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Feasibility of Using Friction Indicators to Improve Winter Maintenance Operations and Mobility

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SUMMARY

The main objective of a snow and ice control operation strategy is to bring the road surface to a safe state for the driving public within a reasonable period of time. An important factor in this operation is the ability to determine the optimum amount of chemicals that need to be applied to achieve a safe surface condition. Over the past several years, personnel at many highway agencies in Europe, Japan, and the United States have come to believe that surface friction measurements may form the basis for improved winter maintenance operations and mobility. In light of all these factors, NCHRP initiated Project 6-14 to evaluate the feasibility of using friction indicators as tools for improving winter maintenance operations and mobility.

Friction measurements for winter maintenance have been used in experimental research in the United States and in operational application (without sufficient supporting data) in some Scandinavian countries, while analytical and theoretical work, including the use of a neural network to predict friction from other data such as weather, traffic, and pavement condition, has been conducted in Japan. This study has found that the use of friction measurements to improve winter maintenance operations and mobility is feasible (especially when deceleration devices are used), but devices with an extra wheel may not represent a practical solution to friction measurement. The use of such devices works well for runways, where one vehicle is sufficient for an airport, but would not work well for highways where many vehicles equipped with an extra wheel would be needed for successful operational use in winter highway maintenance. Therefore, direct friction measurements may not be a viable operational tool in winter maintenance (although they will and should be used as research tools).

Since traction control systems (TCS) appear to be the only way to eliminate the extra wheel used in current devices, and since their use to predict road surface condition has a great potential for enhancing winter maintenance operations, they should be further investigated. However, if such technology is considered, it has to be automated to ensure that traction

applied is beyond the point of slip, thereby eliminating the effect of the traction applied by the driver. Another feasible approach, used by Japan, is to develop models based on climate, traffic, and pavement related data to predict road surface condition. Such indirect measurements have a strong potential for being an operational tool and should be tested extensively in the follow up project. In either approach, simple qualitative indicators, which describe the road condition as “poor, fair, good; or red, orange, green,” may be sufficient for winter maintenance operation

Two proposed scenarios appear to be promising and practical for improving winter maintenance operations, safety, and mobility. One scenario suggests the use of friction measurements or indices to provide information to support winter maintenance decision-making qualitatively and in a simple way. This scenario is thought of as having the highest potential for successful immediate implementation; therefore, it is recommended for operational trial by State DOTs at one or more sites. The other scenario relies on the transmittal of friction measurements or indices and locations in near-real-time from the winter maintenance patrol or snowplow/spreader vehicles to a central office where the information is processed and transmitted to users. This scenario is thought to be the most promising for enhancing winter maintenance operations, mobility, and safety, but requires technology development and integration prior to use.

The study recommends a two-phase follow-up study to validate both scenarios and translate the findings into technology that improves the efficiency and effectiveness of snow and ice control operations, thereby reducing costs, increasing safety, and improving mobility of the driving public. In Phase I, the proposed simple scenario is to be tested in a pilot study, and the collected data found to affect road surface condition, including traffic, temperature, and pavement type is to be used to develop prediction models of friction measurements and testing protocols to evaluate the effectiveness of the TCS in predicting winter maintenance friction. In

Phase II, a test is to be conducted to validate the more comprehensive proposed scenario. Field testing and calibration of the friction indices developed through modeling and TCS technologies are to be carried out during this testing program.

CHAPTER **1**

INTRODUCTION AND RESEARCH APPROACH

1.1 Problem Statement and Research Objective

The expenditure of states, counties, cities and towns in the United States on snow and ice control for their roadways reaches approximately $1.5 billion in direct costs and $5 billion in indirect costs annually in 1997 (*1*). The direct costs arise from such maintenance activities as plowing, salting, and sanding road surfaces. The higher indirect costs stem from accidents, travel delays and related lost economic opportunity, infrastructure degradation, environmental damage to vegetation and water supply sources, and vehicle corrosion (*2*). Since the main objective of a snow and ice control operation is to return the road surface to a safe state for the driving public within a reasonable period of time, the development of new techniques that increase the efficiency and effectiveness of this operation could reduce costs, increase safety, and improve mobility of the driving public. More specifically, the development of inexpensive, reliable, and easy-to-use technology that allows snowplow operators to use friction indicators can produce these desirable results.

When a wet or snow-covered surface freezes, producing a slippery surface, snowplow operators are usually asked to bring the road surface to a bare pavement condition or at least to a bare wheel-track condition. Currently, this request means that road surface conditions and safety are assessed visually. Since this visual determination is problematic, because it is a subjective measure of road safety that can be easily affected by experience and visibility conditions, it is imperative to establish a quantitative measure of road surface safety.

The ability to determine the optimum amount of chemicals that need to be applied to achieve a safe surface condition is another important factor in snow and ice control operations. Presently, snowplow operators in the United States decide only on whether or not to use these chemicals. Although a study has been conducted in New England to quantify material application rates based on road surface conditions, the average snowplow operator has limited means to determine the rate of application. The driver can make a visual determination, but without considering other important factors such as pavement temperature, dew temperature, precipitation rates, and other information obtained through the Roadway Weather Information System (RWIS), chemicals may be applied at rates greater or lesser than needed. This current approach may result in a waste of resources, may aggravate the environmental problems associated with the applied chemicals, and may adversely affect the pavement material properties.

Any new technique developed to measure road conditions should, therefore, be able to determine the safety of the road surface by assessing it quantitatively and assist snowplow drivers in making decisions on the application rate of chemicals without impinging on the safe operation of the plow vehicle. Over the past several years, personnel at many highway agencies in Europe, Japan, and the United States have come to believe that surface friction measurements may form the basis for improved winter maintenance operations and mobility. For example, the Finnish Road Administration has used friction measurements for the last 20 years as operational tools to determine the level-of-service on their roads and decide whether additional winter maintenance activities are needed. If friction is to be a useful operational tool in winter maintenance in the United States, the design of the friction indicator should include features that make it safe to take measurements that are repeatable, easy to interpret, and of acceptable accuracy.

In light of all these factors, NCHRP Project 6-14 was conducted to evaluate the feasibility of using friction indicators as tools for improving winter maintenance operations and mobility.

1.2 Scope of Study

The objective of this research was accomplished by performing seven tasks, which are described below.

Task 1. Collect and review information relevant to the use of friction indicators for winter maintenance operations decision-making, operations performance evaluation, and motorist information.

Task 2. Based on the information obtained from Task 1, identify and categorize the equipment, practices, and techniques used for obtaining friction indicators.

Task 3. Develop scenarios in which friction indicators can be applied to winter maintenance operations decision-making, operations performance evaluation, and motorist information. These scenarios shall incorporate climatic conditions, traffic levels, road characteristics, and other pertinent factors.

Task 4. Based on the findings of Tasks 1, 2, and 3, develop a work plan that utilizes available data and considers different aspects of using friction indicators such as practicality, economics, and safety to evaluate the feasibility of using friction indicators as tools for improving winter maintenance operations and mobility.

Task 5. Prepare and submit an interim report that documents the research performed in Tasks 1 through 4 for review and approval by the NCHRP prior to proceeding with the proposed evaluation plan.

Task 6. Execute the plan approved for evaluating the feasibility of using friction indicators. Recommend scenarios in which friction indicators would yield economic, environmental, and/or other benefits, and develop a plan for future studies to validate these recommendations. If the research identifies scenarios that have potential but cannot be evaluated with available information, recommend research to fill this knowledge gap.

Task 7. Submit a final report that documents the entire research effort.

1.3 Research Approach

Task 1 drew on a variety of sources to collect data addressing the use of friction as a tool in winter maintenance operations from three perspectives: decision-making, performance evaluation, and motorist information. The literature search included information gathered from searching standard databases (TRIS, COPENDEX, NTIS, and others) and contacting knowledgeable sources and field practitioners in winter maintenance. Several individuals from foreign countries offered comments related to the subject at a meeting in Roanoke, VA in September 2000. In addition, the research team acquired relevant unpublished material for use in this research.

On the completion of Task 1, the information was organized to reflect the various ways of collecting friction data for winter conditions (Task 2). Categories include the data related to equipment and techniques used for obtaining friction measurements, and the data related to the reported successes experienced in using these methods, as well as their applicability in operational conditions. In order to assure the quality and applicability of the results, a determination of the effectiveness of the friction measuring technique and method used is required. In addition, an assessment of the applicability of friction measurements as an indicator of winter maintenance effectiveness and vehicle mobility needs to be verified.

Based on the results of Tasks 1 and 2, scenarios of winter maintenance operations (Task 3) where friction measurements could be applied to decision-making, performance evaluation, and motorist information were identified. A work plan that takes into consideration such aspects of the use of friction indicators as practicality, economics, and safety was prepared. An Interim Report that documented and summarized the work performed, discussed the findings of Tasks 1, 2, and 3, and presented the revised work plan for Phase II was submitted for review by the NCHRP. Upon approval and after addressing the review/comments/suggestions, the research team carried out the second phase of this research project. The scenarios proposed in Task 3 were evaluated based on information provided by winter maintenance operators and field supervisors, and other national and international sources in response to two questionnaires.

CHAPTER **2**

FINDINGS

2.1 State-of-the-Art Summary

Information collected in Tasks 1 through 4 is related to friction measurements, indices, and models.

2.1.1 Basics of Friction Measurements

The friction coefficient is a measure of the resistive forces to movement between two opposing object surfaces. In equation form, it is given by the following:

$$\mu = \frac{F_r}{N} \tag{1}$$

where F_r is the resistive force and N is the normal force, Figure 1. When these two opposing forces are a pavement surface and a rubber material (wheel), the friction coefficient is primarily affected by tire factors (size, inflation pressure, rubber composition, tread configuration, and carcass construction); pavement surface condition factors (material composition and micro- and macro-texture); vehicle operating factors (wheel load and speed); and environmental factors (pavement surface temperature, water, snow, ice, and slush) (*3*). Because of all these variables, the friction coefficient is not constant and is usually referred to as a friction number. The relative speed between the rolling tire and the pavement surface is called the slip speed:

$$s = v - v_p = v - \omega * r \tag{2}$$

where s is the slip speed, v is the vehicle speed, v_p is the average tangential speed of the tire, ω is the angular speed of the wheel, and r is the average wheel radius. The slip ratio is defined as the ratio of the slip speed to the vehicle speed and is given by Equation 3:

$$SR = \frac{s}{v} * 100\% \qquad (3)$$

where SR is the slip ratio in percentage. The slip speed is zero when free rolling, while the slip is equal to the vehicle speed in a locked position (referred to as 100 percent slip). Figure 2 shows the relationship of the friction number as a function of the slip ratio during conventional braking. As the wheel rotation is gradually reduced from free rolling to a locked position, the friction number rapidly increases to a maximum number, then gradually decreases. When the wheel is locked, the slip speed is changed to a sliding speed equal to the vehicle speed. If the vehicle continues to reduce its speed until it reaches a full stop, the friction starts to increase until it reaches its static value. The slip ratio at which the maximum friction number occurs is called the critical slip ratio, which is a function of the vehicle speed and the nature of the surface. Typical values for the critical slip ratio are in the range of 10 to 20 percent on dry or wet roads. However, critical slip values are not as well defined for snow- or ice-covered roads.

Due to the complexity of friction mechanisms and the different factors involved, further research is still needed to better understand what happens during friction testing. Consequently, over the years, several friction standards and measurement equipment have been developed. However, since the principle of measurement differs between this equipment, it is possible that a diverse range of friction data could be obtained on the same highway or runway under the same conditions by using different devices.

To overcome the problem of these diverse results, the World Road Association (formerly known as PIARC) conducted a full-scale experiment on selected sites in Spain and Belgium, in September and October of 1992, that provided a means for comparing and harmonizing the results obtained from several internationally used friction devices (*4*). Participants from 14 countries made 51 different friction and texture measurements on 54 sites. The data were entered into a database that also includes equipment descriptions, site characteristics, weather and texture, and friction measurements. The main outcome of the experiment is a well-defined universal friction scale: the international friction index (IFI).

2.1.2 International Friction Index

The IFI is composed of two numbers, the friction number (F60) and the speed number (S_p). F60 represents the friction measured at 60 km/h (37.5 mph), while S_p represents the gradient of the friction values. S_p is obtained from a texture measurement and from regression constants calculated during the PIARC experiment for all the participating texture devices. This is shown in Equation 4:

$$S_p = a + b * T \tag{4}$$

where T is the texture measurement and a and b are the regression constants for the used texture device. Once S_p is calculated, F60 is found by using Equation 5:

$$F(60) = A + B * FRS * e^{\frac{S-60}{S_p}} + C * T \tag{5}$$

where A and B are regression constants for the specific friction device, C is a regression constant used with the texture measurement (T) if the device has a ribbed tire (C=0 for a smooth tire), and FRS is the friction measured at the slip speed S. Once S_p and F60 are determined, the PIARC friction mathematical model is used to determine the friction number at any speed using Equation 6, which is based on the Penn State model (*5*):

$$\mu(S) = F60 \text{ x } e^{\frac{60-S}{S_p}} \tag{6}$$

where μ(S) is the friction number at any slip speed (S). This model shifts the intercept of the Penn State model ($\mu = \mu_o \, e^{\frac{-S}{S_p}}$) to 60 km/hr (37.5 mph). Figure 3 shows the friction variation with the slip speed using the PIARC model with an S_p of 200 km/h and an F60 of 0.35. The slope of this line would be reduced as the macro-texture improves and the micro-texture worsens. This suggests the need for more than one speed to describe the skid resistance (*5*).

2.1.3 The Rado Friction Model

The Rado model (*6*), known also as the logarithmic friction model, was developed to complement the PIARC friction model by incorporating the first "leg" of the friction curve where the friction number increases to a maximum, as shown in Figure 2. The model is given by Equation 7:

$$\mu(S) = \mu_{max} * e^{-\left(\frac{\ln\left(\frac{s}{s_{max}}\right)}{C}\right)^2} \tag{7}$$

where $\mu(S)$ is the friction number at any slip speed (S), μ_{max} is the maximum friction number, S_{max} is the corresponding slip speed (typically about 15 percent of the vehicle speed), and C is the shape factor, which is related to the harshness of the texture of the road surface. The value of C controls the shape of the declining side of the friction curve. Figure 4 shows the friction number as a function of the slip speed using the Rado model and four different values of the shape factor. When the shape factor is greater than 10, the right side of the friction curve becomes flat, meaning that the friction number remains almost constant over the slip speed range. When C is less than one, the friction curve appears to be a spike.

The possibility of using the Rado model constants to predict the condition of the road surface in winter, is based on the preliminary studies conducted by Norsemeter, the Norwegian Road Administration, and the Norwegian Road Research Laboratory in 1994 and 1995 (*7*, *8*). These studies found the large amount of scatter in the friction of snow- and ice-covered surfaces was due to the variability of surface conditions. When a filter was added to smooth the values, better values were established to determine the available friction not at one spot, but over approximately 0.6 m (2 ft). Peak friction and slip speed values can be used to differentiate between the ice and snow conditions with respect to the dry or wet conditions. The shape factor obtained from the Rado model was used to separate loose snow and slush from packed snow and ice. This study also found that friction values could control salt applications, but more field-testing is needed to finalize these findings. The project has shown that friction levels can be monitored in real-time, and salting control does appear to be feasible either with a go/no-go or perhaps with varying levels of salting. Since salting control does appear to be feasible, the experiments are going to continue in the US and Norway. Using the results of this, Norsemeter developed ROAR.

Typical Norsemeter ROAR variable slip measurements are shown in Figure 5 for dry, wet, slush, loose, and packed snow conditions from the MnDOT tests, and an icy condition from the Norwegian tests. The data is fitted to the Rado model to provide the three coefficients required to produce the friction-slip speed curve. It is important to note that Figure 5 shows that the wet friction drops faster with slip percent, which is related to speed; this has been shown to correlate with macro-texture. It is also important to note that the percent slip at which the peak value occurs is around 18 percent on dry surfaces, 20 percent on wet surfaces, and near 30 percent on the winter contaminated surfaces. This, along with the drop in the peak value, appears to be a telltale sign of the road friction. The shape factor also separates the loose snow and slush from the packed snow and ice. The ice is also separated from the packed snow by the low friction.

Another important feature of the Rado model is its ability to simulate the behavior of an anti-lock brake system application. An anti-lock brake system releases the brake in an attempt to operate around the peak level of friction. When the anti-lock brake system is used, the friction follows the Rado model until a predetermined slip percentage is reached and the vehicle speed is reduced. The brake is then released and the friction drops to zero. The brake engages again when the wheels spin, and the cycle is repeated. Each successive cycle follows a Rado model for a lower vehicle speed. Bachmann verified this behavior on wet and dry flexible and rigid pavements (*9*).

Andresen and Wambold have proposed several modifications to the Rado model to account for winter conditions (*10*). They are related to surface shear strength and compressive strength of snow, contaminant displacement drag, surface temperature, rolling resistance, compaction rolling resistance, and viscous and dynamic fluid lift planing. In total, 13 winter parameters have been proposed for one tire configuration and one surface type and condition.

2.1.4 Friction Measurements under Winter Conditions

Although the use of friction measurements in winter highway maintenance will serve a fundamentally different mission than those currently used by the air transport sector, to date airport runways are the sites of the majority of research projects assessing friction under winter conditions. These projects use equipment that measures to a much greater resolution than needed for operational decisions in winter highway maintenance, but provides useful technical information. Specifically, runway friction measurements are developed for relatively short sections of paved surfaces and transmitted to a small, highly trained group of professional pilots, because such accurate characterization is needed to resolve the minute differences in runway stopping distances, especially for runways where estimated stopping distance is close to the maximum runway length. Furthermore, the equipment used for these runway friction measurements is typically too expensive for consideration as an operational tool in the highway sector, nor has it been designed with the degree of robustness that would be required for highway winter maintenance activities. In spite of these conflicts, the air transport sector's work forms the basis of most of the research on winter highway friction measurements and the results of its research are presented below because they are used to establish a technical foundation in this report.

Friction Measurements under Winter Conditions at Airports. Antvik presented a historical review of friction measurements under winter conditions in 1997 (*11*). He claims that airport winter operational friction measurements first began in Scandinavia in the 1940s when Ottar Kollerud, manager of the Oslo Fornebu airport, developed a method for measuring friction under winter conditions. The method consisted of driving a large truck loaded with sand to a speed of 30 km/h (19 mph) and then applying full brakes, thus locking the wheels. The time and/or distance to a full stop were recorded and a deceleration value was calculated. Bertil Florman, manager of Bromma airport, realizing that the Kollerud method was time consuming and was damaging the tires and the brakes of the trucks, introduced the Tapley-meter, a pendulum-type decelerometer, for operational friction measurements.

