to provide again useful information?

These are tough questions to which the media forecasts can hardly provide answers. Therefore, maintenance personnel usually assume the worst case. In Colorado the saying goes, "If it starts snowing, the second snowflake should hit the back of your truck." This may sound good, but it costs an awful lot of money. What if there are only two snowflakes in the whole "predicted" storm? The Colorado Department of Transportation budgets nearly $20 million each winter for snow and ice control. North America puts up in excess of $2 billion each winter for the same purpose. Estimates by the Matrix Corporation, Seattle, indicate that 10 percent or more of these amounts could be saved if we were smarter about weather.

STRIVING TOWARD AN IMPROVED SYSTEM

Timing Problem

Forecast output from the NWS comes in the form of weather maps for the whole United States, usually at 12-hr intervals, to be interpreted by professional or news media meteorologists. Having only two snapshots a day under highly variable weather conditions does not provide enough time resolution to allow precise forecasts. NWS does provide numerical forecasts at time steps of a few minutes, but the communication system is inadequate to handle information transfer with greater frequency than available now.

The WELS system does not require weather maps sent out by NWS. Instead it takes the raw observational data from North American stations distributed by NWS each morning and evening [at 00 and 12 Greenwich mean time, or 5 p.m. and 5 a.m. mountain standard time (MST)], then generates its own numerical forecasts with 3-min time steps. Saving and displaying forecasts at such short time intervals would be

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overkill. Displays at 3-hr intervals usually give enough time resolution to permit detailed tactical planning. The raw data needed to feed the prediction model are in hand 3 hr after the observations have been taken. To run a forecast on a 486/33 MHz machine takes less than 1 hr. Thus, detailed 24-hr forecasts are available with the WELS system as three-hourly time-lapse picture sequences by 9 p.m. and 9 a.m. MST. We call this approach distributed weather prediction, because the forecast computations are not run in a single national center but can be run here or there, wherever needed. So that there are no blind spots between 5:00 and 9:00 MST, one generates 24-hr forecasts overlapping every 12 hr.

Timing Accuracy

One can hardly ever expect a completely accurate weather forecast. Precisely timing an event, such as the arrival of a front or a blizzard, is especially difficult. Weather stations from which the numerical prediction models receive their data are, on the average, 400 km apart, even in the dense network of the United States. Under such circumstances, predicting the arrival time of a snowstorm is impossible, unless one can upgrade forecasts by using observations to correct any discrepancies between prediction and reality. Thus, one could fine-tune the arrival and departure times of weather events to make predictions highly accurate. To offer such a capability, the prediction system must be interactive, that is, the user will have to be able to

- Compare forecast weather with observed developments,
- Decide if there are enough discrepancies to warrant upgrading the forecast, and
- Interact with the forecast by implementing changes affecting the rest of the forecast period.

Of course, such interactivity makes sense only if forecast adjustments can be made quickly and easily. It would not be an acceptable procedure to require re-running the numerical prediction model and waiting for an hour for results that may or may not give the desired answers. The WELS system provides all necessary interactivity through a graphical user interface (GUI), which is a colorful display of weather conditions on the computer screen that can be manipulated and adjusted by simple mouse point-and-click actions. These actions are directed by an embedded expert system that plays the role of a professional meteorologist advising the user.

Precipitation Type

Is it going to snow or not? Several factors play a role in answering this question and related ones enumerated in the earlier list. One first must decide whether there will be precipitation. The WELS system provides numerical model output in terms of liquid water-equivalent precipitation over grid points spaced approximately 24 km apart, either as 3-hr incremental amounts or as three-hourly amounts summed since the start of the forecast period. Plotting these precipitation values on top of terrain and road networks provides an easy first answer as to when and where one should expect precipitation. If reality departs from these predictions, the user can point and click with a mouse to correct timing as well as location of expected precipitation.

Rain, freezing rain, or snow? This decision depends largely on air and ground temperatures. The latter don't change very quickly and depend on the past weather history for the location of concern. At this stage of development, the WELS system does not keep track automatically of such multiday histories. An expert system asks the user for one out of several choices (e.g., deeply frozen, lightly frozen, or thawed ground). Pavement sensors can be consulted for more accurate input.

Air temperatures 600 m above terrain are predicted by the WELS system. If they hover above freezing one should expect rain or sleet. If the ground is frozen, light rain (more so than heavy rain) should give rise to ice warnings. Even fog or drizzle may cause icing conditions. The WELS model does provide estimates of humidity near the ground with predicted values of the differences between dewpoint and actual temperatures. As these differences approach zero, fog and condensation on roadways are likely.

With air temperatures below freezing, one should expect snow, but how much? The colder it gets, the fluffier the snow. Under cold and calm conditions on can expect a maximum of 20 cm of snow from 1 cm of water. Such ideal conditions are rarely ever met, however. Compaction by wind and snowdrift formation cause wide variations, often preventing meaningful estimates. Warm road surfaces will reduce snow accumulation, at least during the early stages of a storm. A 10:1 ratio has been found adequate under many conditions in Colorado. The WELS system lets the user choose snow/liquid-water ratios depending on air temperatures and ground states. These suggested choices can be overridden by the user's own preference of a constant ratio between 1 and 20. And, of course, under the interactive provisions of the system, users may change their minds should an initial choice turn out to be inadequate.

Precipitation Amount

"One to five inches" in a typical media forecast contains a lot of leeway. It is still better, however, than having to plow through 5 in. of "partly cloudy." We realize that such wide error margins—most likely designed to avoid litigation—can be quite costly. Overpredictions mean idle crews eating into precious resources; underpredictions mean delays in service, often costly to the public in terms of accidents, traffic pileups, and ill tempers.

The WELS system places great emphasis on the prediction of precipitation amounts in terms of when and where they can be expected. Again, the user can adjust these predictions as time rolls by if discrepancies with observations begin to emerge.

With more reliance on such forecasts the user can make tactical decisions before, rather than after, emergencies arise:

- From a threat evaluation for each snow patrol (and not just for the whole "foothills" region) it can be determined if available resources are adequate to cope with the predicted storm.

- From a districtwide evaluation of threats it can be determined if resources can safely be pulled from one patrol to aid another, or if priority rankings and road closures should be brought into effect.
- Road hazard advisories could be issued to the public before they occur—assuming that the public listens.