Further research led to the development of the skiddometer (BV-1), proposed by Kullberg of the Swedish Road Research Institute. With the skiddometer method, the maximum friction is recorded instead of the skidding friction that both the Kollerud method and the Tapley-meter record (*11*). Additional development of the BV-1 led to the present BV-11. Because trailers were found to have some disadvantages, SAAB began to develop a friction-measuring unit (the Saab Friction Tester, later changed to the Surface Friction Tester, SFT) in the late 1960s, where a fifth testing wheel was installed in the rear of a SAAB automobile. Tests by the Aeronautical Research Institute in Sweden have shown that reliable calibration friction measurements were obtained using either the BV-11 or the SFT on runway surfaces covered with loose snow or slush. In the early 1950s, cooperation between Bromma Airport and Scandinavian Airlines System (SAS) produced a friction measurement reporting technique. Further studies led to the reporting terminology used in Sweden, shown in Table 1 (*12*).

In 1994, the Swedish Road and Transport Research Institute developed a lightweight twin track skiddometer, BV-14 (*13*). In 1995, two more BV-14 devices were built and extensively tested in the field. In the winter of 1996, a validation test was performed with the three BV-14s and a BV-11, which was used as a reference device. The testing considered four different pavement surfaces: smooth ice, stud roughened ice, compacted snow, and ice-bonded sand. Results have shown strong correlations and good reliability between the devices.

During the joint FAA/NASA Runway Friction Program, several tests using different friction devices were performed under dry, wet, snow-, slush-, and ice-covered runways from June 1983 to March 1986 (*14*, *15*). Over 200 test runs were performed using the specially instrumented NASA B-737 and the FAA B-727 aircraft, and over 1,100 were performed with ground friction devices including the SFT, the FAA Mu-meter, the BV-11 skiddometer, the RFT, the Navy RCR vehicle, the Tapley-meter, and the Bowmonk-meter. The Bowmonk-meter, a decelerometer composed of a finely balanced pendulum that responds freely to any changes in speed or angle, is filled with a special fluid to damp out all vibrations.

The testing program for the compacted snow- and ice-covered conditions produced the following results. All tested ground friction-measuring devices showed reliable and repeatable readings. Friction measurements with the ground friction devices were independent of the forward speed and the surface condition, and similar readings were obtained from the Bowmonk-meter and the Tapley-meter. In addition, friction measurements with the SFT and the BV-11 were greater than those obtained with the Mu-meter and the RFT. This could be due to the fact that the SFT and BV-11 used high-pressure, grooved-tread test tires while the Mu-meter and RFT used low-pressure, smooth-tread test tires.

Since 1996 the Joint Winter Runway Friction Measurement Program (JWRFMP) has collected data using ground vehicles and aircrafts in several airports, including Jack Garland, North Bay, Ontario; K. I. Sawyer, Gwinn, Michigan; Gardermoen, Oslo, Norway; and Frantz Struss, Munich, Germany. Four friction devices (ERD, Griptester, RUNAR, and SFT) were used at Jack Garland Airport in 1996 (*16*). The testing was performed on the runways and taxiways under different surface conditions, including bare and wet, slush, smooth and rough ice, loose snow, and medium- and hard-packed snow. The study concluded that pavements covered with ice and snow are different from wet pavements; the average critical slip value on ice and snow is around 32 percent, which is almost double the critical slip value for wet pavements. The study also concluded that correlation of the friction devices on wet pavements does not apply to ice- or snow-covered pavements.

In 1995, the Winter Friction Measurement and Reporting Working Group, consisting of representatives from the Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), Transport Canada, Airports Council International (ACI), American Association of Airport Executives (AAAE), Air Transport Association (ATA), Regional Airline Association (RAA), Air Line Pilots Association (ALPA), aircraft manufacturers, and a technical advisor, presented the methods, procedures, and runway friction practices used under winter conditions in the United States, Canada, Europe, and Asia (*17*). The group also discussed the history of US research on runway friction measurements and the development of friction-measuring equipment for winter operations, and reported the following conclusions:

- FAA-approved continuous friction measurement equipment (CFME) and decelerometers (DECs) can determine friction characteristics of pavement surfaces under "ice or wet snow" conditions and under "compacted snow" conditions. The friction measurements should not be performed when more than 1 mm (0.04 in) of water is present on the surface, when the depth of dry snow exceeds 25 mm (1.0 in), or when the depth of wet snow/slush exceeds 3 mm (0.12 in).

- Transport Canada has developed a procedure for measuring and reporting friction measurements. At 230 Canadian airports, trained operators use electronic decelerometers in a consistent manner to provide Canadian flight crews with standardized friction value information.

- The importance of friction measurement is still a controversial issue within the US aviation industry.

- Airports, airlines, and flight crews support the standardization of runway friction measurements and reporting methodologies to increase safety during winter operations.

- The type of tire and inflation pressure affects friction measurements of CFME.

NASA holds an annual runway friction workshop at their Wallops Flight Facility in Virginia. There are presently some 36 different friction sites, ranging in wet friction from 0.01 to almost 1.0. In 1999, there were some 10 different friction-measuring devices evaluated for summer friction measurements. To date, there is data for six of the devices that include the following:

- USFT: US version of the Airport Surface Friction Tester from Sweden with two different tires.

- SALTAR: A friction tester designed by Norsemeter for salt trucks.

- SFT97: A 1997 SFT owned by Transport Canada.

- BV11: A Swedish designed friction tester owned by the FAA.

- RFT: RFT designed by K.J. Law and owned by the FAA.

- E 274: An ASTM E 274 skid tester from the Virginia Department of Transportation.

The testers were run on some or all of the 36 sites in a self-watering mode. Values of the different testers show as much as a 50 percent difference in their measured friction values. SALTAR always gave values within the range of the other testers; however, with increasing speed, it measured higher friction values in all but a few cases. Investigation into SALTAR showed that the computation done by Norsemeter appears to be somewhat speed sensitive;

SALTAR was designed for speeds of snowplow/spreader trucks, and it measured in the middle of the range with a speed of 50 km/h (31 mph). Also, the SALTAR results were similar to those obtained from the E 274 trailer at 30 km/h (19 mph). Therefore, it is expected that SALTAR would give reasonable friction measurements at low friction and low speeds.

Further investigation revealed that SALTAR was run at a constant water flow rate, while the other devices were run at flow rates that varied with speed and produced the same water film thickness at all speeds. Therefore, SALTAR had lower water film thickness and increased friction at the higher speed. To determine the real effect of speed on SALTAR, new tests need to be conducted to eliminate the water thickness problem. Since SALTAR was designed to measure winter conditions, a series of tests were run in the winter of 1999/2000 and compared with other friction measuring devices.

The snowplow-mounted Iowa SALTAR unit was taken to North Bay, Canada in January 2000 and tested as part of the JWRFWP. Testing showed that at very low temperatures (-30℃ [-22℉]) the compressed air lines needed better winterization, as all water in the lines froze causing low normal load on the test tire. Overall results did not show a speed effect, but rather a scatter at very low friction levels that is due to the varying normal load caused by the air line. Overall comparisons showed that the friction values from SALTAR measurements were low when compared to the reference device. However, no calibrations were carried out, because it could not be determined if the low readings were due to low contact pressure or to the proper contact pressure. Since comparable data from Norway did not have these problems, they were used to make comparisons. More descriptions of SALTAR will follow in this Chapter because it is design-specific for snowplow/spreader trucks.

Although measurement variations between devices have been reported, it is clear that reliable measurements can be achieved based on the testing and evaluation of friction measurements at airports when certain conditions are taken into account. Although continuous friction measurement devices and decelerometers are thought to be able to determine friction characteristics under winter conditions at airports, such measurements may not be reliable if conducted on dry snow or wet snow that exceeds a corresponding specific depth. In addition, several factors that affect the measurements need to be carefully considered during testing. These include tire type, tire pressure, and water flow rate. The successful experience of measuring friction and the implementation of standardized friction information by the Canadian airports suggest that utilizing friction indicators in winter highway maintenance has a potential.

Currently, many airports provide a measure of friction when snow or ice is present on the runways; however, there is a lack of international uniformity. Norway uses Griptester and BV-11 while France uses IMAG and several variations of SFT. A reference tester is currently being prepared for calibrating ground vehicle testers to the International Runway Friction Index (IRFI) using a variable fixed slip trailer based on the IMAG design. Currently, a Canadian Runway Friction Index is used in Canada.

Friction Measurements under Winter Conditions on Highways. Although more research results into runway friction are available, experimental research results have been reported on the effect of tires and pavement surfaces on friction measurements under winter highway conditions. Additionally, results have been reported on the relationship between winter friction values and vehicle crashes and the use of artificial intelligence to predict friction coefficients under winter conditions.

One of the important parameters affecting pavement-tire traction is tire type. The tractions of different tire types were evaluated under various winter conditions including packed snow, ice, and bare pavement surface (*18*). Field testing was performed using three types of tires (Blizzaks, studded, and all-season) at 40.3 km/h (25 mph) stopping distance test, starting traction and time to reach 40.3 km/h (25 mph), maximum cornering speeds on short-radius curves, and hill climbing ability. Testing was conducted under near-freezing temperatures with an air temperature varying between -4 to 2℃ (25 to 36℉) and a surface temperature varying from -4 to 0℃ (25 to 32℉). Under packed snow, the stopping distance test indicated that there was no significant difference in the traction ability among all the tires. The results were similar to those obtained on bare pavements. However, under icy surface conditions, the stopping distances were typically two to three times longer than those on packed snow. In addition, the results indicated that the studded tires had the shortest stopping distances, followed by Blizzaks tires, and then the all-season tires.

The Finnish National Road Administration (FinnRA) has found that a grooved tire is the best measuring wheel on snow-covered surfaces (*19*). They reported that when a smooth or grooved tire was used on a snowy road surface, driving speed had very little effect on the results of the measurement. Conversely, driving speed had a significantly larger effect when a winter tire was used. Compared to a winter tire, a grooved tire eliminates the effect of the speed of the measuring vehicle. Hence, there is no need to drive at the same speed all the time to have comparable measurements. No significant difference was found between smooth and grooved tires when used at the same speed.

The Swedish Road and Transport Research Institute has investigated the susceptibility of different road pavement surfaces to icing (*20*). The different pavement surfaces included dense hot-mix asphalt (HMA), thin HMA overlays, porous HMA, rubber modified HMA, and HMA with salt additives. Friction measurements and visual observations were performed under varying weather and road surface conditions for several winters, and coarse-textured and newly laid surfaces were found to have good skid resistance. It was also found that porous HMA pavements are less skid-resistant and require more extensive deicing actions than conventional dense HMA pavements. However, HMA with salt additives and rubber-modified HMA surfaces improve skid resistance on frost/ice covered surfaces at temperatures around 0℃ (32℉).

Winter friction was evaluated in Hokkaido, Japan as part of a study to correlate skid resistance values on snow- and ice-covered road surfaces to traffic accident rates (*21*). The winter friction measurements were performed using a skid testing bus with snow tires and locked-wheel braking, traveling at 100 km/h (62.5 mph). It was found that the skid number varied with road condition and temperature, with the lowest numbers occurring at the temperature range of −10 to −5°C (14 to 23°F). When the road surface was covered with snow and ice, the skid number (friction value multiplied by 100) was less than 30 for many meteorological conditions. The study used only one type of tire in analyzing data. However, as would be expected, a newer tire indicated a higher skid number than a worn one. In addition, the physical properties and the tread pattern of the tire had an effect on the skid number in the winter tests. Their study showed that the difference between the characteristics of the different HMA pavements did not have any effects on the skid number values in the winter tests.

To reduce the speed effect on the measured friction coefficient, FinnRA (*19*) has suggested a driving speed in the range of 60 to 100 km/h (37.5 to 62.5 mph) based on measurements using their mobile weather monitoring system (Figure 6). In addition, the slip angle of the measuring wheel was also found to affect the friction readings. On smooth ice, the maximum friction coefficient was found at a slip angle of 3.5 to 6.0 degrees, and a slip angle of 14 to 15 degrees on packed snow. A slip angle of four degrees gives 78 percent of the maximum friction coefficient and reduces the measuring wheel degradation, while a six-degree slip angle gives 88 percent of the maximum friction coefficient. Although testing of the friction meter showed good repeatability of the results, the accuracy was not as good as that obtained with special friction measuring instruments.

Another study was conducted in Japan to predict the friction coefficient under winter conditions using artificial intelligence procedures on data from experienced drivers (*22*, *23*). A multilayer, neural network model was used to express the nonlinear behavior of friction coefficient variation with time and its relation to pavement surface temperature and condition (*24*, *25*).

Field measurements were taken over several days in December 1994, 1995, and 1996 to train the neural network and to check its prediction precision. Measurements included air temperature, total solar radiation, net radiation, traffic volume, and the friction coefficient using a bus-type skid tester with a test wheel mounted in the center. Predictions were made 30 minutes in advance and at 30-minute intervals. Solar radiation data was found to significantly improve the friction predictions. However, several problems were reported with the prediction procedure: the training precision needs to be improved, and the input signals that affect the transition of road conditions in winter have to be assessed quantitatively. Once these problems are solved, it is believed that this neural method can be an effective tool for snow and ice control.

The aforementioned limited studies highlighted several conditions that appear to affect winter friction measurements. These included solar radiation, pavement temperature, pavement surface type, measuring device, speed, and tire type. The tire type has an insignificant effect on the friction measurements on packed snow, but it is important on icy surfaces. In particular, grooved tires showed an insignificant effect on friction measurements with speed changes during measurements. The newly placed HMA and coarse-texture HMA surfaces are thought to improve skid resistance in winter. Porous HMA, which usually provides relatively high skid resistance under dry and wet conditions, was found to provide less skid resistance under winter conditions. Speed and slip angle may affect measured friction; optimized value ranges were suggested for both parameters.

2.1.5 Winter Maintenance Operation Decision-Making

Maintenance agencies are looking for a relatively inexpensive device that can measure roadway friction under winter conditions and inform the snowplow operators in real-time whether there is sufficient friction present for safe vehicle operations. Such a device would assist the operators in determining when and where winter control materials should be applied during snow and ice control operations. There have been studies that utilized braking action friction measurements as indicators; however, this method cannot be used during high traffic volume conditions because it is hazardous.

Nixon has conducted a preliminary examination of the feasibility of using friction indicators as operational tools in winter maintenance in the United States (*26*) by investigating the relationship of friction to crash rates and traffic volume and speed. He concluded that several experiments might need to be conducted in order to gain more knowledge about how friction deteriorates during a storm and how it is restored by the application of chemicals. A cost-benefit analysis has shown that friction indicators can lead to considerable savings. The overall conclusions of the study suggest that friction devices can be useful tools, but require further development before they can be used operationally in the United States. In particular, he raised five issues: (1) effect of the level of friction on traffic volume and speed, and crash rates; (2) deterioration of friction during a storm; (3) improvement of friction by various winter maintenance treatments; (4) combination of price and features that would make a friction measuring device cost effective for winter maintenance; and (5) effective integration of a friction measuring device with other novel computer controlled devices on future plows. The preliminary study found no correlation between the condition of the highway (as measured by time after the start of a storm event) and traffic levels or crash rates. The counter-intuitive nature of this result strongly suggests that further work is needed in this area.

Alternatively, in Japan, the road surface friction coefficient in winter was estimated using a crash reconstruction model applied to rear-end collision (*27*). An integrated model that considers the slip ratio effects and a rigid body model were used. The same models were also used to estimate friction coefficients, which are required to achieve safe traffic conditions when the road surface is covered with snow and ice. Results showed that when the friction coefficient drops below 0.2, the probability of crash occurrence becomes greater than the probability of crash avoidance. However, it has to be noted here that the Japanese also use skid resistance measurements for road surface maintenance work (*28*), because they recognize that the regional differences in weather, topography, and other conditions affect the pavement surface condition and, accordingly, the skid resistance coefficient.

The utilization of friction measurements in winter maintenance in Europe, especially Scandinavian countries, appears more advanced than in Japan and the United States. For example, Finland established quality standards according to well-defined maintenance categories based on traffic volume to assure a safe and efficient flow of traffic, as well as to minimize harmful effects on the environment during the four to six month winter seasons (*12*). Friction measurements, snowiness, and evenness are the variables of the condition standards that have been set to guarantee a pavement surface with high friction numbers all of the time. A condition standard has been defined for each traffic classification. When the actual road condition drops below the specified standard, it must be returned to that standard within a specified time. Table 2a shows the Finnish condition standards for friction, while Table 3 presents their maintenance classes, the day and night target conditions, and the amount of time required to bring a road back to the specified target condition. These condition standards appear to have worked for the past two decades. In the Häme district, for example, a skiddometer (BV-11) is used regularly with a data logger. Deicing operations start when the friction coefficient is less than 0.3 on roads with average daily traffic (ADT) below 1,500 (*29*).

Recently, Finland revised their winter maintenance strategies and quality standards (*30*). The new friction values are related to driving conditions as shown in Table 2b. The new correlation between friction values and driving conditions has been transformed into different winter maintenance classes based on type of road and time. Recommendation on the time needed to bring the road surface to a specific friction value for each condition is specified (Table 3b). The friction requirement is for at least half of the lane width including the wheel paths.

Pöyry has compared the current winter maintenance practices in five Northern European regional road authorities: Lappi Region in Finland, the Northern Region in Sweden, Troms County in Norway, the Highland Council in Scotland, and the Public Road Administration of Iceland (*31*). Skid resistance standards are established in all these regions except for the Scottish Highlands. The friction standards differ from region to another, with the range of requirements wider in Finland than in other countries. While Norway permits little difference in friction level between road classes, Iceland allows for the lowest friction values in the lowest maintenance classes.

In Japan, the Hokkaido Development Bureau (HDB) set winter road surface management objectives using the road surface classification shown in Table 4 (*32*). The friction measurements are performed using tires standard for winter road surface research. The tire size is 165/80 R13 at 1.9 kgf/cm^2 (29 psi) inflation pressure, and its ground contact load is 400 kgf (882 lbs). Table 5 presents the categorization of roads into three classes: urban areas, flat areas, and mountainous areas; and conditions into five categories (A through E). Urban areas are those urban regions with numerous intersections; flat areas are those flat lands not in urban areas; and mountainous areas are those regions that have disadvantageous road slopes and alignments. The management objectives for the five conditions are shown in Table 6. It is to be noted that efforts are being made to meet these management objectives, but this does not ensure their execution considering the severe winter weather and traffic conditions in Hokkaido.

In addition to adopting condition standards, the FinnRA has established weather monitoring systems and night patrol operations at different road maintenance areas. These maintenance areas take needed maintenance measures for changes in weather conditions in a timely manner. Maintenance supervisors have skid testers in their vehicles to monitor the existing road conditions and relate them to the specified standards. These devices are primarily Coralbas (decelerometer devices that are actuated by the brake system of vehicles), called C-Mu in Europe.

FinnRA is working on improving the way road condition information is circulated to road users. It has developed and tested a mobile weather-monitoring system that measures in real-time the temperature and humidity of the air, surface temperature, and friction of the road surface (*19*). The vehicle, shown schematically in Figure 6, was developed to provide more accurate information about the driving conditions on the road. The friction wheel is located underneath the right side of the vehicle, about 150 mm (6 in) inside the track of the wheels. It is installed at a four-degree angle with respect to the longitudinal axis of the vehicle (slip angle). A pneumatic spring is used to apply a 60 kg (132 lb) load to the friction wheel, and a load cell built into the wheel support rod measures the friction force. The location of the weather-monitoring vehicle is determined using a differential global positioning system.

Friction measurements are also used to evaluate different types of deicing materials. In Norway, the Public Roads Administration (PRA) uses a "Digi-slope" device, which operates when the test vehicle brakes at 40 km/h (25 mph) with locked wheels, in order to evaluate brine suitability under different conditions such as temperature, precipitation intensity, and road condition (*33*). The friction readings are qualified as "Good" when the friction reading is more than 0.4; "Adequate" when the friction reading is in the range of 0.3 to 0.4; and "Poor" when the friction reading is less than 0.3.

In January and February of 1991, FinnRA used friction measurements to evaluate the effectiveness of heated sand as a deicing material (*29*). The results demonstrated that heated sand is not a feasible method for a long-term increase in friction on ice packs. In fact, the friction readings in the best case dropped to the initial values only two hours after spreading.

A 1989 study in New Hampshire has compared the ice braking friction coefficient of ice coated with five different sand gradations using a CRREL IV that was configured to operate at a constant slip ratio between 10 and 20 percent (*34*). The five gradations of sand were TC sand, FAA sand, SAE sand, ASTM sand used to make mortar, and very fine graded sand (Table 7). Tests were performed at two air and ice temperatures. An ice temperature of –10°C (14°F) and an air temperature of –12°C (10°F) represented a "cold" condition, while an ice temperature of –3°C (27°F) and an air temperature of –1°C (30°F) represented a "warm" condition. The friction results showed that coarse sands performed better under the "cold" condition, while sands with high percentages of fine grains performed better under the "warm" condition. Sands composed mostly of grains from 1 to 2 mm (0.04 to 0.8 in) in diameter performed well under both conditions. It was also found that the rate of application of sand on ice is more critical to the surface friction characteristics than the sand gradation.

Connor (*35*) has used a Tapley-meter and stopping distance measurements to evaluate the effectiveness of different abrasive products (crushed stone, "pit-run stone," concrete aggregate with high fine sand content, and coal cinders). All four materials were spread on ice with a temperature of –20°C (-4°F) at two different rates: 100 and 2000 g/m^2 (1,300 and 26,000 lb/ln-mi). The friction results showed that coal ash was the best alternative among the four tested materials. This study was also found that materials with angular particles gave higher friction values than materials with rounded particles.

In 1997, the Norwegian Public Roads Administration started the Winter Friction Project using friction measurements to determine the performance of different friction improvement methods and document existing winter maintenance practices on both salted and sanded roads (*36*). During the 1998/1999 winter season, it tested four methods of winter maintenance: the use of dry sand, the use of sand with salt, the use of heated sand, and the use of a mix of sand and hot water. The testing consisted of measuring how much the friction improved, and monitoring how long the improved friction lasted. The results show that warm sand increases the friction coefficient and holds for a longer time than traditional sanding methods. In fact, the effect of dry sand may disappear after the passage of only 50 vehicles, while the effect of warm, wet sand may last even after the passage of 2,000 vehicles. OSCAR and ROAR friction devices were used to evaluate the new spreaders by measuring friction before and after the materials were spread. Findings show that the best spreader results were obtained using trucks with roller distributors.

Friction measurements were collected in Norway in 1991/1992 as part of a three-year research program investigating the effect of using salt on traffic flow and user safety (*37*). Friction measurements were below 0.35 in 7 percent of the cases on salted roads and in 38 percent of the cases on unsalted roads. It was also found that the crash rate was higher in winter than in summer for the unsalted roads. For the salted roads, there was no significant difference in the crash rate between the summer and winter.

In addition, the effectiveness of salt was verified in a two-year experiment that began in Kuopio, Finland in the fall of 1992 (*38*). A total of 360 km (224 mi) of roads was used as experimental sections where the salt amount was reduced by 90 percent (i.e., only 10 percent of usual amount was used). The roads from the neighboring district were designated as control sections, where normal salting procedures were used. It was found that the friction level was below the standard minimum target level of 0.3 for 32 percent of vehicle-km on the roads in the experimental sections and for 16 percent of vehicle-km on the roads in the control sections. The traffic proportion faced with the worst slippery conditions, defined as a measured friction coefficient below 0.2, was less than 3 percent on the experimental and control roads.

In Japan, friction measurements have been used to determine the amount of de-icing application and the effectiveness of deicer effusion methods (*28*). They have suggested that spreading between 15 and 20 g/m^2 (195 and 260 lb/ln-mi) of deicer is effective for four hours on pavements covered with an ice membrane and/or sheet ice, while spreading 30 g/m^2 (390 lb/ln-mi) of deicer is effective for four hours on pavements covered with compacted snow. Friction measurements were also used to evaluate deicer effusion equipment (*27*). The deicer effusion method consists of releasing the deicer onto the road using ejection devices embedded in the road surface and relying on tires of passing vehicles to spread the deicer. Friction measurements were taken 30 m (98 ft) from the location of the ejection devices before and after the release of the deicer. Prior to the operation of the device, two friction readings of 0.185 and 0.193 were taken. After the system was turned on, the friction readings increased to 0.436 after the passage of 20 vehicles and to 0.511 after the passage of 40 vehicles. At that time, these tests encouraged the use of this system, which was installed on national highway 235 in Hokkaido in 1996. However, the system is currently not in service.

Japan has also used friction measurements as one of the criteria to evaluate 15 freeze-resistant pavements (*39*). The friction characteristics of the freeze-resistant pavements rely on either chemical reactions, achieved by mixing different chemical substances with the pavement materials (to lessen ice formation), or physical actions, achieved by either roughening the surface texture or coating the surface with elastic substances. A friction device installed on a sedan automobile measured the friction coefficient at a driving speed of 30 to 40 km/h (18.8 to 25 mph). Daily averages and fluctuations of the friction coefficient were monitored for the 15 pavement sections. The best friction performance was noted as a conventional pavement that was grooved with the grooves filled with urethane materials.

Between October 1999 and May 2000, Legget used friction in a laboratory setting in Kamloops, British Columbia to determine whether the transition of typical anti-icing chemicals from liquid to solid and from solid to liquid results in chemical slipperiness (*40*). Testing was performed in a climate controlled test chamber. A drag sled with a BF Goodrich tire was used to measure the friction coefficient. The asphalt-testing surface was 1.5 m (4.9 ft) long by 0.3 m

(1.0 ft) wide and was cut from a road after approximately 15 years of service. The speed of the drag sled was kept constant at 1 km/h (0.6 mph) during all testing. This study showed that tire degradation affected friction readings, and lower friction readings would result during the transition phase of anti-icing chemicals.

In the United States, the Strategic Highway Research Program (SHRP) funded a multiyear study for the development of anti-icing technology in 1991. The overall objectives of the research program were to better understand the conditions for which anti-icing is effective, and to develop successful anti-icing techniques for different conditions (*41*). A total of 106 individual measurements were made with a Coralba friction tester and 41 were made with a skid trailer on three sites that included three pavement types (HMA, concrete, and newly constructed 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 the analysis.) The Coralba was used in two modes, with and without lockup, resulting in 58 and 48 measurements, respectively.

The analysis of the data determined that the Coralba friction tester should be used for winter testing in a lockup mode at a speed of 64.4 km/h (40 mph), or at a speed of 48.3 km/h (30 mph) if demanded by safety considerations. It was found that the variability of Coralba readings increased with decreasing speed. The friction measurements were intended to be reported as part of the storm documentation and not as decision-making tools for the application of winter control materials.

Following the SHRP study H-208, Development of Anti-Icing Technology (*42*), the Test and Evaluation Project No. 28 (T&E28) was initiated (*43*) with the objective of implementing and evaluating existing technologies that were tested under SHRP H-208. The field evaluation was conducted over a two-winter period with the participation of highway agencies from 15 states. Nine of these states, California, Colorado, Maryland, Minnesota, Missouri, Nevada, New York, Ohio, and Washington, had also participated in the SHRP study H-208. The six additional states were Iowa, Kansas, Massachusetts, New Hampshire, Oregon, and Wisconsin. Experiments were conducted at different sites using different anti-icing and conventional treatments. Friction measurements and observational records of the pavement condition were used to evaluate the effectiveness of the different anti-icing treatments. The experimental program for only 12 sites from 11 states was reported in the final T&E28 report (Table 8).

Friction measurements at all sites were performed using commercially available friction meters that were installed in the agencies' vehicles, as presented in Table 9. For consistency of data analysis, the friction measurements were made in the wheel paths of the driving lanes. At least seven friction measurements were made at random locations during each pass on the test section and on the control section. To allow the examination of the friction variation with time, friction measurements were performed at 30-minute, 1-hour, or 2-hour intervals depending on the storm duration. Friction data was analyzed statistically using Tukey box plots, and comparisons between the test section data and the control section data were performed using the Mann-Whitney rank sum nonparametric test. The New York site test section indicated that friction decreases with decreasing pavement temperature, increasing precipitation rate, and decreasing traffic rate during a storm even when successful anti-icing operations are being carried out. Pavement temperature, followed by precipitation rate and then traffic rate had the greatest impact on friction. The study concluded that friction measurements using the deceleration device were successful and therefore recommended this device be used as a measurement technique during patrols. It reported that these devices are not very expensive, could be easily installed in any vehicle, and produce reliable measurements. Their repeatability was found to be acceptable for treatment analysis and decision support purposes, provided they are calibrated and operated in accordance with manufacturer specifications.

The aforementioned field cases show that friction measurements have been utilized with some success in selecting the most appropriate winter control materials to be applied, quantifying the application rate of selected winter control materials based on winter conditions and traffic, and determining the effectiveness of the ice/snow control materials to restore the safe driving conditions of the road.

As a result of the research underscoring the importance of winter friction measurements, new ideas and new equipment for winter maintenance have been developed in the past decade in Scandinavia and Japan. Finland developed brine production units, simple liquid salt spreaders and prewetting systems, snowplows, multifunction vehicles, cameras, and friction readings (*29*). Norway developed a wet sand distributor based on the encouraging results obtained with the wet sand method discussed earlier (*36*). Two new spreaders, developed using that principle, were ready for use and testing during the 2000 winter season.

A recent development that has not yet been fully tested is the potential collection of data from anti-lock braking systems on vehicles, which is being investigated in Sweden in a project termed MoRRS (the Mobile Road Reporting System). This collection method has the potential to avoid altogether the need for separate friction measuring devices, because it uses such devices as anti-lock braking systems that are becoming standard on vehicles and interprets the data these systems collect to give a useful friction value. Although still in experimental stages, developments in this area should be closely tracked. Further details of this technology are discussed under Traction Control and ABS Devices.

2.1.6 Operation Performance Evaluation

The privatization of winter maintenance operations on public roads created a need for better methods of quality assurance (*44*). This need arises for two primary reasons. The first is to ensure that winter maintenance operations are performed within specified standards. The second is to guarantee objective ways to evaluate winter maintenance operations in case of contract disputes. To assure quality of winter maintenance operations, friction measurements could be used in three different ways: the threshold level approach, the contaminant classification approach, and the spatial homogeneity approach. Preliminary studies have shown that the three approaches are promising. However, further investigations are still needed prior to fully implementing these approaches.

The threshold level approach defines a friction value as the cutoff point between safe and unsafe conditions. This means that if the friction measurements reach the threshold value, the road is considered safe no matter what surface contaminants (water, slush, snow, ice, sand, etc.) are present at that time. Perchanok reported that this approach was proposed in Norway, where a friction coefficient of 0.25 was suggested as the threshold for spreading sand on snow packed roads (*45*). Similar friction thresholds could be established for other conditions.

There are, however, two major drawbacks to the threshold level approach. The first is the variability of friction measurements on snow- and ice-covered surfaces. Even though some efforts have reportedly investigated the magnitude of measured friction variability and its effect on the minimum required sampling frequency (*46*, *47*), these studies were limited to specific surface conditions and specific friction devices. In addition, friction threshold values could be achieved by subjective selection of sample boundaries and data averaging. The second drawback is the increased potential for agency liability in case of an accident, which may happen if a vehicle slips even though the friction threshold is met or even if a small portion of the road does not meet the friction threshold, but was not measured.

The contaminant classification approach defines the nature of a surface contaminant that is permitted under specified weather conditions. Friction data in this approach are used to detect surface contaminants that are not allowed for the given weather condition. This approach decreases the potential for agency liability in case of a crash.

The spatial homogeneity approach determines spatial variability between friction readings. The objective of this approach is to have a road with similar driving characteristics over long distances so that drivers can adjust to the road condition. The autocorrelation function is used with the friction data to detect portions of the road that have different driving conditions.

Drawing on five data sets (three data sets of variable slip friction and two data sets of snow-covered conditions), Perchanok (*48*) has suggested that data obtained by variable slip devices could be used qualitatively to measure compliance with level of service standards on snow-covered roads. However, to classify the snow type, further research was recommended.

Vaa (*49*) has presented a procedure for measuring winter maintenance activities that combines friction measurement, photographs, activity logs, and observations. While this procedure is currently used in Norway to evaluate the performance of specific friction improvement methods, it could also be used to document winter maintenance practice and evaluate overall performance. The procedure uses the four processes listed above to evaluate test sections for compliance with established standards.

2.1.7 Motorist Information

Currently, there is no significant information on road friction communicated to motorists. Since little information is available on the motorists' responses and behavior to changing road friction in winter, it may be necessary to teach drivers the significance of the relationship between road friction and vehicle handling.

The Swedish National Road and Traffic Research Institute developed an experiment to study driver behavior on winter roads (*50*). A driving simulator with moving base, wide angle visual range, vibration generators, sound generators, and temperature regulators was used for the study. The selected experimental subjects were male drivers who all had had a driver's license for at least five years, drove at least 10,000 km/year, and were in the age range of 25-40 years old. Six scenarios were evaluated. Scenario A represented a dry summer road with a friction coefficient of 0.8; scenario B represented a winter road with summer friction of 0.8; scenario C represented a winter road with mostly summer friction, but also with slippery sections and a friction coefficient of 0.25; scenario D represented a good winter road with a friction coefficient of 0.4, but with some slippery sections; scenario E represented a good winter road with a friction coefficient of 0.4 over the entire road; and scenario F represented a winter road with slippery conditions over the entire road. Driver behavior was evaluated by measuring the speed and the lateral position. The main conclusion of the study was that visual information is by far the most important factor for driver behavior, and drivers are very poor at evaluating different friction conditions. Therefore, a simple friction indicator that can communicate friction conditions to the drivers is urgently needed.

In another study, Tokunaga and his colleagues (*51*) have investigated the effect of winter road surface management on skid number and driving behavior based on eight measurements using a skid testing bus. The study concluded that "skid number allows the most direct estimation of road surface condition." However, the effect of driving behavior and road traffic conditions should not be overlooked in determining road management levels.

2.1.8 Summary

A few countries, such as Finland, have established quality standards for winter maintenance based on traffic volume using friction measurements derived from the deceleration method. Such measurements are done in real-time using friction meters mounted on maintenance supervisors' vehicles and have successfully been used in decision-making and quality assurance for the past two decades. Currently, work in Finland is underway to circulate information on road conditions to users in real-time. Friction measurements have also been used successfully in several countries in Europe and in Japan to determine the effectiveness of deicing materials, and to optimize their rate of application and their effect on road safety. Friction measurements have also been used in Japan and Europe to evaluate the effect of pavement surface on winter maintenance. The results of using the deceleration method for friction measurements under winter conditions in the United States are encouraging. In general, standards for winter maintenance have been established in some countries in Europe based on limited data, while more advances in modeling were reported in Japan.

In Norway, the use of friction measurements for operation performance appears to be successful. However, the use of a threshold value in the United States may not be the most appropriate method due mainly to the liability that the winter maintenance agencies may be held responsible for. On the other hand, the contaminant classification method may offer a reasonable approach for application in the United States if it is found feasible. The investigations to date suggest that the expected accuracy of friction measurements in winter maintenance may not be as reliable as on wet or dry pavements; therefore, qualitative indication may be sufficient.

As part of this project, the research team contacted many national and international experts in the field to identify and categorize equipment, practices, and techniques used for obtaining friction indicators. Twenty-five persons participated in a working session held in Roanoke, Virginia in September 2000. Information gathered in this session is presented in Appendix A. The following five principle findings emerged from this working session:

1. Friction measurements have been and continue to be successfully used in Finland as a decision support tool and quality assurance measure for winter maintenance activities. This success has resulted, in part, from skills developed over the past 20 years to measure friction under winter conditions and interpret the measured friction values. This experience includes the use of a friction-measuring device that requires hard braking of the test vehicle.

2. Friction measurements (and other measures of pavement state that are indexed to friction) hold high potential as operational tools in winter maintenance activities. However, the on-going difficulties in obtaining repeatable friction measurements with robust and cost effective devices have rendered the technology, for the most part, impractical. Conversely, there are strong indications that the United States domestic efforts at understanding and utilizing friction in winter maintenance activities are comparable to other similar international efforts. In general, all symposium participants indicated that they would continue to vigorously pursue friction measurements as potential tools for their winter maintenance sectors.

3. There is a need to make friction measurements (as they translate into a measure of safe mobility) available to public road users in a simple way.

4. There is a fundamental need, with respect to friction in highway winter maintenance, to stay highly focused on *operational* needs and requirements. Specifically, the level of detail in friction measuring for highway winter maintenance may be of a fairly broad scale. Resolving friction changes that are 30 to 50 percent of the roadway's dry/bare value (summer friction) or wet/bare value are sufficient for many operational issues in highway winter maintenance. Friction measurements that lead to credible, qualitative descriptions of winter pavement state (poor, fair, good; or red, orange, green, for example) may be satisfactory for many operational winter maintenance activities.

5. Highway winter maintenance friction needs and requirements are somewhat different from those of the air transport runway winter friction community. Therefore, lessons learned, techniques, and cost estimates from the air transport sector do not translate directly into those for the highway winter maintenance community.

2.2 Identification and Categorization of the Equipment, Practices, and Techniques Used for Obtaining Friction Indicators

When using a friction indicator in an operational situation, a high level of accuracy may not be needed. It is quite possible that a friction indicator for operational use may only need to differentiate among three levels of friction (for example, good, transitional, and poor), and numerical values of friction may not be needed, nor may they be desirable in an operational setting. If friction measurements are to be used in a research or evaluation project where small changes in measurements may result due to a change in winter maintenance technique, it is clearly important to have an exceptionally accurate friction measuring device that provides values close to true friction measurements.