In tests during the winter season of 1991–1992, and in current operational deployment at several locations in Colorado, including the Avalanche Information Center, the WELS model performed very well in predicting wind conditions over the mountains and plains of Colorado, thus providing a good handle on where and when to expect blizzard conditions. Because the WELS system interacts with a geographic information system, locations known for hazardous snowdrift formations could be identified in the computer display, if such a data base were made available.

Tactical Planning

The WELS system offers the capability of on-line, real-time weather prediction with details of timing, intensity, and location of snow events as influenced by large-scale weather conditions and local topography. Furthermore, forecasts can be corrected locally and regionally as observational evidence accumulates. With such capabilities in hand, state highway departments must learn to be much more demanding in the access to, and use of, weather information. No longer must they be satisfied with "one to five inches in the foothills tonight"!

To make full use of detailed and customized weather predictions, their information contents need to be integrated into all levels of decision processes.

First of all, some soul searching will be needed as to the level of service that needs to be provided. Colorado currently adheres to a dry-pavement policy, meaning that during and after a snowstorm roadways will be restored to "dry" surface conditions as quickly as possible. This policy is comforting to tourists and carries minimal risk of litigation, but it is very expensive to the taxpayer. What is an acceptable compromise that still provides more-than-adequate service to the public but measures more judiciously the risks and threats of inclement weather against financial burdens? By better identifying the times and mileposts under threat, confining service to these targets, and minimizing risks of neglect by keeping a watchful eye on observations and upgraded forecasts, significant savings in annual road maintenance costs could be realized.

But these are only the beginnings of weather input applications. Weather forecasts, as those provided by the WELS system, can be combined with data bases on "cold spots" (i.e., locations of frequent road ice formations under certain weather conditions), preferred snowdrift corridors, avalanche hazards, and so forth. Only a few such locations need to be equipped with sensors whose data can provide verification of forecasts or cause for their correction. The forecast details provided by the WELS system can then be used to gauge the impact of predicted weather on other potential hazard points identified in the data base within a relatively wide area, without having to plaster the whole state with instruments. Such hazard points can be identified on the computer screen whenever predicted conditions or corroborating observations give cause for caution.

Detailed threat predictions for individual maintenance sections, and even individual snow patrol areas within such sections, invite the use of computerized data bases on personnel and equipment availability in a direct access mode. The rate of snowfall predicted by the WELS system for certain times and over certain patrol areas can provide a reasonable estimate of the frequency of plowing and sanding operations needed to maintain road trafficability and safety. These estimates can be checked against rosters of available personnel and equipment. Under prolonged storm conditions the scheduling of maintenance operations can be complicated by work safety rules that restrict the lengths of duty shifts and impose "off time" conditions. Equipment may not be available when needed, due to repair work and unanticipated breakdowns. Highway engineers have learned over the years how to cope with these pitfalls. Nevertheless, weather information integrated with computerized data bases can provide significant help in exploring a variety of scenarios on the computer screen before committing to one that might be far from the best. Thus, "whose patrol, how many plows should be sent when and where and for how long" should rely on information of considerably more substance than a look out the window.

CASE STUDY: MARCH 8, 1992

Weather forecasts provided by the media tend to be more cute than they are accurate: a sun disk hiding behind clouds, raindrops scattered here and there, snow crystals covering half a state, and maximum and minimum temperatures each with a 10-degree margin of error. Forecasts released by the NWS and accessible to users in a repackaged format through value-adding vendors usually are more instructive but leave a wide range of possibilities in their interpretation. They are issued in the form of "stories," because average nonmeteorologists cannot be trusted with interpreting pressure contour and vorticity advection charts. As an example, the forecast distributed by WeatherBrief at 5:30 a.m. MST on Sunday, March 8, 1992 (before the "Big Blizzard of '92" hit eastern Colorado that evening) read:

> Colorado state forecast: heavy snow warning today and tonight San Juan and central mountains. Snow advisories northern mountains ... southwest and northeast through tonight. Periods of snow today mountains and west. Accumulations of 6 to 12 in. San Juan and central mountains south of Aspen today, 3 to 6 in. possible lower elevations of southwest. Increasing clouds with scattered showers and a few thunderstorms east. Turning windy and colder afternoon with rain changing to snow. Periods of snow tonight mountains and east, decreasing late. Partly cloudy west. Highs today 40s west, upper 20s and 30s mountains, 40s and 50s east. Lows tonight 20s and 30s with 10s mountains. Highs Monday upper 20s to mid 40s mountains and west. Colder east with highs 30s to mid 40s.

An update issued at 5:05 p.m. on March 8 reads:

> Conditions across Colorado will deteriorate tonight and many winter storm warnings and advisories are in effect through early Monday. Snow will fall over much of the state. Low temperatures

> will be in the 20s and 30s with 10s in the high country. On Monday showers will continue over the state and are expected to decrease in the early afternoon in the east. High temperatures will be cooler ... only reaching the upper 20s to mid 40s.

Another update followed at 6:30 p.m.:

> The winter storm will continue to develop today and should bring precipitation to all of Colorado by this afternoon. A heavy snow warning has been issued for some of the mountain areas of Colorado today and tonight . . . and snow advisories have been issued for much of the rest of the state.

The first forecast, issued at 5:30 a.m., aside from being wrong, provided too much latitude. The WELS forecast, using data collected at 5 a.m. MST on March 8, delivered the meteorological charts shown in the following figures. (These diagrams are actual screen reproductions, albeit without color, of the WELS GUI. Weather is presented as icons whose size and color indicate the severity of an event.) Already by 11 a.m. strong winds of about 20 m/sec were predicted to prevail over northeastern Colorado while temperatures there remained above freezing (Figure 1) and the first widespread precipitation (rain in the lower elevations, snow in the high country) started to appear (Figure 2). Especially south of Denver convective cloud buildup was expected. We, too, made a small mistake: although threatening clouds were obscuring the mountains already by mid-morning, precipitation in Boulder did not start until shortly after 2 p.m. with a strong thunderstorm. (By clicking the right mouse button on the map location of Boulder, detailed forecasts as shown in Figure 3 can be obtained in an instant.) We jumped the gun by a couple of hours with our forecast. The 3-hr period between 2 p.m. and 5 p.m. MST called for heavy snow in the mountains west of Boulder (Figure 4) and also southwest of Fort Morgan. The total 24-hr precipitation expected by 5 a.m. on March 9 (Figure 5) reveals the scope of the disaster. Hardest hit were the Front Range area west and south of Boulder and Denver and the region between Fort Morgan and Limon in northeastern Colorado. According to Colorado Department of Transportation personnel in Greeley (Maintenance Section 1 responsible for this area), several snowplows got stuck in the blizzard out there.