One of the challenges of determining the friction between a vehicle and a snow- or ice-covered road surface lies in the extremely high (in an absolute sense) temperature of the snow or ice. At -4°C (25°F), ice is at more than 98 percent of its melting point, as measured using an absolute temperature scale. Under such conditions, most materials are so malleable that they are unable to carry any load at all. Ice can carry a load at such temperatures, but it is extremely thermodynamically active. One result of this is that any force applied to the ice or snow is likely to change its mechanical properties. Intuitively, this is known from our own experience with snowballs. Snow is often too light and fluffy to throw effectively when it is freshly fallen. But by compressing this snow in our hands, the snow becomes sufficiently dense and cohesive to become an effective missile. On a more practical level, whenever a vehicle drives over a snow-covered roadway, it compresses the snow and thus changes the mechanical properties of the snow.

There are many issues that must be considered when friction on a snow- or ice-covered road is measured. Friction may be affected by the amount of traffic, the temperature, the rate and type of new precipitation, the methods used to treat the road, and the tires on the vehicles, to name a few parameters. The effects of these parameters are not fully understood at present and realistically may not be easily discerned.

For example, the friction between a vehicle and the roadway may change substantially every time a vehicle drives over a given stretch of roadway. However, after a sufficient number of vehicle passages, the change in mechanical properties due to subsequent vehicle passages will diminish and become operationally unimportant. Not only are friction measurements important, but the level of traffic that has passed over the road is also important. The influence of new fallen snow will also have to be considered.

On the other hand, friction measurement in winter maintenance is of value, because a high level of friction between the surface and the vehicle allows the vehicle to stop in a short distance, allows it to move again once stopped, and allows it to maneuver safely. However, friction may be difficult to measure operationally during a winter storm; it might be better to measure one of the "results" of friction such as the ability to stop a vehicle (braking), to start a vehicle moving (acceleration), and to maneuver a vehicle (turning). Under low friction conditions, all three abilities are compromised, thus reducing safety.

The quality and applicability of the measured friction results require a determination as to the effectiveness of the friction measuring technique and method used, as well as an assessment of the applicability of that type of friction as an indicator of winter maintenance effectiveness and vehicle mobility. Substantial and fundamental difficulties in obtaining good friction values from snow- and ice-covered roads are recognized. When friction measurements are made on wet or dry pavement, the tire on the friction device is the "sacrificial" surface: some of this surface is transferred to the pavement during the interaction between tire and pavement. However, wheel contact with snow produces a change in the material state; it is compressed. This compression changes both its physical properties (e.g., density) and its mechanical properties (e.g., shear strength). In addition, contaminant displacement drag, surface temperature, rolling resistance, compaction rolling resistance, and viscous and dynamic fluid lift planing are all important factors.

Thus, the act of driving across a snow-covered road changes the friction characteristic of that road. In addition, because winter roads are so often at or close to the melting point of snow and ice, water may also be present to create additional, mechanical complications that are currently poorly understood. Hence, any successful effort to assess and recommend friction as an indicator of winter maintenance effectiveness and driving mobility must include complete consideration of the friction mechanics.

It appears that development of a new theory of friction between snow-covered roads and vehicle tires, and new friction measuring devices are both needed before friction indicators can be fully understood within the context of winter maintenance effectiveness and vehicle mobility. Conversely, and despite the complexity of the mechanics of friction on snow- and ice-covered pavements, it is challenging to find useful engineering value from winter pavement friction measurements and measuring techniques that may not otherwise be completely understood from an engineering science perspective. The fact that winter pavement friction can be and has been measured, and that these measurements are repeatable, is sufficiently compelling from an empirical standpoint to support the continuing quest for engineering value in these measurements and to relate this value to indicators of winter maintenance effectiveness and mobility.

Currently different methods of friction measurement being considered for use during winter maintenance operations range from simple observational methods to the employment of sophisticated devices. The observational method of friction testing is widely used in areas of the world that experience winter weather. At its best, a trained observer visits certain pre-determined sites on a road system, stops at those sites, and leaves his/her vehicle to observe the road surface. These observations often involve “scuffing” a foot across the road surface to determine (solely by feel) how slippery the surface is. The advantage of the observational method is that, in the hands of a skilled observer, it probably gives a very good indication of the road condition. The drawback is that too often the observations are made from within a vehicle by people who lack the training and knowledge to make an effective determination of road conditions.

There are several devices for measuring road surface friction (*52*). All practical techniques for friction measurement fall into one of six groups: stopping distance, deceleration devices, locked wheel devices, side force devices, fixed slip devices, and variable slip devices. In addition, the increasing availability of automatic anti-lock braking systems (ABS) and traction control systems (TCS) on new vehicles offers the possibility of using such vehicles to gather information on the friction of the road surface.

2.2.1 Stopping Distance

This is the simplest and most natural method for determining the friction number. It consists of driving a vehicle, locking the wheels when the desired speed is reached, and measuring the distance the vehicle travels before it comes to a full stop. This method is specified in ASTM E 445 (*53*). The coefficient of friction is determined from Equation 8:

$$\mu = \frac{v^2}{2 * g * d} \qquad (8)$$

where v is the vehicle brake application speed, g is the acceleration of gravity, and d is the stopping distance. Obviously, this method can only be used for research purposes and not during winter maintenance operations.

2.2.2 Deceleration Devices

These devices measure the deceleration of the vehicle under full braking by using Newton's second law of motion as their principle of operation. A small mass in a sensor acts on a strain gage to generate a signal proportional to the deceleration force. The measured deceleration force is then used to calculate the friction coefficient. One of the earliest devices to calculate friction based on measured deceleration was the James Brake Decelerometer, first used in the 1950's in Europe and then in the 1960's in Canada and the United States. More recently, during the SHRP H-208 (*42*) project and the subsequent FHWA T&E-28 project (*43*), a deceleration device known as the Coralba meter was used. Some other available electronic recording deceleration devices include the Tapley-meter and the Bowmonk-meter. In Norway, a deceleration device called C-mu is used. Its measuring principle is based on recording the speed when the braking starts and ends and the braking time. The mean value of the deceleration is calculated by taking the difference between the two speed values and dividing it by the braking time. The mean value of the friction is then obtained by dividing the calculated deceleration with the gravitational constant ($g = 9.81 \ m/s^2$). The recommended braking time with this kind of instrument is approximately 2 seconds.

When sufficient training is provided, the deceleration method is repeatable and appears to be reliable. The major drawback of the method is that it requires a sudden braking maneuver to be made, and such maneuvers may not be operationally desirable.

2.2.3 Locked Wheel Devices

More than 40 states use the locked wheel trailer to measure the skid number (defined as 100 times the friction coefficient), which evaluates the friction characteristics of the pavement. ASTM E 274 (*54*) describes the locked wheel test. The test tire is installed in a trailer, which is towed behind the measuring vehicle at a speed of 64 km/h (40 mph). Water may be applied in front of the test tire, a braking system is forced to lock the tire, and the resistive drag force is measured and averaged for one second after the test wheel is fully locked. Figure 7 shows the Virginia Department of Transportation (VDOT) locked wheel trailer. Locked wheel devices have been used to monitor the Long Term Pavement Performance (LTPP) sections (*55*).

2.2.4 Side Force Devices

These devices maintain the test wheel in a plane at an angle to the direction of motion. The side force perpendicular to the plane of rotation is measured. The advantage of these systems is that their measurements are continuous throughout the tested pavement sections. The British Sideway Force Coefficient Routine Investigation Machine (SCRIM), with a wheel yaw angle of 20°, is the most commonly used device of this type. Arizona uses another system, the Mu-Meter, which measures the side force developed by two yawed wheels. The Mu-Meter procedure is described in ASTM E 670 (*56*).

Another side force friction device is the SafeDrive. FinnRA has tested this device, which can be used for simultaneous measurement of road surface friction, surface and air temperature, and air humidity (*19*). The device is an intelligent independent unit that can be installed in practically any heavy vehicle. It is provided with a GPS unit for orientation of the measuring route and with a GSM Mobile telephone for the transmission of the measured results in practically real-time. The measuring wheel is loaded by an air spring and the side force is measured by a load cell. The yaw angle and the vertical load can be varied.

2.2.5 Fixed Slip Devices

These devices usually operate between 10 and 20 percent slip. Some of the known equipment that operates on this principle is the roadway and runway friction tester (RFT), the Airport Surface Friction Tester (ASFT), the Saab Friction Tester (SFT), and the Griptester. The main drawback of these devices is that they take readings at a specified slip speed. Their slip speeds do not always coincide with the critical slip speed value, especially over ice- and snow-covered surfaces.

2.2.6 Variable Slip Devices

These devices measure friction as a function of slip between the wheel and the road surface. The results are presented in a graph similar to the one shown in Figure 2. These devices give information about the frictional characteristics of the tire and road surfaces. The initial increasing portion of the friction slip curve is dependent upon the tire properties, whereas the portion after the peak is dependent upon the pavement surface characteristics. Some known variable slip devices are the French IMAG and the Norwegian Norsemeter RUNAR, ROAR, and SALTAR systems.

The measuring device ROAR (Figure 8) is a "spot" measuring system with a variable slip test wheel. The ASTM E-1551 test tire (*57*) is used as the test tire with a 207 kPa (30 psi) inflation pressure. The test wheel is located in the left wheel track and mounted directly on the axle of a hydraulic wheel slip controller, which is programmed to perform a desired braking action on the test wheel. One such braking action is a linearly decreasing rotational wheel speed from free rolling to locked wheel. During this action, the torque on the wheel axle is measured and converted to a friction coefficient by the digital computer of the device. A vertical static load of 1.2 kN (300 lbf) is applied on the test wheel, which has a four bar suspension with no spring and no shock absorber. The rotational speed of the test wheel is converted to a distance and distance traveled per unit time. The computer is programmed to calculate several friction process parameters, including peak friction coefficient, the slip speed at which the peak friction occurred, the slope of the friction coefficient curve as a variable of slip speed, among others. The computer program uses the Rado Friction Model for deriving these parameters. Friction coefficients for all slip speeds can be computed from each braking action, including friction at lower slip ratios such as 15 or 18.5 percent and at speeds other than the one at which measurements were taken.

The measuring device SALTAR (Figure 9) is a spot measuring type with a variable slip test wheel. It is mounted on the snowplow frame behind the driver in the left wheel track. The unit uses an electric brake to bring the test wheel to a stop. The braking action is released and the rotational wheel speed goes from locked wheel to free rolling. During this action, the wheel speed is measured and the torque on the wheel is calculated and converted to a friction coefficient. A vertical static load of 0.7 kN (155 lbf) is applied to the test wheel. A Bridgestone 8F-228 135R X 12 tire is used as the test tire with a 207 kPa (30 psi) inflation pressure. The computer is programmed to calculate the average friction, which is used to provide the operator with a one to five levels of friction, one being poor and five being the best. For evaluation and research, the actual friction calculated can be reported.

The SALTAR friction meter incorporates symmetrical layout of the mounting frame and an in-line design that makes it modular. The extremely slim design perpendicular to the direction of travel/measurement gives the possibility of mounting the device virtually anywhere on a large plow truck or winter maintenance vehicle. The unit was designed to be mounted in the left or right wheel track or in the middle of the vehicle. The main mechanical component in the SALTAR device is the measuring wheel system. The measuring wheel mechanism is designed as an extendable ladder frame that consists of three horizontal crossbars and two vertical cylinders. The keyboard operator panel is a palm size "hard wired remote control" unit of the measurement system that also displays in real-time the measurement results. The control button indicators and LEDs are arranged to give the operator maximum flexibility and easy observation. Because of the small size, the operator panel can be placed anywhere in the driver's cabin of the host vehicle. SALTAR's unique and simplified design makes it possible to operate the unit in forward or reverse without any difficulty. Thus, the unit can be turned 180° if mounting it to the vehicle makes that decision necessary.

2.2.7 Traction Control and Anti-Lock Brake Devices

The increasing availability of ABS and TCS on new vehicles offers the possibility of using such vehicles to gather information on the friction of the road surface. In order for this approach to be feasible, a number of steps must be considered and addressed.

The first item of consideration is whether these technologies can measure friction values in a way that is useful. Certainly, both the ABS and TCS perform measurements that may be indicative of a road surface friction level, but of the two, it appears that the ABS will be less useful than the TCS. The ABS only operates under braking conditions, while the TCS also operates when the vehicle is not braking. The TCS senses traction on the driving wheels of the vehicle, and this sensing occurs even when the vehicle is moving at a constant velocity (58). Thus, while both systems have the potential to measure friction, the TCS is able to measure friction more often and will thus have the potential to provide more data.

It should be noted that at least one ABS based friction measuring system already exists: the AeroTechTelub MoRRS (Mobile Road Reporting System). This system, which was developed and is being marketed in Sweden, appears to be a more modern version of a deceleration-based friction-measuring device. It measures friction as soon as the ABS begins to operate under braking. The final report on the MoRRS study (*59*) provides some extremely valuable insights into how friction data may be gathered from ordinary vehicles. In the study, four vehicles, each equipped with ABS were also equipped with a collection of sensors and other equipment that are jointly termed a Mobile Road Reporting System, or MoRRS.

The MoRRS consists of a GSM platform that serves as a micro-controller for all other sensors and circuitry, circuitry to monitor the activation of the vehicle's ABS and measure the applied brake pressure, a GPS unit to record vehicle location, a GSM Modem (Siemens M20), a temperature sensor, and a power supply. Data on temperature, braking, and friction are sent via the modem to a central location and then are displayed in real-time on a web-based server.

The field test of the MoRRS used four friction levels. Level 0 indicated no friction data available (i.e., the ABS had not been activated or the brakes had not been used, but temperature data had been passed). Levels 1, 2, and 3 indicated levels of friction that were good, slippery, and very slippery. To obtain such readings, the ABS had to be active, and brake pressure was used to differentiate thereafter between the friction levels. The actual brake pressure used to differentiate between friction levels was obtained by field-testing on a skid pan, and was different from vehicle to vehicle.

Nearly 400 non-zero friction level data readings were obtained from the four vehicles used in the study. Two of the vehicles were public transportation vehicles, which tend not to make severe braking maneuvers as "it causes discomfort for the passengers." Nonetheless, in spite of a rather sparse data set, good results were obtained. The system worked and transmitted real-time reports of low levels of friction on the roads to a web site. Further, this system has the potential to be fully scalable. In addition to a successful proof of concept, the report provided several implications for future developments. As indicated in the report, the drawback of using ABS as a friction-measuring (strictly, a friction-indicating) device is that readings are only obtained under severe braking conditions. If public vehicles are to be used, a different method of obtaining friction indications must be used. System integration of data from many different vehicles and systems will pose substantial (but not insurmountable) challenges. Finally, commonality of communication and server architecture will be a critical requirement for broader development of such systems. The MoRRS study indicated that obtaining data from vehicle systems is difficult at times. Significant problems were experienced when obtaining ABS data from one type of vehicle tested. Such difficulties should be expected regardless of whether the ABS or TCS is used to obtain friction related data.

Of the two systems, it would appear that the TCS is better suited to providing friction related data in this particular situation. The ABS will only provide friction related data when the system is activated, which is under severe braking conditions. From the point of view of the vehicle operator, any friction data generated under such conditions are too late to be of value, although other vehicles may benefit (see below in the proposed system description). In contrast, a TCS may provide friction related data under normal driving conditions, as the system senses differential loading between the vehicle wheels.

Many models of domestic and imported Sports Utility Vehicles (SUVs) and sport sedans/wagons are now equipped with various levels of traction control technology. The purpose of these devices is to decrease the torque applied to a wheel or set of (front or rear) wheels that have begun to spin faster than their roadway tangential speed due to a loss of friction with the roadway. The net result is to maintain vehicle stability and control at highway speeds and/or to insure mobility at lower speeds over exceeding rough or slippery terrain. These traction control technologies become germane to this investigation when this net wheel slip information is thought of as a basis for friction measuring over stretches of winter roadway. Additionally, this information is collected by on-board systems at highway speeds *without* a need for vehicle braking. However, the mechanisms by which wheel spin information and torque reduction in traction control is accomplished are crucial.

In one commonly found traction control technology, the entire process is controlled hydraulically within the vehicle's transmission. When wheel or axle slip occurs, the resulting drop in transmission hydraulic pressure is used to further reduce the torque to that wheel or axle. There is no attempt made to measure each individual wheel's (tangential) speed and compare it with the average vehicle velocity for the purpose of determining net wheel slip. Further, in hydraulic traction control, there are no electronic sensor systems, either at the wheels or transmission, which would result in a wheel/pavement interaction data stream.

In a less common, but highly developed, traction control technology, there are individual wheel or axle speed sensors that measure the rotational velocity of each wheel. The resulting wheel tangential velocity at the road surface is then compared to the vehicle's net velocity for the purpose of determining if there is net wheel slip. Processor rates are in the kilohertz range. When wheel slip is sensed, torque adjustments (reductions) or very modest, automated braking are made to those individual wheels. These electronic traction control systems are effectively sampling wheel/roadway interaction, a measure of roadway friction, at kilohertz rates. These net wheel slip data, if accessed and archived, along with attendant position or milepost information, have the potential to serve as viable roadway friction measures. There are no (known) efforts underway domestically to use vehicle electronic traction control in this fashion. Three specifically identified vehicles, GMC Military Vehicle Division "Hummer," Audi Avant Quattro, and Subaru H6-3.0 VDC, have individual wheel speed sensors as elements of their on-board electronic traction control systems that may warrant investigation as roadway friction measuring devices.

2.2.8 Comparison of Field Friction Measurements

As part of the evaluation system for different winter maintenance activities, the Norway Winter Friction Project used four different friction devices: C-mu, Kofriks, ROAR (Mark I and Mark II), and OSCAR (*49*). C-mu is a deceleration meter with a recommended braking time of two seconds. Kofriks is designed to be mounted on maintenance vehicles as well as on trailers. The measuring wheel is loaded with a stable force in the radial direction and is free rolling in the driving direction. Mark I ROAR is a variable slip continuous measuring device that measures force, while ROAR Mark II measures torque and is more cost effective than Mark I. Both systems can be installed on snowplow/spreader trucks. All equipment was calibrated using OSCAR (fixed slip) as the reference measuring equipment. Friction readings were taken twice a day and during precipitation periods. Figure 10 shows some of the collected friction data using the ROAR Mark I device to evaluate sanding methods. The sanding treatment was performed on February 9, 2000 from 16:45 to 17:10. The friction measurements were conducted on the same day at 15:18 and 18:30 and on the next day at 08:12. The air temperature during the three friction measurements was -9.5°, -12.8°, and -1.2°C (14.9, 9.0, and 29.8°F), respectively. The traffic count was 40 vehicles between the first two readings and reached 270 vehicles before the third and last reading.

Field studies were conducted in Minnesota and Norway during the 1995/1996 winter season in a joint MnDOT/Norsemeter project. The Minnesota study initially used the Mark I and later the Mark II, as it was found to be more improved and more cost effective. The work was then carried over to a joint concept snowplow project to incorporate state-of-the-art equipment onto a snowplow (*60*). The project started with the states of Iowa (lead State), Minnesota, and Michigan. Three spin down Norsemeter ROAR systems were independently installed in three different snowplow vehicles. One system was mounted just behind the cab on the left wheel track and was able to collect data in the Iowa prototype vehicle. Because the Minnesota unit was mounted on the rear of the plow truck behind the dual wheels, it took much of the salt spray from the tires and tremendous shock resulting from truck bounce during operation. Michigan installed the friction unit in a separate trailer. In addition, Minnesota and Iowa provided two KJ Law ASTM E 274 skid trailers to be used for comparisons. Four sites were used at the test track to evaluate the units.

The tests were conducted under both wet and dry pavement conditions at speeds of 32, 48, 64, and 80 km/h (20, 30, 40, and 50 mph). It was found that the units did compare favorably in their measurements of μ_{peak} and F40 with 0.8 and 0.75 R^2 correlations, respectively. However, the Iowa unit gave a different slope than the others for μ_{peak}. The units where later tested individually under winter conditions in each state. The Minnesota units measured satisfactorily but were not durable. The difficulties reported with the system, durability, and cost of the ROAR units led Norsemeter to develop SALTAR.

The Norwegian Road Administration conducted similar testing in Norway in February 2000, where SALTAR and ROAR were evaluated together to make comparisons. ROAR was calibrated with the OSCAR and found to have the same measurements. Figure 11 shows that SALTAR provided lower friction coefficients than the ROAR; however, the values appeared to increase or decrease in a similar manner. The same sections first had hot sand and then cold sand placed on the middle half, and the measurements were then repeated. Figure 12 shows clearly that SALTAR measurements changed with the friction level. Based on this, a correlation was made and the results are shown in Figure 13. This correlation was then applied to the SALTAR data shown in Figures 11 and 12 and the modified values are re-plotted as Figures 14 and 15 together with the ROAR data.

Friction devices were categorized in four types (locked wheel, deceleration, variable slip, fixed slip). Friction devices that measure the retarding force only actually measure the sum of the drag from the contaminate and the braking force due to friction. Devices that measure torque only, measure the braking force due to friction. Some devices measure both load and torque as drag and friction. Table 10 presents the reported resolution, repeatability, use, and approximate cost of the systems along with the studies where the devices were used.

2.2.9 Summary

Data indicate that deceleration and variable slip methods may offer the most appropriate techniques for friction measurement under winter conditions. The deceleration method is cost effective, easy to operate, and offers repeatable and reliable data. Although the sudden braking may not be desirable, it could be used on snowplow/spreader trucks. Both the recent development in the variable slip method and the development of a portable device show that the technique is feasible for potential implementation in winter maintenance. In addition, both methods have successfully been used for conducting repeatable friction measurements for highways under winter conditions. The required accuracy of highway winter friction measurements is less than that for dry and wet pavements or for ice- or snow-covered runways; hence these measured values can be accepted as qualitative, but further evaluation is necessary. An example of a cost effective and portable deceleration method device is the Coralba. Likewise, SALTAR is an example of a cost effective and portable variable slip method device. In addition, a cost effective variable slip unit for snowplow/spreader trucks is currently under development in Hungary.

Clearly, the TCS and ABS can both provide information that relates to road surface friction. Of the two systems, the TCS is better suited for continuous friction measurements, as it is operational for most of the time compared to the ABS that provides friction data during heavy braking situations only.

2.3 Scenarios for Winter Maintenance Operations and Mobility

Both the spatial and temporal distribution of friction measurements over a section of road provides a means of establishing winter maintenance effectiveness. It is unlikely that either spatially or temporally continuous measurements of winter road friction will be collected on every road during every winter storm by operational road maintenance organizations. Much more likely, an incomplete subset of the entire record of winter road friction will be collected. However, to be of value, these points and/or continuous friction measurements, collected at various irregular intervals during winter maintenance periods, must provide an indicative sample of the winter road conditions over the entire area of interest. Therefore, determination of the minimum friction measurement sample size and the interval between the friction measurements will be needed for a given service area.

Efforts on the part of the Scandinavian countries to use friction measurements in winter maintenance operations decision-making and operations performance evaluation are the most advanced to date. Domestic and international acceptance of friction measuring as the sole method for reliably measuring winter maintenance effectiveness is not yet forthcoming. However, because of early successes, efforts into the use of friction measuring in winter maintenance activities are warranted.

Four broad scenarios for the use of friction measurements have been developed to highlight some of the ways for using friction measuring in winter maintenance activities. These scenarios involve data collection and actions taken based on data analysis. Climatic conditions, traffic levels, road characteristics (e.g., surface type, gradient, etc.), and other factors influence the data collection phase only where hard braking is required. The actions taken under each scenario will be greatly effected by climatic conditions, traffic levels, and road characteristics.

The four scenarios, numbered in order of escalating technological and implementation complexity, are described. For example, Scenario 1 relies on the use of friction measurements in a similar manner to their use in Finland. It involves simple use of friction measuring hardware devices, implementation of auxiliary technology, operator training, and limited difficulties with adapting it to winter maintenance. Conversely, Scenario 4 has not yet been tried (it requires friction measuring devices that may not yet be available). It requires the implementation of significant auxiliary technology.

2.3.1 Scenario 1: Friction Measurements by a Winter Maintenance Patrol Vehicle

In this scenario, point or continuous friction measurements are used to provide information to support the winter maintenance decision-maker. Specifically, a winter maintenance patrol vehicle is dispatched to travel over portions of the road system during and after winter maintenance activities have been performed, making either periodic or continuous measurements of roadway friction. The friction information may be presented to the patrol vehicle operator in simple, qualitative terms (i.e., a green, yellow, or red pavement friction condition). Little or no effort is made to record, transmit, or archive the friction information for either electronic transmission or later consideration.

If some or all these measurements do not meet certain friction criteria, then the winter maintenance decision-maker may recall the maintenance fleet and re-treat those sections of the road that do not meet the criteria. This need is communicated through the radio frequency channels used by winter maintenance operations; portions of roadway that need additional winter maintenance effort are identified verbally by milepost. This utilization of friction measurements has been in use in Finland.

Also, friction information may be used to advise winter maintenance vehicle operators of the application rates for spreading snow and ice control materials. The friction information is radioed to the entire winter maintenance fleet where it is used to manually set snow and ice control material spread rates prior to departing on winter maintenance routes. Friction criteria may be different across agencies as they are dependent on climate, traffic, surface condition, roadway gradient, and equipment used.

2.3.2 Scenario 2: Friction Measurements by Winter Maintenance Snowplow/Spreader Vehicles

Friction measurements on individual winter maintenance snowplow/spreader vehicles would control one or more of the winter maintenance functions of those vehicles, such as the application rates of snow and ice control materials and down pressure on forward and under-body snowplows. In this scenario, all winter maintenance snowplow/spreader vehicles are equipped with an independent friction measuring capacity and have in-cab control capacity of snowplow and spreader functions beyond simply up/down or on/off.

It should be noted that measured friction alone cannot and should not completely control chemical delivery or the plowing process. Other factors (pavement type, temperature, and forecasted weather conditions) will also need to be considered. Also, because of the demanding task environment on snowplow/spreader operators, it is unlikely that this operator group will have an opportunity to safely and effectively take regular friction measurements with any device that requires hard braking of the snowplow/spreader vehicle.

2.3.3 Scenario 3: Recorded, Archived Friction Measurements by Winter Maintenance Patrol or Snowplow/Spreader Vehicles

As in Scenarios 1 and 2, either a winter maintenance patrol vehicle or a snowplow/spreader vehicle measures the friction. The enhancement in this scenario is that the friction measurements are recorded for future consideration. In addition to the manual or automatic (electronic) entry of the friction information, the patrol or snowplow/spreader vehicle operator must enter the milepost location of the friction data record. Alternatively, the vehicle may be equipped with GPS or another type of automatic vehicle location technology, and the location of a given friction measurement is automatically recorded, along with the measurement value itself.

Similar to Scenario 2, it is unlikely that snowplow/spreader operators will have an opportunity to safely and effectively record friction data and location manually. Additionally, these friction measurements cannot be reasonably garnered from devices that require hard braking of snowplow/spreader vehicles.

In this scenario, friction measurement records are used in post-winter maintenance periods to assess the effectiveness of the winter maintenance activities for the purpose of evaluating or assuring the quality of the resulting winter roadway levels-of-service. This category of friction measurement usage becomes, primarily, *a quality assessment and assurance* technology for winter maintenance activities. The importance of quality assessment and assurance in winter maintenance activities is paramount when these activities are conducted by contracting organizations.

Alternatively, both individual and sets of recorded, archived friction measurements can be used to evaluate the effectiveness of incorporating new winter maintenance technologies or techniques within a winter maintenance organization. These records of friction measurements and locations can also be used to develop spatially averaged maps of the pavement friction state during winter maintenance periods, similar to the pavement thermal state maps developed for winter maintenance purposes.

Although neither timely nor specific to any given storm, these maps of average pavement friction data during storm and winter maintenance periods can be provided as public information that can influence route-of-travel selection and travel planning. Additionally, an analysis of the expected frequency and duration of the pavement conditions found on these maps can be used to influence vehicle decisions for procurement of vehicles used regularly on a specific route. This may be significant, especially to public safety agencies and entities, as well as private sector and commercial transporters, if a fleet of vehicles is to be procured. This non-real-time information can be communicated to the public as web based and printed material.

2.3.4 Scenario 4: Recorded, Archived, and Real-Time Transmitted Friction Measurements by Winter Maintenance Patrol or Snowplow/Spreader Vehicles

Building on the activities in Scenarios 1, 2 and 3, the records of friction measurements and locations are transmitted in near-real-time from the snowplow/spreader vehicles to a central location where the information is processed by cell phone and radio. Friction data and location volumes, and the regular intervals at which these data must be transmitted, preclude using voice communication radio frequencies that are presently in use.

There are a variety of ways in which timely, near-real-time pavement friction measurements can be used in winter maintenance practices. Some of these require investments in auxiliary technology including RWIS, over-the-road techniques such as anti-icing, technologically and staff intensive Traffic Operations Centers (TOCs), and Advanced Traveler Information Systems (ATIS).

Real-time, transmitted friction information by region or specific roadway section, along with RWIS data (including the pavement temperature forecasts), can be used to dispatch snowplow/spreader vehicles to existing and anticipated trouble spots. Also, chemical snow and ice material application rates for different periods during a storm could be changed in near-real-time, as the storm intensifies or winds down.

Timely winter friction measurements can be used to alert both private and commercial road users of roadway sections where pavement friction may be inadequate for safe mobility at speeds typical of that road section. Friction measured by either winter maintenance patrol vehicles or individual snowplow/spreader vehicles is used as a base to continuously monitor the road network for areas of inadequate friction. Where available in near-real-time, winter road friction information will help road users in pre-trip planning and en-route travel decision support. Winter pavement friction measurements can be transmitted by television and radio, web-based postings, and daily periodicals for public use. En-route public use of winter friction communications would include public agency or commercial radio and dial-in cell phone advisories, as well as wireless web-based postings.

Traffic control devices, such as mandatory road closures, variable message signs indicating a mandatory reduction in speed, and variable message signs that provide motorist warnings and advisories, may be activated manually or automatically based on winter pavement friction measurements. Many of these traffic control operations can be implemented by local and regional TOCs, given that they receive the friction measurements in a timely fashion.

2.4 Questionnaire Development

To determine the feasibility of using different friction measurement techniques to support winter maintenance operations and mobility and to evaluate the proposed scenarios, expert opinions were obtained. Two questionnaires were developed: one for winter maintenance operators and field supervisors, and one for national and international knowledgeable sources. The first questionnaire (Appendix B) was sent to 20 winter maintenance and field supervisors to solicit their opinion on the feasibility and perceived benefits of using friction measurements described in the proposed scenarios to support the winter maintenance operations. Also, the questionnaire solicited information on the efforts needed to ease the implementation of these scenarios, as well as the possible technological impediments to their implementation and the need for additional research or testing.

The second questionnaire (also in Appendix B) was prepared to solicit opinions on the feasibility of the proposed scenarios, and identify the most promising technologies for friction measurements for each scenario. This questionnaire was distributed to 29 individuals who are known to be national and international knowledgeable sources in this field. A multi-attribute, decision-making approach was used and consisted of the following steps:

1. Definition of the criteria used for rating the scenarios and the technology type that may be used for their implementation. The following criteria were used:
   a. *Scenario evaluation criteria:*
      - Potential to enhance winter maintenance operations (benefit to DOT),
      - Potential to enhance user mobility (benefit to road users),
      - Potential to enhance roadway safety,
      - Implementation feasibility,
      - Implementation practicality,
      - Prior domestic experience,
      - Prior international experience.
   b. *Equipment evaluation criteria:*
      - Effectiveness,
      - Reliability,
      - Repeatability,
      - Robustness,
      - Deployment cost,

- Operational cost,
- Operational safety,
- Road user safety,
- Ability to be integrated into agency's operation,
- Ability to present results in a simple format.

2. A set of appropriate rating levels for each decision-making criterion was set. Five levels were used.

3. A weight was defined for each of the criteria considered. Two weighing systems were considered: one for the scenarios, and one for the technologies. The respondents were asked to assign a relative weight to each criterion.

4. The second questionnaire included a summary description of the scenarios, and the respondents were asked to rate each of the criteria according to the levels defined, and to rate one or more types of friction measuring technologies with respect to their effectiveness, cost, and safety for that particular scenario.

CHAPTER **3**

INTERPRETATION, APPRAISAL, AND APPLICATIONS

3.1 Interpretation of Responses Related to Feasibility and Perceived Benefits of Friction Measuring

The questionnaire provided to winter maintenance operators and field supervisors solicited opinions on the feasibility and perceived benefits of using different friction measurement techniques to support the winter maintenance operations in accordance with the proposed scenarios. Nineteen responses (95 percent responded to the questionnaire), representing fifteen State DOTs and the US Army Cold Regions Research and Engineering Laboratory (CRREL), were received. These responses are presented in a graphical form in Appendix C. The analysis of the responses was used to assess efforts to ease implementation of the developed scenarios in domestic winter maintenance practices, identify possible technological impediments to domestic implementation of the scenarios, and fine-tune the proposed scenarios. The opinions of the surveyed group are discussed in the following sections.

3.1.1 Background Information

All the respondents' professions are at least somewhat related to winter maintenance and most of them (89 percent) have duties that are directly related to winter maintenance. However, only five agencies (26 percent of the respondents) use friction measurements to support winter maintenance operations and, in most cases, these uses are limited to experimentation and testing. The friction measurement devices used include the Norsemeter (conceptual vehicle test only), Coralba, and SALTAR. Some of the problems with the friction measuring equipment used by these agencies included lack of reliability and calibration requirements. Furthermore, it is important to note that approximately 40 percent of the respondents were familiar with the friction measurement technologies that can be used under snow and ice conditions, as Figure 16 shows.

3.1.2 Usefulness of Collecting Friction Data

The majority of the respondents (67 percent) indicated that the use of friction measurement would improve winter maintenance operations in their jurisdictions or settings. The most suggested applications include quality control, level-of-service determination, and decision support. It is important to note that CRREL is working on the development of a "road condition index" that combines friction, snow depth, precipitation event, road temperature, and other related variables to support decisions on when, where, how, and what to apply as anti-icing and de-icing treatments (*61*).

The respondents indicated that a simple indication of the pavement friction (e.g., a green, yellow, or red surface friction condition) may help field supervisors make a decision on re-treating a particular roadway section. Also, they indicated that recording and storing the friction data may be beneficial for future uses such as assessing the effectiveness of the winter maintenance activities. They also noted that installing a GPS or other automatic vehicle location device to automatically record the location of the surface friction measurement could be cost-effective. Other uses of the information include supporting legal cases, quality control, model development, and identification of trouble spots. Additional data that should be included in the database are: date and time, pavement temperature, surface conditions, weather conditions, and air temperature (Figure 17). However, use of a simple friction indicator to help with the selection of appropriate application rates for ice control materials and or downpressure on underbody snowplows was not clearly indicated.

3.1.3 Friction Measurements Technology

All respondents indicated that equipping winter maintenance supervisors' vehicles with friction measuring devices would be beneficial, and approximately two thirds agreed that it would also be useful to equip snowplows/spreaders.

The majority of the respondents (72 percent) indicated that the cost of the equipment should be less than $5,000. However, some respondents indicated that costs up to $15,000 might be reasonable. Several respondents emphasized the need for a reliable, easy to use, and robust piece of equipment, but they dismissed the use of devices that require hard braking, citing safety considerations.

3.1.4 Potential Uses of Snow- and Ice-Covered Pavement Friction Measurements

The opinions of the winter maintenance practitioners regarding potential uses of the friction measuring devices are summarized as follows:

- There was strong indication towards the usefulness of real-time friction measurements, along with Roadway Weather Information System (RWIS) data, in allocating snow-fighting resources in real-time.
- There was a recognition of the benefits of collecting and analyzing real-time records of friction measurements and locations at a data control center, and incorporating near-real-time surface friction records into existing winter maintenance or traffic management practices.
- There was a lack of support for using friction records for developing spatially average maps of surface friction during snow fighting periods, or posting the historic information on the web or other media for user information.

3.1.5 Summary of Responses

In summary, it was clear that the respondents believe that the use of friction measurements would improve winter maintenance operations. The information collected by low cost, reliable friction measuring devises, complemented by other data such as pavement temperature, surface conditions, weather conditions, and air temperature, could be useful to allocate snow-fighting resources in real-time. The opinions were divided on the use of the simple friction indication in aiding in the selection of appropriate application rates for ice control materials and/or downpressure on underbody snowplows. Furthermore, the respondents did not see a potential benefit in using friction records for developing spatially average maps of surface friction during snow fighting periods, or posting this information on the web or other media for user information.

3.2 Interpretation of Responses Regarding Proposed Scenarios

Of the 29 distributed questionnaires, 23 responses (79 percent) were received: 13 (57 percent) were from North America and 10 (43 percent) were from overseas. The overseas responses were from Japan, Norway, and Finland, all countries with extensive winter maintenance experience. The responses were analyzed as a whole, and for each of the domestic (North America) and international responses.

3.2.1 Winter Maintenance Scenario Evaluation

The first part of the questionnaire sought to evaluate the feasibility of the developed scenarios for the use of friction measurements to improve winter maintenance operations decision-making.

Evaluation Criteria: The first step for the scenario evaluation was the definition of the criteria used for rating the scenarios. The respondents were asked to provide a percentage weight for each criterion, which represented the relative importance of each criterion. The criteria considered for the evaluation of the proposed scenarios and the average weight assigned by the respondents for each criterion are listed in Table 11, and shown graphically in Figure 18, for all responses and for the North American and Overseas responses. This table indicates that the potential to enhance winter maintenance operations is the most important criteria, followed closely by the potential to enhance safety and mobility, which are given approximately the same weight. Implementation feasibility and practicality both received roughly the same weight (9 and 11 percent, respectively). Prior domestic and international experience received the lowest weights (4 percent each).