There is no doubt that the "southern" storm predicted by NWS did not materialize: Alamosa in the San Luis Valley of southcentral Colorado went from a 6-in. snow cover on the day before the alleged storm to a 4-in. cover after the storm. Trinidad, next to the San Juan Mountains, reported only a trace of precipitation. Table 1 provides more comparisons with observation reports issued by WeatherBrief in terms of inches of liquid-water equivalent (or inches of snow in parentheses).

During the 1991–1992 winter, WELS tested its prediction system on 25 Colorado snowstorms, some of them lasting for several days. During the 1992–1993 season, the operational system encountered one of the snowiest winters on record, as reflected in avalanche accidents. Because of its detailed attention to terrain effects, the WELS system provided significantly better guidance in terms of timing, location, and intensity of predicted events than that provided by the media or NWS, even without user-generated adjustments.

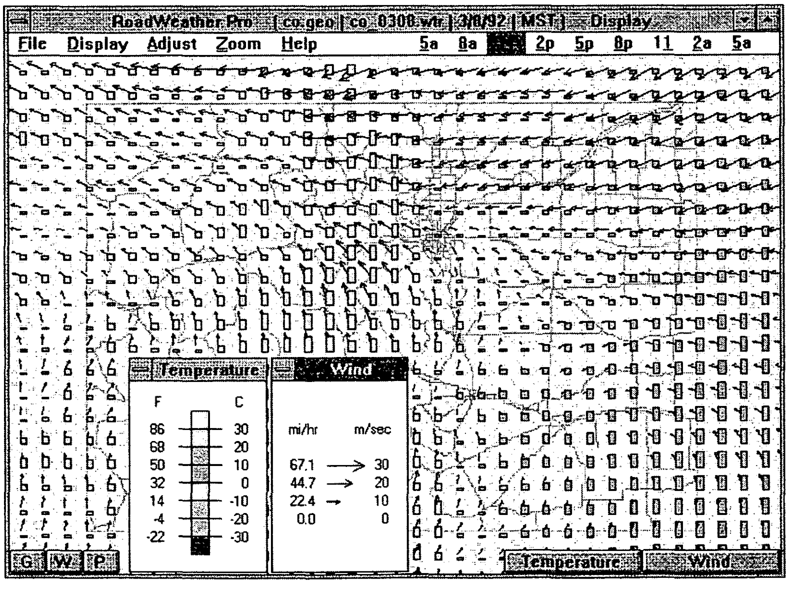


FIGURE 1 Temperatures and winds at 600 m above terrain predicted for 11 a.m. MST on March 8, 1992, from observations at 5 a.m.MST. Over eastern Colorado these rectangles would be red, indicating temperatures above freezing. A fully extended dark rectangle indicates + 10°C. Lighter shades of red, first appearing at bottom of such rectangles (see southeast corner of Colorado) signify still warmer temperatauares. Over the mountains light blue (gray) rectangles indicate temperatures below freezing. A full-height rectangle means −10°C.

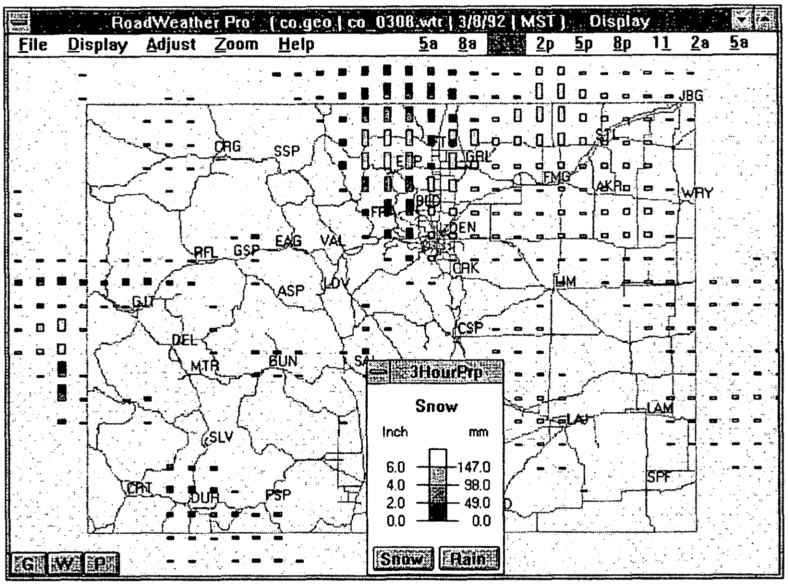
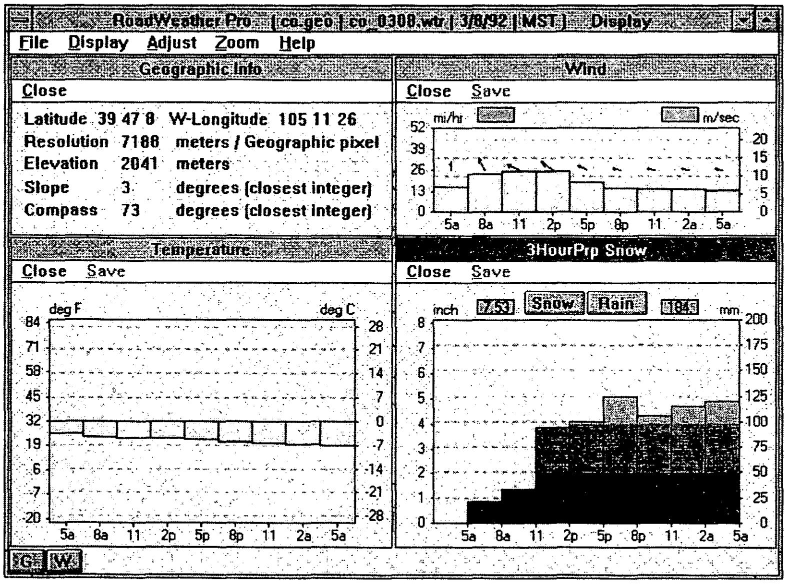


FIGURE 2 Precipitation predicted for 3 hr ending at 11 a.m. MST, March 8, 1992. Over the mountains snow is predicted, as indicated by size and shade of rectangles. Heavier snowfall is symbolized by lighter shades. Over the plains, rain is predicted and shown by rectangles in shades of green. (Scale display in scale window can be switched from "Snow" to "Rain" by clicking on appropriate button.)