Analysis: The research team set a five-level rating scale for each decision-making criterion and asked the respondents to rate each criterion according to the levels defined. The average (overall and divided by location), standard deviation, minimum, and maximum were computed for each criterion and scenario, as shown in Table 12. The average levels assigned to the scenarios for all criteria are compared in Figures 19 and 20. Figure 19 depicts the average level assigned, and Figure 20 depicts the levels after applying the average weight factors. The plots show that Scenario 4 has the highest potential to enhance winter maintenance operations, mobility, and roadway safety, and Scenario 3 provided the lowest potential; Table 12 shows this is particularly true among North American respondents. This could be attributed to the fact that Scenario 3 could be considered a first step before advancing to Scenario 4. The main difference between the two is that Scenario 4 requires coordination with related agencies (RWIS data for example), which is achievable in North America.

Table 13 indicates that Scenario 4 was considered the most promising, followed closely by Scenarios 1 and 2 (in order of decreasing promise). Scenario 3 received the lowest raking. To verify that averaging the weights and assigned levels did not bias the decision, the individual ratings were computed for each respondent using his or her individual weight and ratings. The average, standard deviation, minimum, and maximum overall ratings are shown in Table 13.

The average is also broken-down based on each source's location. As can be observed, although the averages are slightly different, the relative order of importance is maintained in all cases.

3.2.2 Friction Measurement Technology Evaluation

The second part of the questionnaire included questions regarding the perceived operational characteristics of the equipment and the relative weight that the respondents would assign to each of the considered characteristics.

Evaluation Criteria: In this part of the questionnaire, the respondents were presented with a series of characteristics (also considered technology evaluation criteria) and were asked to provide a percentage weight for each characteristic that represented the relative importance of the criterion. Table 14 presents the average weights assigned to each of these criterion, both for all the respondents and broken-down by their locations, in decreasing order of importance. Repeatability, reliability, and effectiveness were the most highly regarded characteristics. The weights assigned by the North American and international sources are in reasonable agreement, except that the North American sources again rated the safety criteria slightly higher than their overseas counterparts.

Analysis: The research team set a five-level rating scale for each technology characteristic or decision-making criterion. The respondents were asked to rate the technologies according to the considered criteria using the levels defined. The average (overall and divided by location), standard deviation, minimum, and maximum for each technology and characteristic are shown in Table 15. The average ratings assigned to the friction measurement technologies are compared in Figure 21. Figure 22 shows the same evaluation after using the average weights assigned to each characteristic.

The deployment costs ratings indicate the opinion of the respondents on what would be a reasonable cost for deployment of a friction measurement device on a supervisor's vehicle and on snowplow/spreaders. A higher rating corresponds to a lower cost technology. It is important to note that some of the respondents were not very familiar with some of the technologies. The percentage of respondents indicating adequate familiarity (at least a level of three out of five) with the technologies was 91 percent for deceleration, 65 percent for slip, and 83 percent for anti-lock brake system devices.

Using the average criteria and weight, the overall rating of the three friction measuring technologies evaluated is presented in Figure 23 (Table 15). According to this analysis, the TCS is the most promising technology, followed closely by deceleration and slip devices.

CHAPTER **4**

CONCLUSIONS AND SUGGESTED RESEARCH

4.1 Conclusions and Recommendations

The following conclusions have been derived from this research:

- Individuals with adequate familiarity of friction issues believe that the use of friction measurements to improve winter maintenance operations and mobility is feasible.
- Traction control systems (TCS) appear to be the only way to eliminate the extra wheel used in current friction measuring devices, and their use to predict road surface condition has a great potential for enhancing winter maintenance operations.
- Developing a model to predict road surface condition utilizing climate, traffic, and pavement related data is feasible.
- Significant work needs to be conducted in the area of human response to better understand drivers' reactions to winter maintenance and to determine the best method of communicating roadway friction to drivers in a simple way.
- Use of friction measurements to provide information to support winter maintenance decision-making qualitatively and in a simple way appears to be promising and practical for improving winter maintenance operations, safety, and mobility. In this scenario, a winter maintenance supervisor's vehicle is dispatched to travel over portions of the road system during and after winter maintenance and make either periodic or continuous measurements of roadway friction, and the operator of this patrol vehicle is given the collected friction information in simple, qualitative terms (e.g., a green, yellow, or red surface friction condition). If some or all of these

measurements do not meet approved friction levels-of-service, then the decision-maker can call the maintenance fleet to re-treat those road sections. Additionally, appropriate application rates for ice control materials for the monitored conditions can be relayed to the entire winter maintenance fleet so that individual operators can use this information to manually set the spread rates of their ice control material. Since this scenario is also thought to have the highest potential for successful implementation, it should be considered for an immediate, near-term operational implementation trial at one or more State DOT trial sites.

- Transmittal of friction measurements and locations in near-real-time from the winter maintenance patrol or snowplow/spreader vehicles to a central office where the information is processed was thought to be the most promising scenario for enhancing winter maintenance operations, mobility, and safety that requires further technology development and integration prior to an operational trial. In this scenario, RWIS data are used for dispatching snowplow/spreader vehicles to existing and anticipated trouble spots, and for selecting ice control material application rates for different storm periods. The information (or a summary) can be made available to both public and commercial road users with warnings about sections of roadway where surface friction may be inadequate for safe mobility.

4.2 Suggested Research

Friction measurements for winter maintenance have been used in experimental research in the United States and in operational application (without sufficient supporting data) in some Scandinavian countries. Also, analytical and theoretical work, including the use of a neural network to predict friction from other data such as weather, traffic, and pavement condition, has been conducted in Japan. While work continues on developing devices that can produce reliable friction data without hard braking and/or affecting traffic flow (although this could be acceptable for low volume roads), work should be also directed toward new technologies that utilize indirect measurements to develop models that correlate roadway surface condition to parameters such as pavement temperatures, pavement type, traffic, and climate.

Based on the opinions of knowledgeable individuals, two scenarios have been recommended for field testing. Table 16 summarizes the potential of the two scenarios for supporting winter maintenance operation decision-making, operation performance evaluation, and motorist information. The table also presents other important factors that determine the overall implementation feasibility, including the need for research and development, cost estimate for research and development, and time to market. The comparison is made on the basis of supporting the category of practice: 1 for strong support; 2 for moderate support; and 3 for little or no support.

A two-phase research program has been recommended to address the two scenarios:

<u>Phase I will include the following:</u>

- Validate the proposed Scenario 1 through a pilot study. Considered friction technology should include existing and available deceleration and variable slip devices. Utilizing new technologies such as TCS should be strongly encouraged.
- Develop and validate road surface condition prediction models of friction measurements from related easily-measured and/or readily available parameters, including traffic, temperature, pavement type, etc.
- Develop protocols to evaluate the effectiveness of the TCS in estimating winter maintenance friction. Also, demonstrate the use of TCS technology for measuring or indexing winter roadway pavement friction. Private sector entities, including the vehicle manufacturers, should be encouraged to participate in the research and development demonstration.

Phase II will include the following:

- Test the validity of the proposed Scenario 4. Technology development should include more robust, reliable friction measurement or indexing systems; on-board and fixed location friction data handling and communications technology demonstration; integration and demonstration of integrated friction measurements with (automated) vehicle locations; and a system integration and demonstration project. These research, development, and integration efforts require expertise in winter maintenance, data handling, AVL, wireless communications and advanced traveler information systems (ATIS).
- Test in the field and calibrate the friction indices developed through modeling and TCS technologies.

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Table 1. Terminology used in Sweden for reporting friction measurements (12)

Reported Condition	Friction Coefficient
Good	0.40 and above
Medium to Good	0.36 –0.39
Medium	0.30 –0.35
Medium to Poor	0.26 –0.29
Poor	0.25 and below

Table 2. (a) Finnish friction condition standards (12) (b) Relation between friction values and driving conditions in Finland (30)

(a)

Condition Standard	1	2	3	4	5
Skid Number	0.0-0.15	0.15-0.25	0.25-0.3	0.3-0.45	0.45-1.00

(b)

Friction value	0.00-0.14	0.15-0.19	0.20-0.24	0.25-0.29	0.30-0.44	0.45-1.00
Description of road surface	Bad driving conditions, wet ice **Very slippery**	Icy **Slippery**	Tightly packed snow **Satisfactory winter conditions**	Rough, packed ice and snow **Good winter conditions**	Bare and wet **Not slippery**	Bare and dry **Not slippery**

Table 3. (a) Finnish target conditions for friction (12) (b) Quality standards of winter maintenance in Finland (30)

(a)

Maintenance Class	Traffic Volume (ADT)	Target Conditions		Cycle Times (h)	
		Day	Night	Deicing	Snow Removal
I Super Divided	Freeways	4	4	2	2.5
I Super	≥ 6000	4	4	2	2.5
I	1500 –6000	4	3	2	3
II	200 –1500	3	2	4	4
III	≤ 200	2	1	6	6
IV	Pedestrian and Bicycle paths	2	2	4	4

(b)

Winter maintenance class	Is	I	Ib	II	III
Normal	0.3	0.28	0.25	According to traffic needs	According to traffic needs
Friction requirement	Road surface below -6℃ 0.25	Road surface below -4℃ 0.25	Spot sanding 0.25 line treatment 0.20-0.22		
At night	10PM-5AM 0.28	10PM-5AM 0.25	10PM-5AM as needed	10PM-6AM as needed	10PM-6AM as needed
Cycle time	2h	2h	Salt 3h Sand 4h	6h line sanding	10h line sanding

Table 4. Road surface condition classification used in Japan (32)

	Classification of road surface	Friction Coefficient
1	Very slippery ice film	~0.15
	Very slippery ice crust	
	Very slippery compacted snow	~0.2
2	Ice crust	0.15~0.20
	Powder snow on ice crust	
	Ice film	0.15~0.3
3	Granular snow on ice crust	0.2~0.3
	Compacted snow	
4	Powder snow	0.25~0.35
	Granular snow on ice crust	
	Slash	
5	Wet	0.45~
	Dry	

Table 5. Road classification in Japan (32)

Roadside conditions / Daily traffic volume	Urban area	Flat area	Mountainous area
20000~	A	B	B
10000~20000	B	C	B
4000~10000	C	D	C
1000~4000	D	D	D
~1000	E	E	E

Table 6. Management objectives in Japan (32)

Management objectives	
A	Road surface standard 4 to be ensured 24 hours a day.
B	Road surface standard 4 to be ensured between 6:00 AM and 10:00 PM. In other time zones, road surface standard 3 to be ensured.
C	Road surface standard 3 to be ensured 24 hours a day.
D	Road surface standard 3 to be ensured between 6:00 AM and 10:00 PM. In other time zones, road surface standard 2 to be ensured.
E	In principal, road surface standard 2 to be ensured 24 hours a day. Appropriate response to snow removal and road traffic conditions to be promoted.

Table 7. Gradation of sands used in study (34)

Sieve #	Opening (mm)	TC	FAA	SAE	ASTM	Fine
4	4.75	100	100	100	100	100
8	2.36	42.8	97.7	99.0	97.7	100
16	1.18	20.3	57.2	71.1	95.1	100
30	0.59	7.9	19.3	11.9	68.8	83.9
50	0.3	1.3	3.5	1.4	28.2	38.1
80	0.18	0.5	1.1	0.5	11.0	18.7
100	0.15	0.4	0.7	0.4	7.6	15.0

Table 8. Test matrix for sites having data in the final T&E28 report (43)

Site	ADT	Principal Chemicals or Abrasives Used on Control Section	Principal Chemicals or Abrasives Used on Test Section	Site-Specific Weather/Pavement Data and Forecast Services
California; I-5 in Siskiyou County, near Mt. Shasta	22,000	Salt, cinders, and mixture of both	Magnesium chloride-based solution, cinders if needed	RWIS installation within 3 km (2 mile) of site, RWIS-vendor pavement temperature/weather forecasts
Colorado; I-70 in western end of Glenwood Canyon just east of Glenwood Springs	8,000 to 10,000	Sand treated with salt (8% by volume)	Magnesium chloride-based solution, sand-salt mix when temperature too low for solution use	Elaborate RWIS installation in the canyons, RWIS-vendor pavement temperature/weather forecasts
Iowa; I-35 in West Des Moines	22,000	Salt and sand in 1:1 mix	Sodium chloride solution (salt brine)	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts; 2nd weather forecast vendor
Kansas; US81 in Cloud County at Concordia, undivided highway with one travel lane in each direction	4,000	Salt, sand, and mixture of both	Sodium chloride solution (salt brine) and/or solid fine salt prewet with salt brine	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecast
Maryland; US219 in Garrett County, undivided highway with one travel lane in each direction	3,000	Salt mixed with abrasives at salt-to-abrasives ratios from 1:9 to 1:1, and salt	Salt and abrasives use at ratio listed at left for the control section, with earlier initial treatments and subsequent preventive treatments	Weather monitoring station at maintenance station near site; handheld pavement temperature sensors
Missouri; US7 in Cass County, divided highway with two travel lanes in each direction	6,000	Salt and cinders mixed at 1:1 ratio	Salt and cinders premixed at 1:1 ratio, prewet with calcium chloride solution at rate of 21l/t (5 gal/ton) mix	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecasts; 2nd weather forecast vendor
Nevada; US395 in Reno, divide highway with two travel lanes in each direction	40,000	Salt and sand mixed at 1:5 ratio	Magnesium chloride-based solution, salt-sand-sand mix if snowpack developed	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecast; additional weather forecast consultants/vendors
New Hampshire; NH10 in the towns of Hanover and Lyme, undivided highway with one travel lane in each direction	4,000 to 8,000	Salt and abrasives treated with salt	Potassium acetate-based solution, salt or abrasives if needed	Weather station equipped with pavement temperature sensors placed at the site for the project; weather forecast vendor

New York; NY104 in Rochester metropolitan area within a few kilometers of Lake Ontario	13,000 to 25,000	Salt and mixtures of salt-sand at 1:3 ratio	Fine salt, conventional salt, calcium chloride prewetting solution at rate of 167 l/t (40 gal/ton) salt, and mixtures of salt-sand at 1:3 ratio	RWIS installation for research at the site; RWIS-vendor pavement temperature/weather forecast; additional weather forecast consultant consultants/vendors
Ohio; I-70 west of Columbus in Madison County	35,000	Salt	Salt prewet with calcium chloride solution at rate of 42 l/t (10 gal/ton) salt	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecast
Ohio; I-71 southwest of Columbus in Franklin and Pickaway Counties	30,000	Salt mixed with abrasives in 1:1 ratio	Salt prewet with calcium chloride solution at rate of 42 l/t (10 gal/ton) salt	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecast
Wisconsin; I-34 in the Green Bay metropolitan area	10,000	Salt	Sodium chloride solution (salt brine)	RWIS installation at the site; RWIS-vendor pavement temperature/weather forecast

Table 9. Friction measurements during T&E28 project (43)

	Version # of Coralba friction meters	Make and model of friction measurement vehicle	Make and model of tires of friction measurement vehicles	Does the vehicle have an anti-lock braking system? Is it a two-wheel or four-wheel system?
California, I-5, Mt. Shasta, Siskiyou County	1991, #3465	Dodge Spirit 1993, four door	Goodyear, P185/70R14 M&S F32-S All Weather Radials	No
Colorado, I-70, Glenwood Canyon	3	1992 Chevy pick-up ½ton 2-WD, 1986 Ford F150	Goodyear All-season F32-S	One does, One doesn't
Iowa, I-35, Des Moines	C-MU	1989 GMC Sierra S.L. 1500	Goodyear All-weather Radials P225/75/15	Yes, two-wheel
Kansas, US 81, Cloud County	3	1991 Pontiac 6000, 4-dr, Sedan	Goodyear F32-S All-Weather Radial (Steel belted)	No
Maryland, US 219, Garrett County	2	Ford 1993 F350 4x4	LT235-85R16 Goodyear	Yes, 4x4
Massachusetts, I-95 and I-93, Boston Metro Area	C-MU	Chevrolet ½ton pickup Cheyenne	FHWA –Standard tires for testing	Yes, two-wheel-disconnected
Minnesota, I-35, Downtown Duluth	2 and 3	1991 Plymouth Acclaim Sedan and 1989 Chevrolet ½ton pick-up	Goodyear F32-S Radial Sedan P185/70/R14 pick-up P225/75/R15	Yes, with two-wheel system
Missouri, US 71 at Archie in Cass County	Blank	1992 Dodge Dynasty	Goodyear F32-S Radials	No
New Hampshire, Route 10, Hanover	3	1993 Plymouth Sundance	Goodyear F32-S	No
New York, Route 104 Research Site, Webster*	3.06	1992 Chevrolet Corsica	Goodyear 185/75R/14	Yes, four-wheel system
Nevada, US 395, Panther Valley**	2	Chevrolet W/T 1,500	Goodyear P234/75RIS Mud and Snow, F32-S All weather Radial	Yes, two-wheel system
Ohio, Franklin County, I-71	2	89 Reliant, Plymouth	Goodyear, F32-S	No, two-wheel system
Ohio, Madison County, I-70	2	89 Reliant, Plymouth	Blank	No, two-wheel system
Oregon, Portland, I-5 I-405 Loop	3	1988 Chevrolet Citation	Project Specified Goodyear F32-S Radials	No
Washington, I-90, King County	C-MU	GMC 1500 two-WD Extended Cab pickup	P235/75R15 Goodyear	Yes, two WD
Wisconsin, I-43, Green Bay	3	1993 Chevrolet Cavalier Station Wagon	Goodyear F32-S P185/75R14	Yes, four-wheel system

*An attempt is being made to replace the Corsica/Coralba with a different type of friction-measuring vehicle that would better lend itself to the peculiarities of the NY 104 site.