Latitude 39 47 8 W-Longitude 105 11 26
Resolution 7188 meters / Geographic pixel
Elevation 2041 meters
Slope 3 degrees (closest integer)
Compass 73 degrees (closest integer)

FIGURE 3 Clicking right mouse button on location of Boulder, Colorado, in previous map reveals 24-hr forecasts of temperature, wind, and precipitation for Boulder. Upper left window shows location of point and characteristics of geographic pixel on which mouse was clicked.

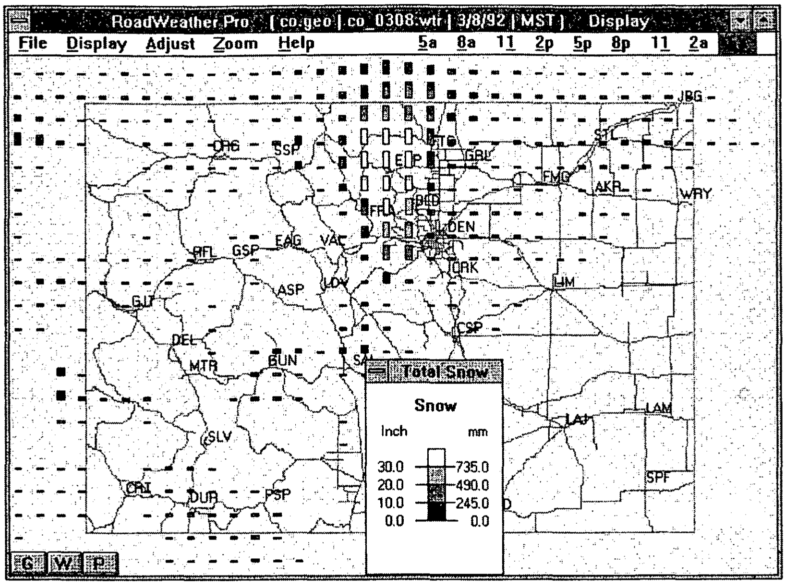


FIGURE 4 Total snowfall predicted for 24-hr period ending at 5 a.m. MST, March 9, 1992. Amounts are indicated by size and shade of rectangles.

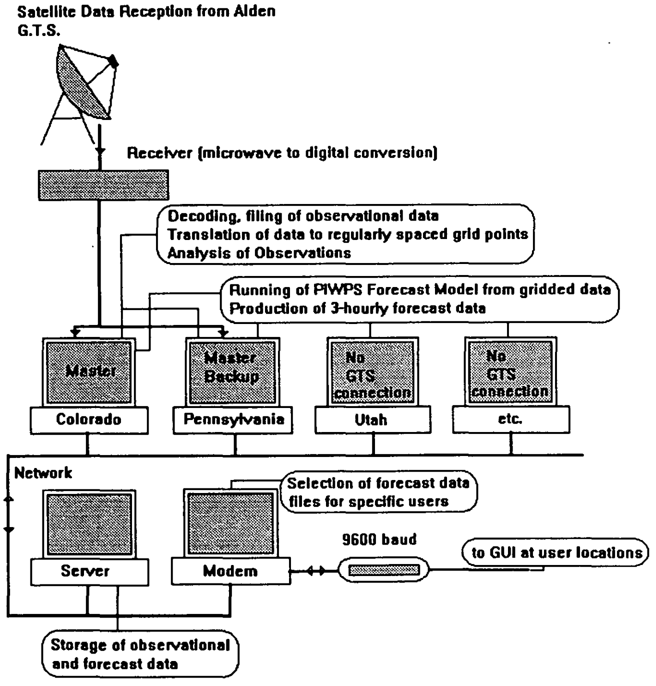


FIGURE 5 System configuration at WELS Weather Central.

GRAPHICAL USER INTERFACE

The weather examples given in Figures 1 to 4 came straight off the laser printer hooked to the WELS computer. The computer screen output of these maps is much clearer, showing precipitation systems of increasing intensity in different colors. WELS took full advantage of Microsoft Windows 3.1 graphics capabilities in a relatively inexpensive PC environment. The WELS system design includes a GUI that serves the following purposes:

- It provides quick access, by simple mouse point-and-click choices from a menu or from "buttons," to geographic information data bases used to display terrain elevation, slope, or azimuth angles with user-specified horizontal resolution. Since underlying terrain has a strong effect on the behavior of snowstorms, we deemed it important to show terrain details in the manner they deserve, and not just as state boundaries. (In the previously shown examples, terrain details have been omitted to avoid clutter in a black-and-white rendition.)
- A detailed road network data base and city locations can be overlaid on the terrain and exhibited on the computer screen.
- Different degrees of horizontal resolution can be attached to different data bases stored on hard disk for quick display purposes. Thus, a map of Colorado provides an overview of statewide terrain, roads, and weather. A map of Maintenance Section 1 brings to the computer screen a more detailed display of terrain and weather in the northeastern sector of Colorado. A data base for the Boulder-Denver region shows even higher resolution with about 1-km horizontal data point spacing.
- A "rubber-band" zoom capability is part of this GUI. When placed on any of the displays just mentioned, it will magnify the area within the zoom box to fill the whole computer screen. This option is of specific benefit if road networks should be shown in details that may get lost on large-area maps.

To suit the design of this GUI, geographic data bases have been translated into geographic pixel objects. Each of these objects knows its location on the globe and on the computer screen, and carries values of elevation, slope, azimuth angles, and such. (With access to appropriate data bases, we can attach additional values for vegetation, soil cover, soil con-

TABLE 1 Precipitation Observations at Colorado Stations for 24 hr Ending 5 a.m., March 9, 1992.