**NDOT has expanded the use of the Coralba friction meters to other maintenance supervisors.

Table 10. Identification and categorization of friction devices for winter maintenance

Device	Type of Friction	Reference	Resolution	Repeatability	Application and Use+				Cost
					HR (Y/N)	HO (Y/N)	AR (Y/N)	AO (Y/N)	
Coralba	Deceleration	2	Fair	Fair	N	Y	Y	Y	L
ERD	Deceleration	6, 7	Good	Fair	Y	N	Y	Y	L
NASA –DBV	Deceleration	6	Good	Fair	N	N	Y	N	H
Tapley-Meter	Deceleration	6	Fair	Fair	N	N	Y	Y	L
Bowmonk-Meter	Deceleration	6	Fair	Fair	N	N	Y	Y	L
C-Mu	Deceleration	10	Fair	Fair	Y	Y	N	N	L
Stopping Distances	Deceleration	5	Fair	Fair	Y	Y	N	N	L
ASFT	Fixed Slip	6, 7	Good	Good	N	N*	Y	Y	H
BV-11	Fixed Slip	6, 7	Good	Good	Y	Y	Y	Y	H
Findlay Irvine-Grip Tester	Fixed Slip	2, 6, 7	Good	Good	Y	Y	Y	Y	M
RFT	Fixed Slip	6, 7	Good	Good	N+	N	Y	Y	H
SFT	Fixed Slip	6, 7	Good	Good	N	N	Y	Y	H
VTI-BV-14	Fixed Slip	2	Fair	Fair	Y	N	Y	N	H
E274	Locked Wheel	2	Good	Good	Y#	Y#	N	N	H
Skid Testing Bus	Locked Wheel	8	?	?	Y	?	N	N	?
IMAG –France	Variable & fixed slip	6, 7	Good	Good	N	N	Y	Y	H
NASA –ITTV	Variable & fixed slip	6	Fair	Good	N	N	Y	N	H
Norsemeter - OSCAR	Variable & fixed slip	5, 6	Good	Good	Y	Y	Y	N	H
Norsemeter - RUNAR	Variable & fixed slip	6, 7	Fair	Fair	N	N	Y	Y	M
CRREL IV	Variable & fixed slip	9	?	?	Y	?	N	N	?
Norsemeter –ROAR	Variable slip	1, 2, 3, 5, 6	Fair	Fair	Y	Y	N	N	M
Norsemeter –SALTAR	Variable slip	4, 5, 6	Fair	Good	Y^	N^	N	N	L
Mu-Meter	Side force	6	Fair	Fair	Y#	Y#	N	Y	H
Navy RCR Vehicle		6	?	Good	N	N	Y	N	?
Kofriks		10	?	?	Y	Y	N	N	?
Mobile weather monitoring system	ABS	10	Fair	Good	N	Y	N	N	?

- + HR: Highway research; HO: Highway operation; AR: Airport research; AO: Airport operation.
- * Currently being promoted for highway; + Being considered for open grade steel bridge decks; # not used for winter conditions; ^ prototype under development; - cost: L = <$50,000; M = $50,000-$100,000, H = >$100,000.
- Study Ref.: 1 Minnesota 1996; 2 Minnesota 1997; 3 Minnesota/Iowa/Michigan 1998; 4 Minnesota/Iowa/Michigan 1999; 5 Norway 1995-2000; 6 JWRFMP; 7 Used at airports; 8 Japan; 9 CRREL; 10 Finland.

Table 11. Average weights for the scenario evaluation criteria

Scenario Evaluation Criteria	Criteria Weight (%)		
	Total	North America	Overseas
Potential to enhance winter maintenance operations (benefit to DOT)	28.3	28.1	28.5
Potential to enhance user mobility (benefit to road users)	20.9	19.2	23.0
Potential to enhance roadway safety	22.3	26.2	17.5
Implementation feasibility	9.3	8.8	10.0
Implementation practicality	11.1	10.0	12.5
Prior domestic* experience	3.6	3.6	3.5
Prior international* experience	4.5	4.1	5.0

* Domestic: respondent's country; International: other than respondent's country.

Table 12. Scenarios rating according to the different criteria

Scenario	Criteria	Average	North America	International	Std. Dev.	Minimum	Maximum
1	Enhance Operations	3.7	3.8	3.6	1.1	1	5
	Enhance Mobility	3.4	3.6	3.2	1.1	2	5
	Enhance Safety	3.8	4.0	3.6	0.9	2	5
	Successful Implementation	4.3	4.1	4.5	1.1	1	5
	Practicality	4.0	3.8	4.3	1.0	1	5
	US Experience	2.4	2.0	3.0	1.3	1	5
	International Experience	3.3	3.2	3.6	1.4	1	5
	Overall	**3.7**	**3.7**	**3.7**			
2	Enhance Operations	3.9	4.1	3.6	1.1	1	5
	Enhance Mobility	3.5	3.7	3.3	1.1	1	5
	Enhance Safety	4.0	4.2	3.8	0.8	2	5
	Successful Implementation	3.7	3.4	4.0	1.2	1	5
	Practicality	3.6	3.3	4.0	1.0	2	5
	US Experience	2.3	1.8	3.0	1.3	1	5
	International Experience	2.6	2.3	2.9	1.4	1	5
	Overall	**3.7**	**3.6**	**3.7**			
3	Enhance Operations	3.3	2.8	4.0	1.0	2	5
	Enhance Mobility	2.7	2.7	2.8	1.1	1	4
	Enhance Safety	3.0	2.7	3.3	1.2	1	5
	Successful Implementation	3.2	2.8	3.7	1.3	1	5
	Practicality	3.3	3.1	3.6	1.1	1	5
	US Experience	2.2	1.6	3.0	1.4	1	5
	International Experience	2.8	2.8	2.9	1.2	1	5
	Overall	**3.1**	**2.7**	**3.5**			
4	Enhance Operations	4.5	4.2	4.9	0.9	2	5
	Enhance Mobility	4.3	3.9	4.8	1.1	2	5
	Enhance Safety	4.3	4.0	4.7	1.1	1	5
	Successful Implementation	3.6	3.2	4.1	1.0	2	5
	Practicality	3.9	3.8	4.0	1.0	2	5
	US Experience	2.2	1.7	2.8	1.2	1	5
	International Experience	2.6	2.6	2.5	1.2	1	5
	Overall	**4.0**	**3.7**	**4.5**			

Table 13. Summary of individual scenarios rating

Scenario	Overall Average	North America	International	Std. Dev.	Minimum	Maximum
Scenario 1	3.7	3.7	3.7	0.8	1.6	4.8
Scenario 2	3.7	3.6	3.7	0.7	1.7	5.0
Scenario 3	3.1	2.7	3.5	0.9	1.4	4.4
Scenario 4	4.0	3.7	4.5	0.9	1.8	5.0

Table 14. Friction measuring technology evaluation criteria weights

Criteria	Overall Average	North America	International	Std. Dev.
Effectiveness	15.4	15.0	16.0	11.0
Reliability	17.4	16.2	19.0	13.8
Repeatability	13.5	11.9	15.5	12.3
Robustness	7.6	8.5	6.5	6.2
Deployment cost	10.0	9.6	10.5	9.0
Operation cost	9.3	8.1	11.0	7.4
Operator safety	7.4	8.5	6.0	6.9
User safety	8.3	10.4	5.5	6.5
Integration ease	5.8	5.2	6.5	5.8
Simple presentation	5.3	6.7	3.5	5.9

Table 15. Friction measuring technology rating according to the different criteria

Technology	Criteria	Average	North America	International	Std. Dev.	Minimum	Maximum
Deceleration	Effectiveness	3.2	2.9	3.6	1.0	1	5
	Reliability	3.5	3.3	3.6	0.8	2	5
	Repeatability	3.2	3.1	3.4	0.9	1	5
	Robustness	3.9	3.5	4.2	1.0	1	5
	Dep. Cost Supervisor (1)	4.6	4.4	4.8	0.8	3	5
	Dep. Cost Snowplows (1)	4.4	4.3	4.6	0.9	2	5
	Operation Cost	3.8	3.3	4.4	1.2	2	5
	Operator Safety	2.6	2.6	2.6	1.2	1	5
	User Safety	2.5	2.6	2.3	1.1	1	5
	Integration Ease	3.4	2.8	4.2	1.2	1	5
	Simple Presentation	3.8	3.7	3.9	1.1	1	5
	Overall	**3.4**	**3.2**	**3.7**			
Slip	Effectiveness	3.7	3.8	3.4	1.0	2	5
	Reliability	3.3	3.2	3.6	0.9	2	5
	Repeatability	3.5	3.3	3.8	0.8	2	5
	Robustness	3.3	3.0	3.7	0.9	2	5
	Dep. Cost Supervisor (1)	3.3	3.6	3.0	1.2	1	5
	Dep. Cost Snowplows (1)	3.2	3.7	2.7	1.3	1	5
	Operation Cost	2.7	2.8	2.6	1.4	1	5
	Operator Safety	3.9	3.9	3.8	0.9	2	5
	User Safety	3.7	3.8	3.7	1.0	1	5
	Integration Ease	3.2	3.1	3.3	1.1	1	5
	Simple Presentation	3.6	3.6	3.6	1.2	1	5
	Overall	**3.4**	**3.4**	**3.5**			
TCS/ABS	Effectiveness	3.7	3.5	4.0	0.9	2	5
	Reliability	3.7	3.9	3.4	0.9	2	5
	Repeatability	3.5	3.6	3.3	0.9	2	5
	Robustness	3.9	3.9	3.8	0.8	2	5
	Dep. Cost Supervisor (1)	4.3	4.1	4.4	0.8	3	5
	Dep. Cost Snowplows (1)	3.9	4.1	3.6	1.2	1	5
	Operation Cost	3.9	3.4	4.4	1.1	2	5
	Operator Safety	3.8	3.3	4.6	1.1	2	5
	User Safety	4.0	3.4	4.7	1.1	2	5
	Integration Ease	3.5	3.0	4.2	1.1	1	5
	Simple Presentation	4.0	3.8	4.2	1.0	2	5
	Overall	**3.8**	**3.6**	**4.0**			

(1) a higher level indicates a lower expected deployment costs: 5: <$5,000; 4: $5,000- $10,000; 3: $10,000-$15,000; 2: $15,000-$20,000; 1: >$20,000

Table 16. Friction measurements in winter maintenance scenarios vs. broad categories of winter maintenance practice

	Scenario One	Scenario Four
Winter Maintenance Operations Decision-making	2	1
Operations Performance Evaluation	2	1
Motorist Information	3	1
Presently Avail. Technology	Yes	No
Additional Research and Development	Yes –Operational Implementation Trials	Yes –Continued Technology Development and Integration Cycles
R & D Cost Estimates	Modest ~$50 –100K/year/trial site	~$300 - $600K (total) in R & D, followed, by Trials
“Time to Market” Estimate	One to Three Years, including Trials	~Two to Three Years of R & D, followed by Trials –five years

1: scenario strongly and primarily supports category of practice; 2: moderately supports the category of practice in an auxiliary way; and 3: provides little or no support to the category of practice.

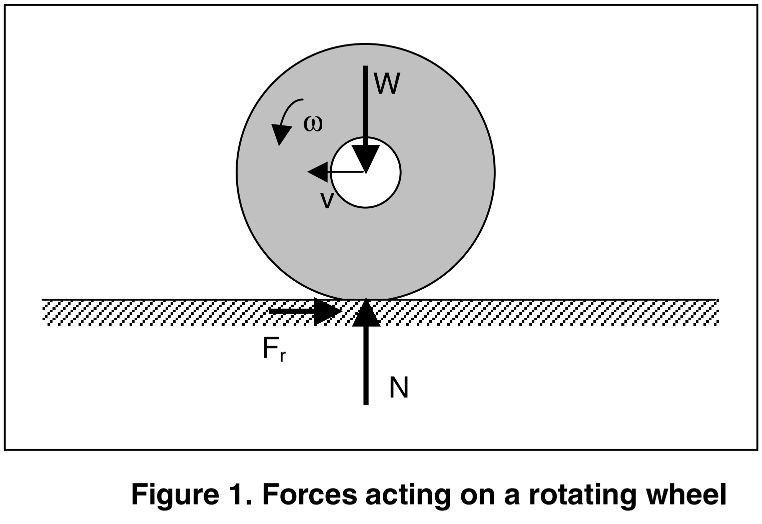

Figure 1. Forces acting on a rotating wheel

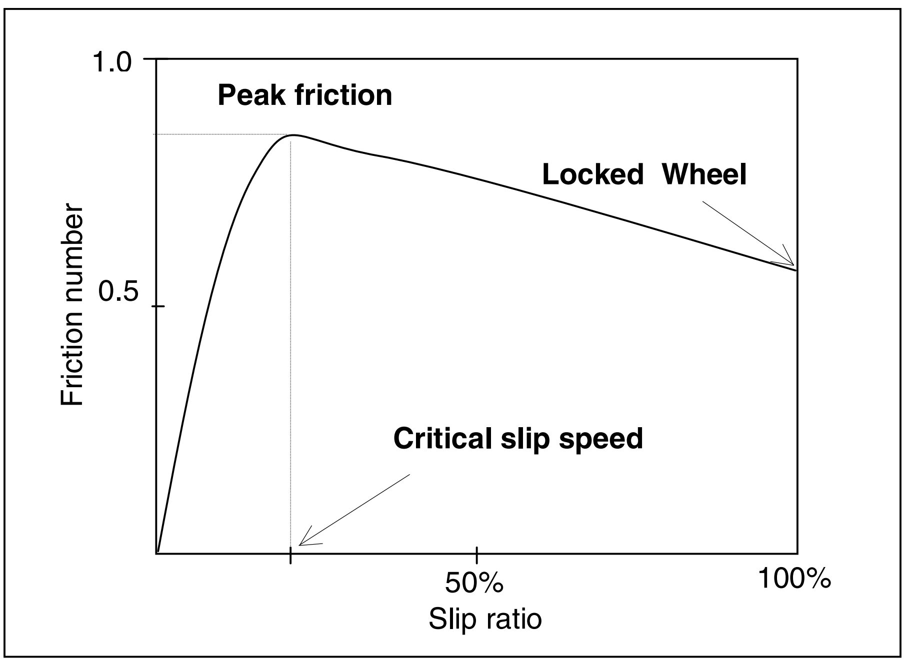

Figure 2. Friction number vs. slip ratio

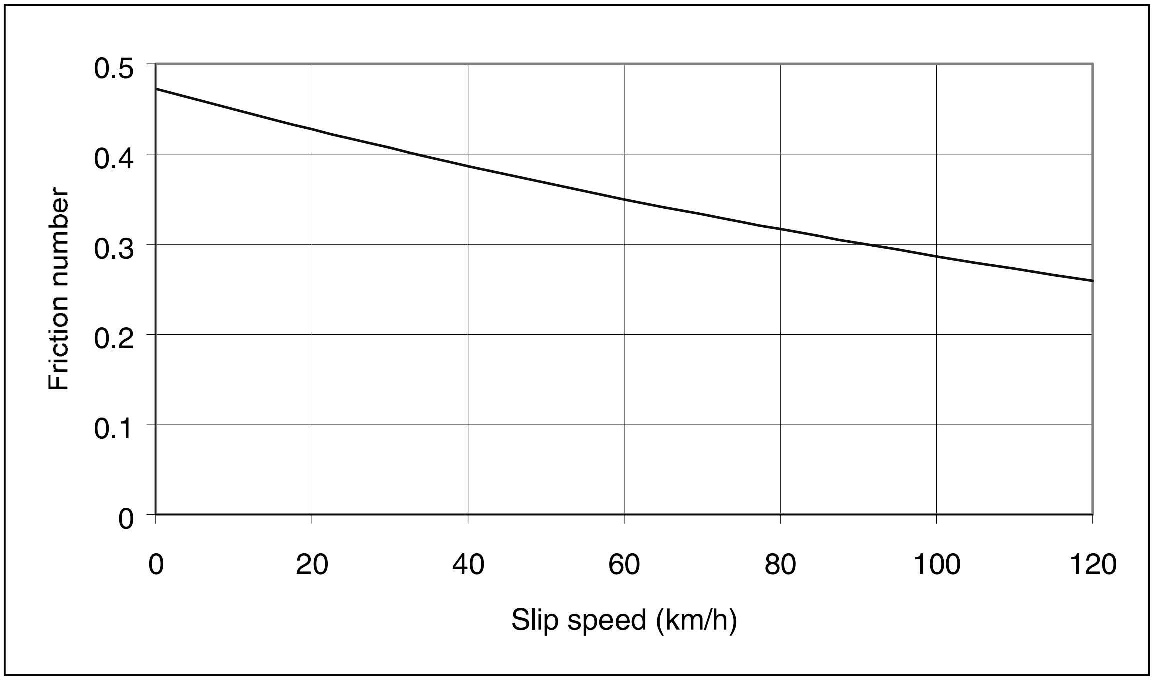

Figure 3. International friction index model (F60 = 0.35 and S_p= 200 km/h)

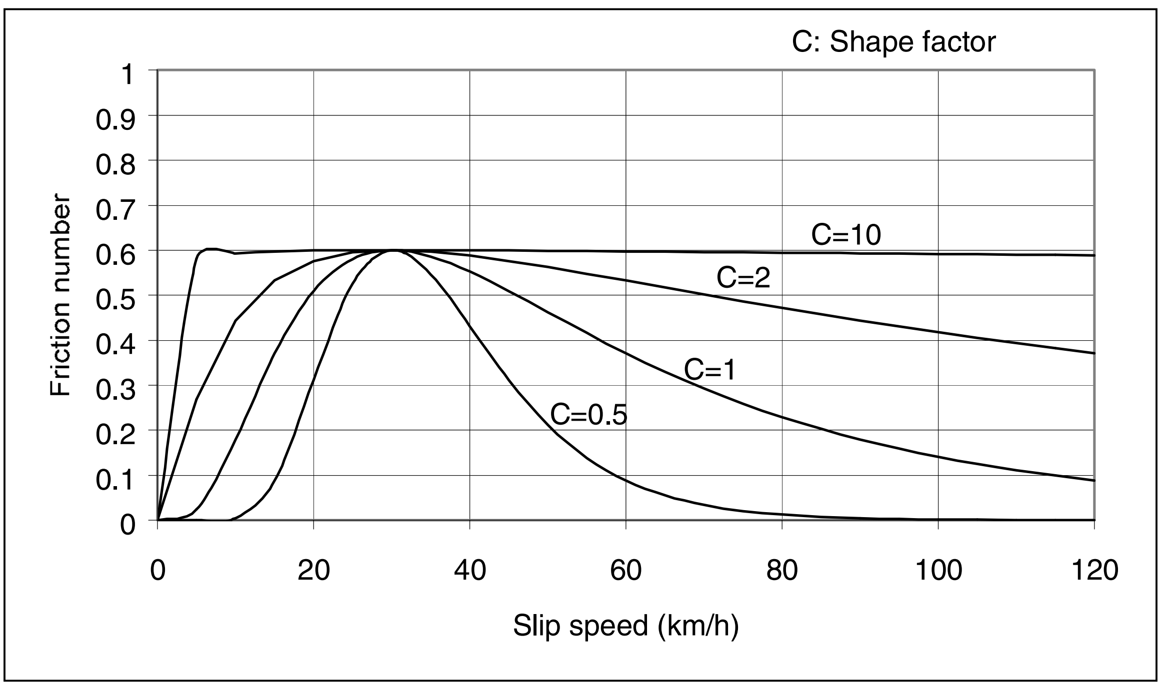

Figure 4. Rado friction model (μ_{max}=0.6 and S_{max}= 30 km/h)