Station	Observed (in.)	WELS Predicted (in.)
Akron	0.60	2.0
Alamosa	missing	none
Boulder	missing (20)	1.8 (ca. 18)
Denver	0.67	1.8
Eagle	0.12	0.1
Ft. Collins	1.18	1.2
Ft. Morgan	missing	1.2
Glenwood Springs	missing	Trace
Grand Junction	0.08	0.08
Greeley	missing	0.8
Gunnison	missing	0.1
La Junta	0.14	none, showers in area
Lamar	missing	none, showers in area
Leadville	missing	0.8
Limon	0.32	0.4
Longmont	missing	1.2
Pueblo	0.02	none, but 10 miles to west
Salida	missing	0.1
Trinidad	Trace	none

dition, etc.). Because of this object-oriented structure, the user can specify on the fly what should be shown (or blotted out) on the screen: for example, "elevations between 4,500 and 12,000 ft." Making such choices allows emphasis on certain elevation bands that might be prone to specific weather conditions (such as the expected freezing level in a mountainous region experiencing precipitation).

The output from the described WELS forecasting model of predicted weather parameters are translated automatically into the same object-oriented geographic pixel format. Instead of showing weather maps, the WELS system now can depict weather in the form of icons superimposed on terrain and road displays. These icons are not as cute as umbrellas or raindrops in a TV forecast show, but they are much more informative. In the present configuration, rain and snow are shown by differently colored rectangles arranged on the computer screen, with the underlying terrain and road details still clearly visible. These rectangles fill up with increasing amounts of rain or snowfall expected during 3-hr intervals. As certain threshold values are exceeded (e.g., 2 in. of snow or 0.2 in. of rain in 3 hr), the rectangle changes color, filling up again until the next threshold is reached. Through this form of display, areas and intensities of rain and snow clearly stand out on the computer screen. Temperature and humidity forecasts are displayed in a similar manner, either together or separately. Winds are shown by the length and directions of arrows, as in Figure 1.

Because the system no longer draws weather maps but calls on graphical icon data loaded into fast computer memory, the displays can be changed instantaneously by clicking on different weather parameters in a display as shown in Figure 3. A simple mouse click in any of the histograms allows the user to change predicted values.

This object-oriented GUI approach to terrain and weather display is a major step in giving the user quantitative information on expected weather developments with detailed resolutions in time and space.

INTERACTIVITY

Weather forecasts cannot be expected to be 100 percent accurate, so we designed a way by which the user can adjust predictions according to local observational evidence. Again, the output from the numerical prediction model is used to depict the forecast history for specific locations on the map. These locations can be selected by simple mouse point-and-click actions. If reports from human observers (e.g., a snowplow operator or a highway patrolman) or from data from roadway sensors indicate that the forecasts of precipitation, wind, or temperature are off significantly, a simple mouse click in any of the histograms shown in Figure 3 will adjust the forecasts. Such adjustments may become necessary because of errors in the timing or the intensity of the predicted phenomenon. Corrections to forecasts are made by simply moving the cursor on the screen to the desired coordinate position and clicking a mouse button. An expert system will figure out what the user's action should do to the rest of the forecast period.

If the user erred in the imposed adjustments, no harm will be done. The original forecasts are still in computer memory and can be recalled to go through different adjustment steps. Thus, the weather forecast can be played as a "what if" game, to test different scenarios and road maintenance strategies. Even on a PC such forecast adjustments take only fractions of a second, because the numerical prediction model need not be run again. (It would take an hour to do so.) Instead, weather "objects" are manipulated through the GUI at lightning speed, making use of object-oriented computational procedures (*2*).

Because observational data can be used to upgrade and correct forecasts, a state highway department would be well advised to gain access to local and regional weather data. Such access should be instantaneous, at any time, and on a statewide basis. Data from pavement sensors and roadside weather stations can be interrogated via a microwave data link. Such data could be displayed on the screen at any desired time. Furthermore, any significant discrepancies between such observations and the forecast issued for that time could be computed automatically and exhibited on the computer screen, prompting the user for an upgrade decision.

SYSTEM OVERVIEW

Figure 5 provides a schematic overview of the current system: raw radiosonde (balloon) and surface data are received from NWS via satellite communication link each morning and evening. These data are processed at WELS Weather Central to produce numerical weather forecasts saved in computer memory at 3-hr intervals. The forecasts are customized for statewide regions. Road weather data can be processed by the system, provided that access to such data is available on a routine basis. Formatted forecast data to feed the interactive GUI are piped to users via modem. At user locations with at least a 386 computer and sufficient memory and hard disk capacity, Windows and WELS software are installed to receive and display these data. End users at these locations have full access to forecast manipulation tools, but, if they so desire, they can ask Weather Central to perform such manipulations and provide them with the updated end results.

Minimum hardware configuration for on-site weather and terrain displays and forecast adjustments by the user are a 386 computer (25 or 33 MHz) with math coprocessor, 8 megabytes of RAM, an 80-megabyte hard disk, a mouse, and a modem link to WELS Weather Central or to a licensed location where the numerical weather predictions are generated. Performance is greatly enhanced on a 486/50 or 66 MHz machine. Software requirements are Microsoft Windows 3.1 and WELS ROADWEATHER PRO software and license. The computer at the user's location need not be dedicated exclusively for weather forecasting; it can be used for all other reporting, accounting, and other such tasks.

Experiences with this system configuration and the results of extensive tests during the 1991–1992 winter are described in great detail by Reiter et al. in a final project report to the Strategic Highway Research Program (SHRP) (*3*).

ACKNOWLEDGMENTS

The development and testing of the system consisting of PIWPS (Portable Interactive Weather Prediction System) and ROADWEATHER PRO with its user-interactive GUI have been supported through in-house investments by WELS; by SHRP, National Research Council under Contract SHRP-IDEA 018; and under Colorado Department of Transportation Contract DOH-351.

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On the Prediction of Road Conditions by a Combined Road Layer–Atmospheric Model in Winter

HENRIK VOLDBORG

An effective forecasting system for slippery road warnings has been operational in Denmark for some years and was recently extended to the whole country except for the island Bornholm. The system is based on a network of road-weather stations throughout the country that submit a continual flow of data, every 10 min, to the road master; the data are the current values of road-surface temperature, air temperature, and humidity. An instrument to measure the amount of resting salt is also installed in connection with most stations. Before making any decisions, the road master also has access to very short range weather forecasts that are issued every other hour and are valid for 3 hr. Each forecast is limited to a specific county. So far the forecasts have been worked out manually, but an automatic forecasting system based on a combined model for the prediction of atmospheric and road surface changes has been developed and tested to some extent. The atmospheric model is called the HIRLAM (High Resolution Limited Area Model). The model results are continually adjusted by observations from nearby weather stations so that the predicted parameters can be corrected before they are entered in the combined model. The purpose is to produce a short-range forecast of air temperature, humidity, and road-surface temperature for each of the more than 200 road-weather stations in Denmark. The combined model was tested last winter in five locations in Denmark. Some results of this test will be presented.

Fifteen years have passed since the first modest steps toward forecasting slippery roads took place in Denmark. Two stations were established for measuring road-surface temperatures: one on the high road passing the Danish Meteorological Institute (DMI) and another near the road master's headquarters in a suburb of Copenhagen. The road master and the forecaster exchanged data by telephone twice a day (at 4:00 a.m. and 1:00 p.m.) and discussed what could happen during the coming rush hour in view of the risk that the roads would become slippery or the weather would cause any other traffic difficulties.

About 10 years ago some action was taken toward establishing a nationwide warning system for slippery roads, designed for use by the road masters in the different counties. During the 1985–1986 winter, Roskilde county (west of Copenhagen) was the first to act on the basis of direct measurements, but it still stuck with the old system, that based on human observations by patrol drivers. Since then the system has increased to cover nearly all of Denmark (13 of 14 counties), and now all road masters base their decisions on a combination of information from man and machine, excluding patrol driving (Figure 1).

Each county has direct access to data from its own road-weather measuring stations (5 to 25, according to the size of the county), and the data are presented to the road master by various PC-screen images (Figure 2). Moreover, forecasts of relevant weather parameters for the next 3 hr are issued by the forecaster on duty at DMI every other hour and made available to the road master directly on the computer screen. Some counties also receive radar images of precipitation.

The predicted air- and road-surface temperatures, dew-point, cloudiness, precipitation (especially frozen precipitation), and wind velocity are all expressed as intervals valid for the entire county (Figure 3).

This operational system works quite well, and it has been developed further during the past 7 years. Both the road masters and the meteorological forecasters have learned much about what is going on in the foot level, so to speak, of the atmosphere. Today the road masters generally make their decisions on the basis of all this information. Doing so is not at all easier, but it is hoped to be better.

From the forecaster's point of view, sometimes (such as during mild winter conditions) it might be very easy to work out this type of "nowcasting," but when temperatures vary near freezing, as they often do during the Danish winter, it can be a hard task to produce detailed forecasts for 13 counties every other hour, day and night. That is one of the reasons for the development of a combined prediction model for road traffic conditions; the model is intended to issue a 6-hr forecast every hour for every observation site in Denmark (more than 200).

DESCRIPTION OF MODEL

The prediction model, developed by Sass of DMI (*1*), consists of two main components: a purely atmospheric prediction model, and a model treating the heat transfers in the layer just under the road surface, down to a certain depth. The change of road-surface temperature is determined at any time as a result of either net heat gain (leading to rising temperature) or net heat loss (leading to falling temperature). This net heat gain or loss, however, depends on many factors. Heat exchange between the road surface and the atmosphere (or partly direct loss to space) goes on in several ways:

- Sensible heat flux due to temperature difference between the air and the road surface (H),

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Danish Meteorological Institute, Lyngbyvej 100, Copenhagen DK-2100 Denmark.

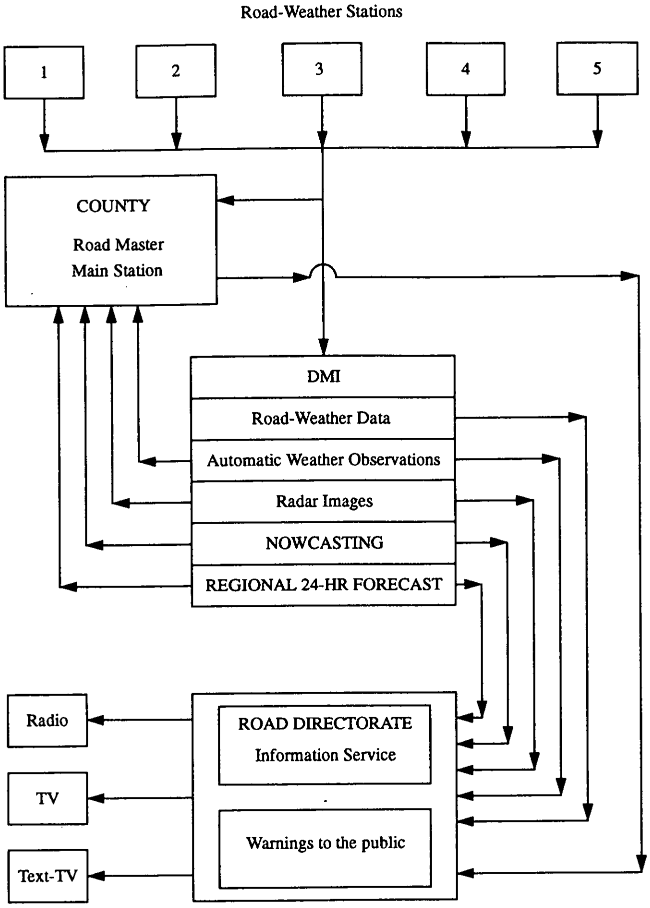


FIGURE 1 Flow chart for the integrated traffic warning system.

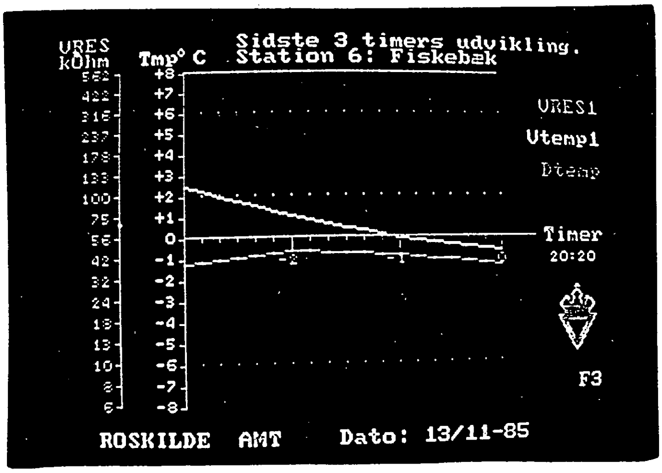


FIGURE 2 Evolution during the last 3 hr of road temperature and dewpoint. VRES-KOhm expresses the road surface condition by a resistance of electric current between two electrodes in road surface, but it remains at maximum value (562 KOhm).

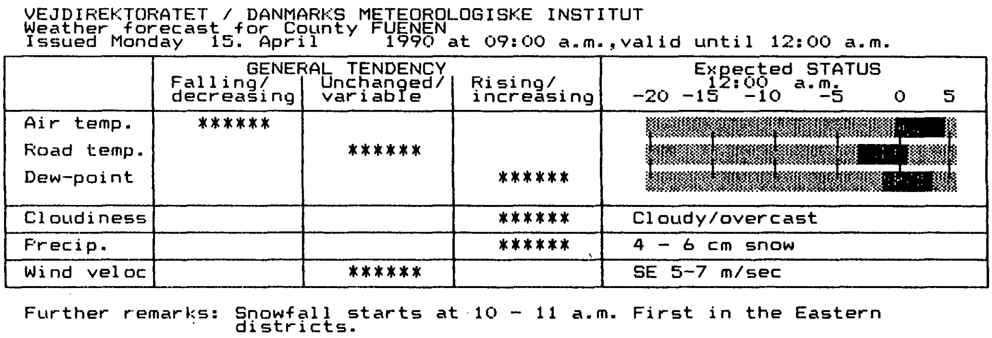
- Latent heat flux by evaporation or condensation and sublimation (Q),
- Latent heat flux by melting or freezing (R), and
- Net radiation flux (balance between incoming and outgoing radiation (S).

The second component of the model (beneath the road surface) consists of only one item: heat conduction in the solid road layer (G).

Figure 4 shows qualitatively the sign and magnitude of these quantities during a calm, clear night.

The final result of the combined model is then to work out a prediction of road-surface temperature, as well as water, ice, or snow on the road, by the following calculations:

- S, H, Q, and R based on predicted atmospheric data.
- Water, ice, or snow as a function of predicted precipitation in relation to eventual evaporation, condensation or sublimation, melting or freezing, and runoff from the road.



VEJDIREKTORATET / DANMARKS METEOROLOGISKE INSTITUT
Weather forecast for County FUENEN
Issued Monday 15. April 1990 at 09:00 a.m., valid until 12:00 a.m.

	GENERAL TENDENCY Falling/ decreasing	Unchanged/ variable	Rising/ increasing	Expected STATUS 12:00 a.m. -20 -15 -10 -5 0 5
Air temp.	******			
Road temp.		******		
Dew-point			******	
Cloudiness			******	Cloudy/overcast
Precip.			******	4 - 6 cm snow
Wind veloc		******		SE 5-7 m/sec

Further remarks: Snowfall starts at 10 - 11 a.m. First in the Eastern districts.

FIGURE 3 Copy of weather forecast issued for Fuenen county.

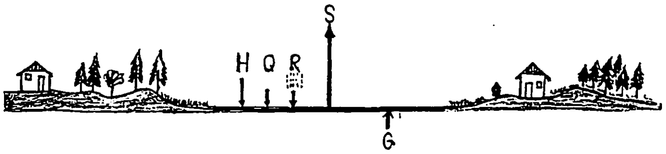


FIGURE 4 Energy budget during a calm, clear night.

DOMINANT FEATURE

All of this appears very complicated, and it is; however, one quantity often dominates everything: radiation. The net radiation is largely dependent on cloudiness. If it is overcast with thick, low clouds, very little short-wave radiation (sunlight) reaches the ground, but at the same time the net long-wave radiation is also very small. The result is little or no change in road-surface temperature. On the contrary, when skies are clear, the net outgoing long-wave radiation is large and, during winter, the ingoing short-wave radiation is usually small during the day and equals zero during the long winter night. Result: large heat loss to space by radiation, leading to rapid decline in road-surface temperature.

This fact is well known to all people who work in this field, but it is mentioned here to illustrate what is needed most of all: exact predictions of cloudiness, both amount and height. Unfortunately, cloudiness is one of the most difficult parameters to predict by models on such short time scales. Therefore, running corrections of the model output must be carried out by means of observed values from nearby synoptic stations.

HIRLAM

The atmospheric model used for the experiments is called HIRLAM (High Resolution Limited Area Model); it is a three-dimensional operational model run twice a day at the DMI up to 36 hr ahead. The model was developed in a Nordic research project.

Any detailed description of this model is beyond the scope of the paper; all that will be said is that the road-surface model is fed constantly by predicted data with some time frequency, such as 1 hr. Predicted parameters used are temperature and specific humidity at various levels, including 2 m. Furthermore, fractional cloud cover, accumulated precipitation, surface pressure, and horizontal wind components at a level of 10 m are used. The initial values of road water, ice, and snow are zero, unless additional information is available.

MODEL EXPERIMENTS

The first experiment with the combined road layer–atmospheric model was carried out from February 14 to 28, 1991, for one road-weather station, VOJENS, in southern Jutland. Data from the nearby synoptic station SKRYDSTRUP were used to make current corrections of the predicted HIRLAM parameters. The result looked very promising (Figure 5), and all were optimistic. However, some of the success was apparently due to the location of VOJENS—on a bridge without shadow—whereas most other stations in Denmark are situated in the coldest places, the so-called "white spots" on the road network, which are characterized by maximal shadow. So, it

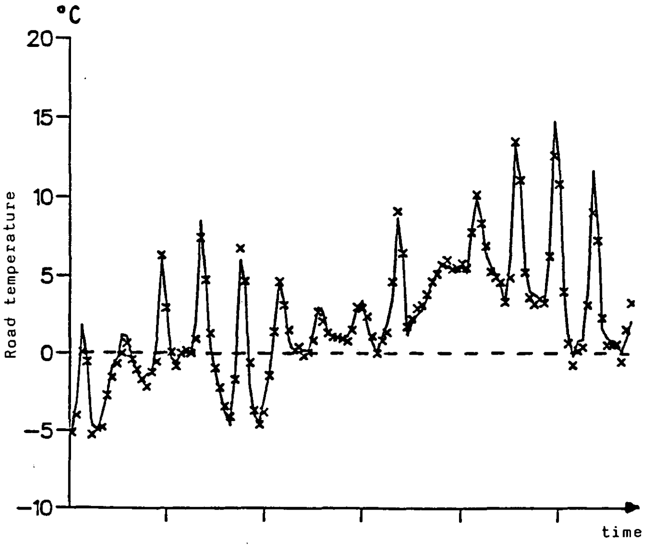


FIGURE 5 Observed road temperature (solid line) versus forecasted temperature (x) at VOJENS February 14 to 28, 1991.

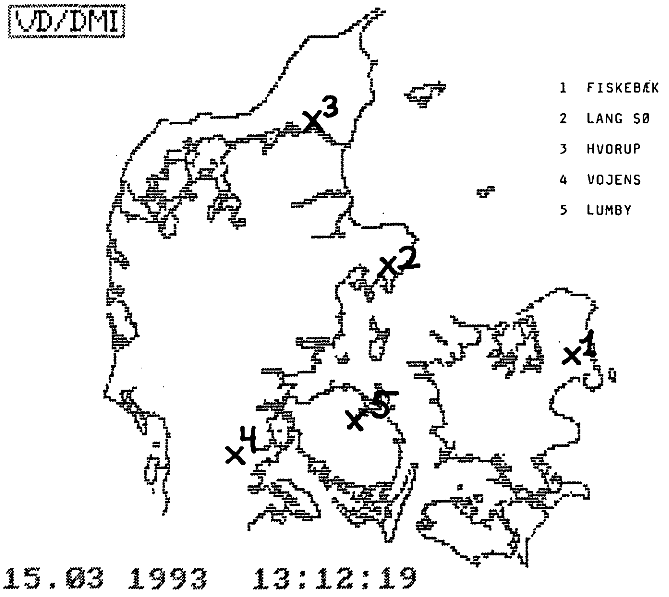


FIGURE 6 Stations used for experiment from February 10 to March 10, 1992 (Numbers 1 through 5).

became necessary to incorporate some kind of station characteristics if the model was to be used for other locations.

The next experiment took place from February 10 to March 10, 1992, at five locations in Denmark (Figure 6). Some results are given in Tables 1 and 2. (In the table, the results in parentheses apply to experiments not using additional data from the nearest synoptic station.) The largest bias, expressed by the mean error, shows up at Station LA, which is situated at a wind-protected place with no sunshine at all.

FUTURE PROSPECTS

A joint experiment is planned for the coming winter: it will be the first real operational experiment, involving 20 stations throughout the country. The verification will not only consist of calculation of mean errors and such, but also include the road masters' views of the practicability of the system. Various layouts will be presented in order to fulfill the users' desires (Figure 7).

Next spring the results will be discussed in the so-called winter council, and it is hoped that during the 1993–1994 winter the new automatic forecast system can replace the "manual" forecasts.

CONCLUSIONS

The preliminary experiments with the combined road layer–atmospheric model were promising. Some alterations, however, have become clearly necessary:

1. Station characteristics, such as duration of shadow, must be incorporated.

TABLE 1 DMI Road Temperature Forecasts, February 10 to March 10, 1992: Mean Error

Forecast Projection (hr)	*N*	Mean Error (°C)			
		FI	LA	HV	VO
1	580	-0.0(-0.6)	0.3(-0.2)	-0.0(-0.6)	-0.1(-0.6)
2	568	-0.1(-0.8)	0.2(-0.3)	-0.1(-0.7)	-0.2(-0.8)
3	559	-0.1(-0.8)	0.3(-0.3)	-0.1(-0.8)	-0.2(-0.9)
4	550	-0.1(-0.9)	0.3(-0.4)	-0.1(-0.9)	-0.3(-1.0)
5	542	-0.1(-1.0)	0.3(-0.4)	-0.2(-1.0)	-0.4(-1.1)

NOTE: FI = Station FISKEBÆK, LA = Station LANG SO, HV = Station HVORUP, VO = Station VOJENS

TABLE 2 DMI Road Temperature Forecasts, February 10 to March 10, 1992: Mean Absolute Error

Forecast Projection (hr)	*N*	Mean Absolute Error (°C)			
		FI	LA	HV	VO
1	580	0.7 (1.1)	0.7 (1.0)	0.6 (1.0)	0.5 (0.9)
2	568	0.9 (1.3)	0.9 (1.3)	0.8 (1.2)	0.7 (1.1)
3	559	1.1 (1.5)	1.0 (1.4)	0.9 (1.3)	0.9 (1.3)
4	550	1.2 (1.7)	1.1 (1.5)	1.0 (1.4)	0.9 (1.4)
5	542	1.3 (1.8)	1.2 (1.6)	1.1 (1.5)	1.0 (1.5)

NOTE: FI = Station FISKEBÆK, LA = Station LANG SO, HV = Station HVORUP, VO = Station VOJENS

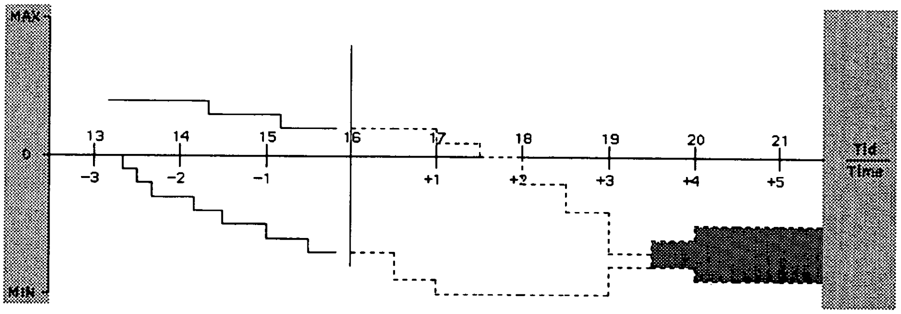


FIGURE 7 **Last 3 hr of road temperature and dewpoint and forecast up to 6 hr ahead. Solid line is observed road temperature, and broken line is forecast road temperature; shaded area is danger: road temperature is below zero and the dewpoint.**

2. The correction of atmospheric model outputs by observed values from one or more synoptic stations is indispensable.
3. The determination of the initial road surface condition (wet or dry, etc.) must be more accurate.
4. A higher time frequency for observations is desirable.
5. The model output presentation, especially in graphical form, should be redesigned to present large amounts of data to the road masters and to the meteorologists.

It is hoped to implement the first three items by next winter and the rest the following winter and, at the same time, extend the automatic winter warning system to all of Denmark.

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