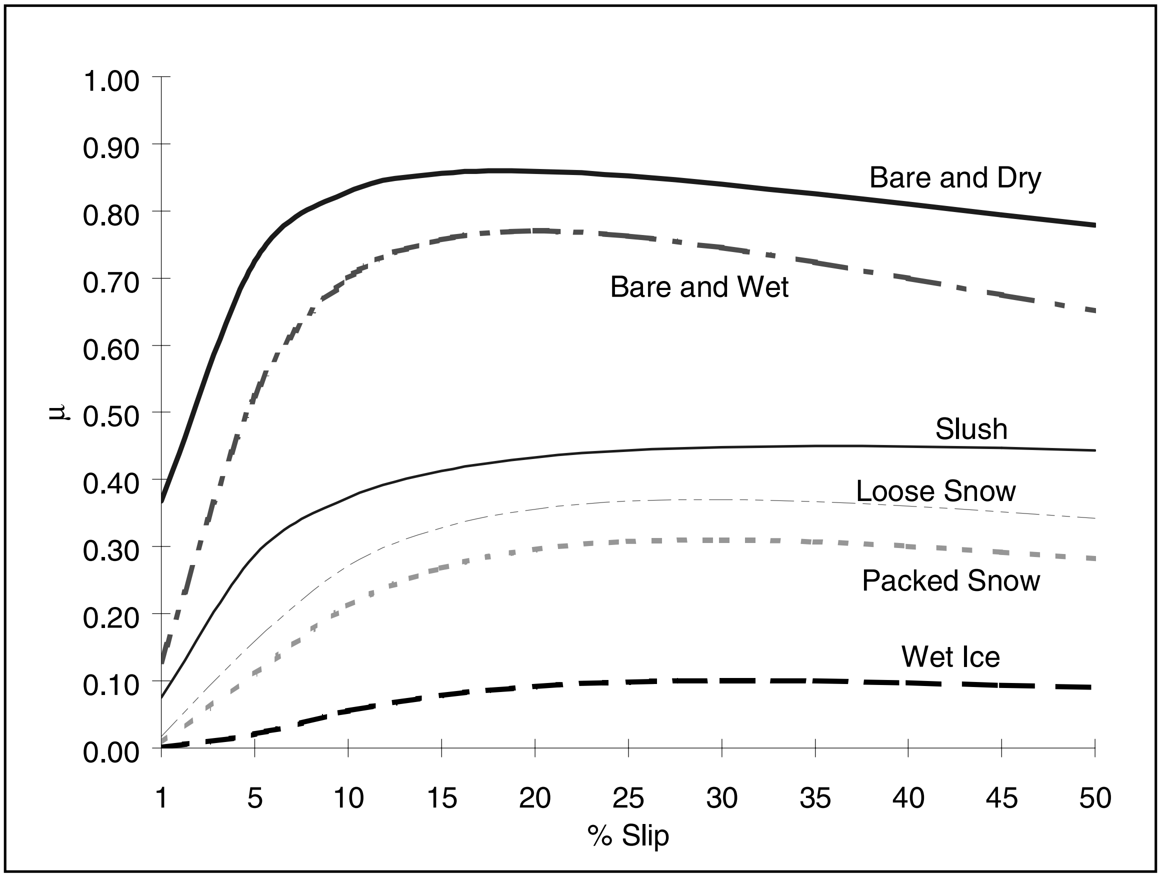

Figure 5. Sample Norsemeter friction versus percent slip for six conditions (7)

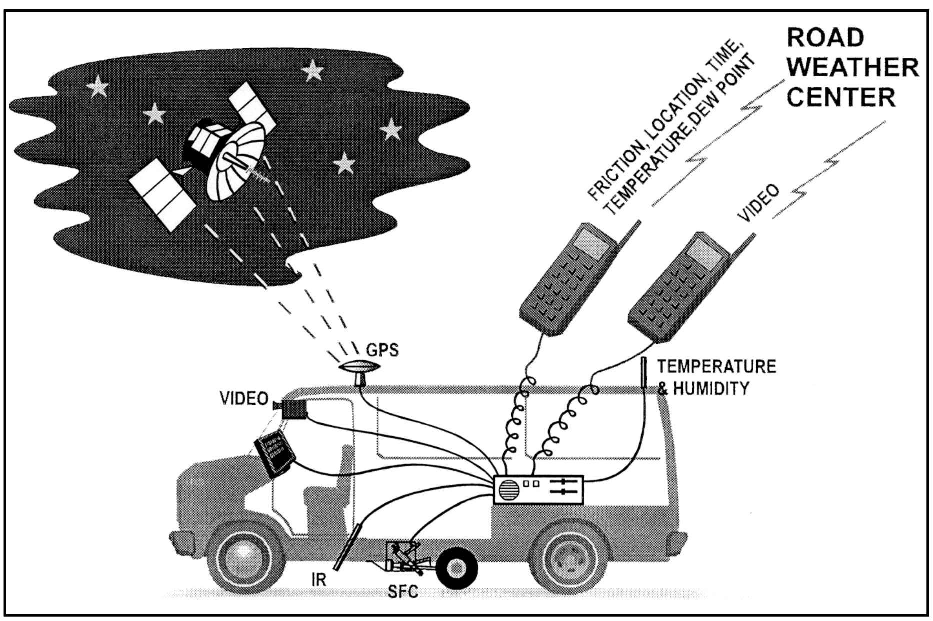

Figure 6. Weather monitoring vehicle (18)

Figure 7. VDOT Locked Wheel Trailer

Figure 8. ROAR Friction Trailer

Figure 9. SALTAR Friction Measuring Device

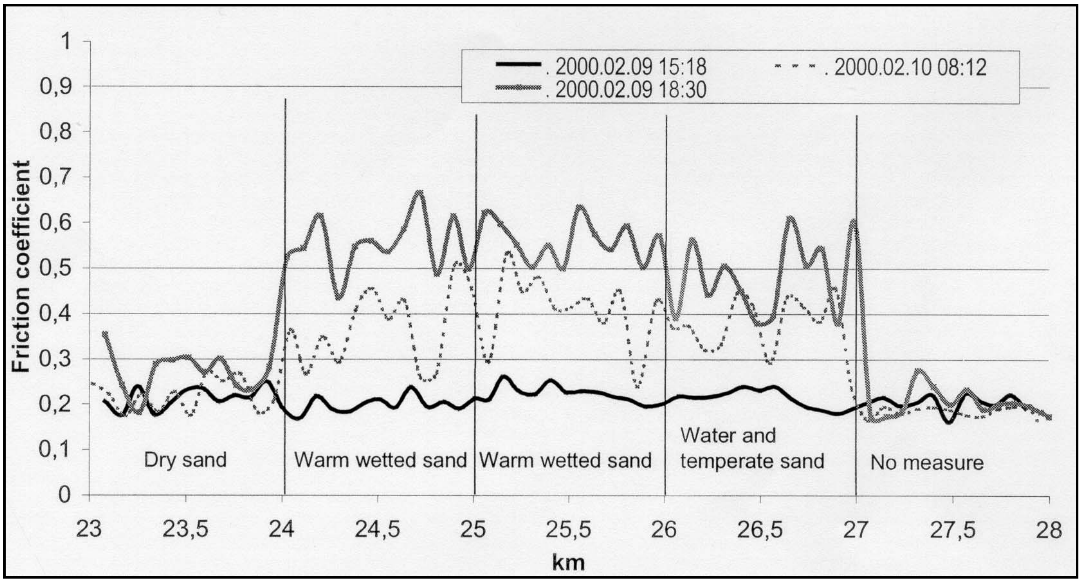

Figure 10. Friction measurements during a sanding trial (49)

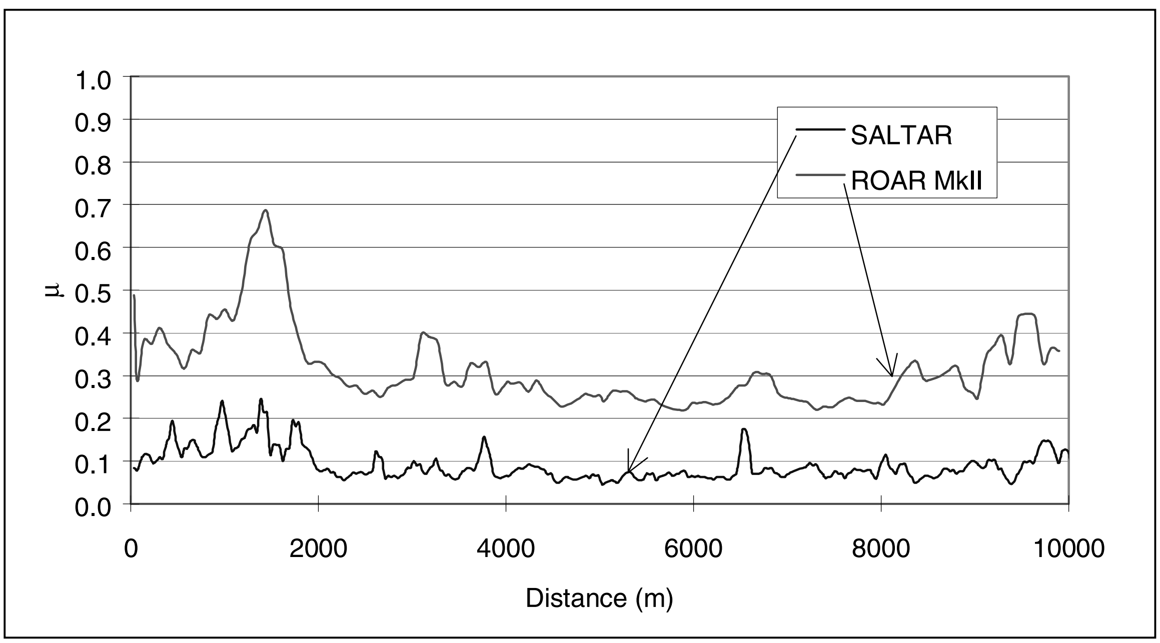

Figure 11. Friction by SALTAR and ROAR on a section of road covered with ice

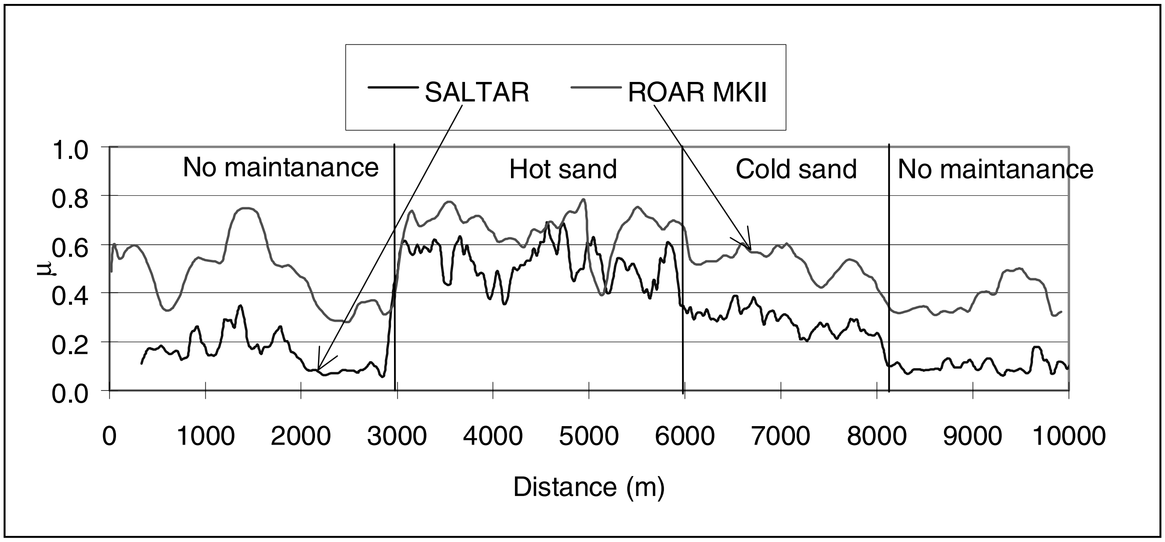

Figure 12. Ice covered road given in Figure 8 with hot and cold sand applied to the mid-section

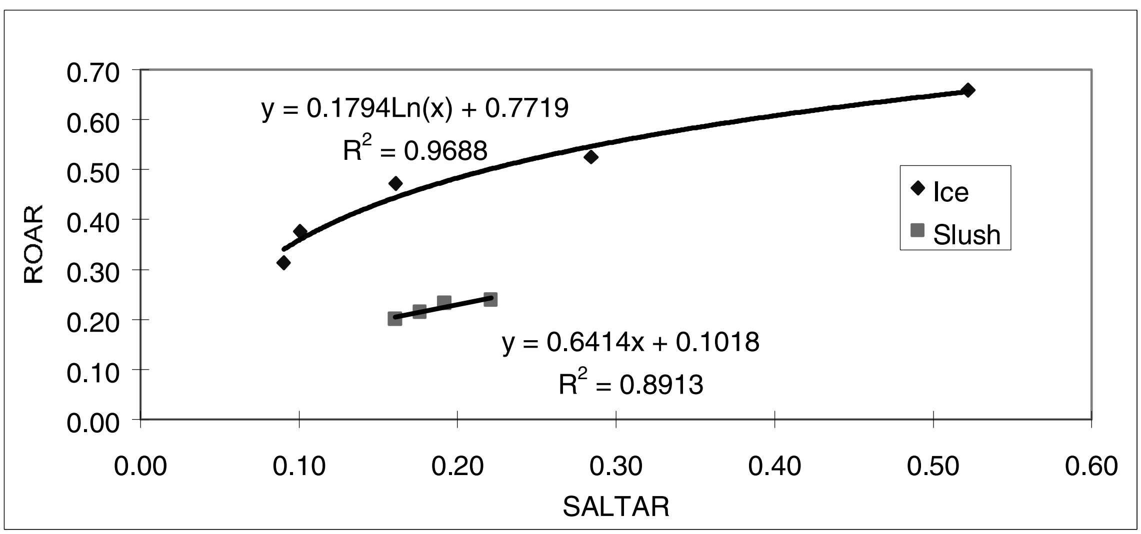

Figure 13. Correlation of friction coefficients as measured by SALTAR and ROAR

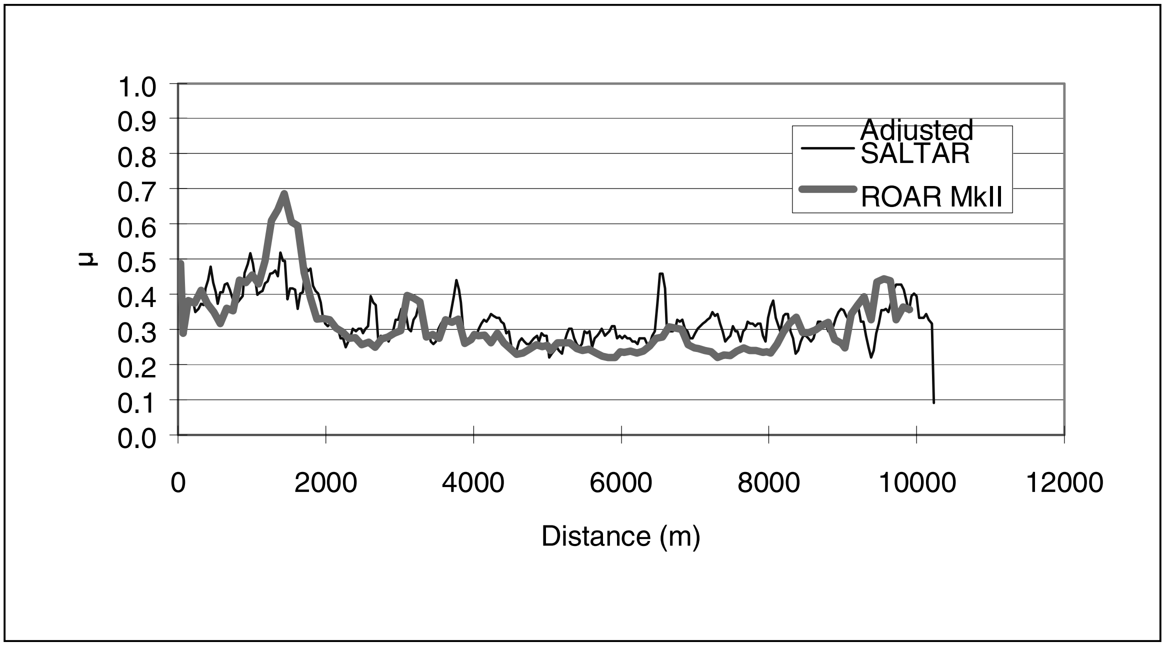

Figure 14. Data from Figure 11 with correlations applied

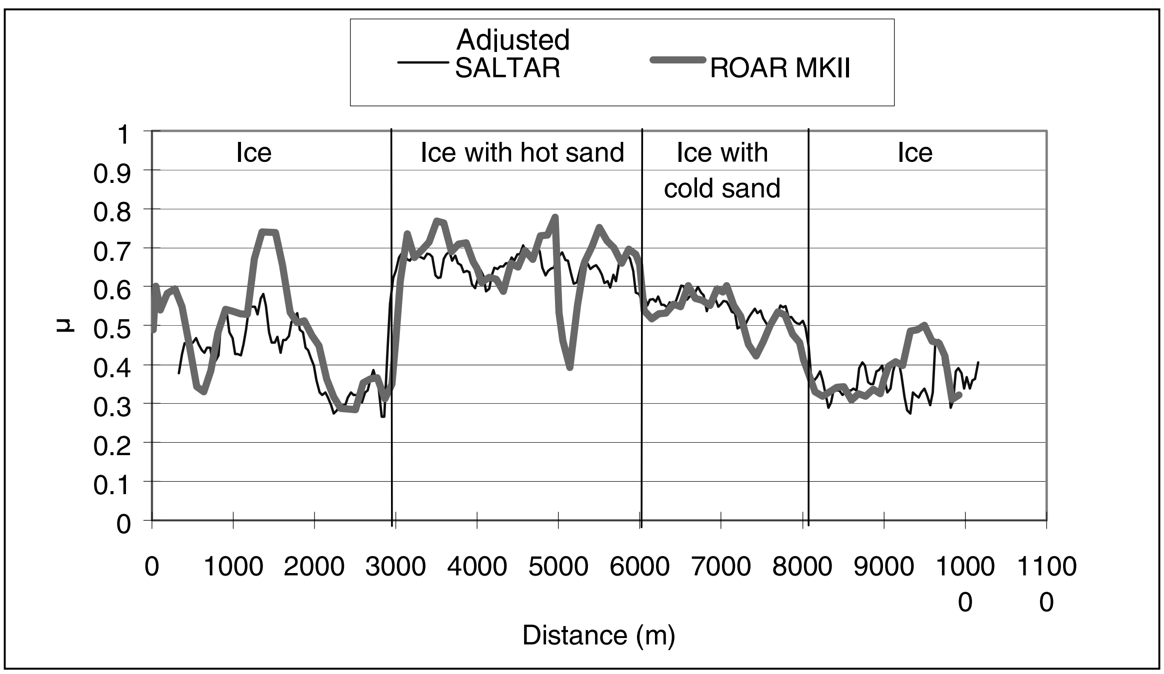

Figure 15. Figure 12 with correlations applied

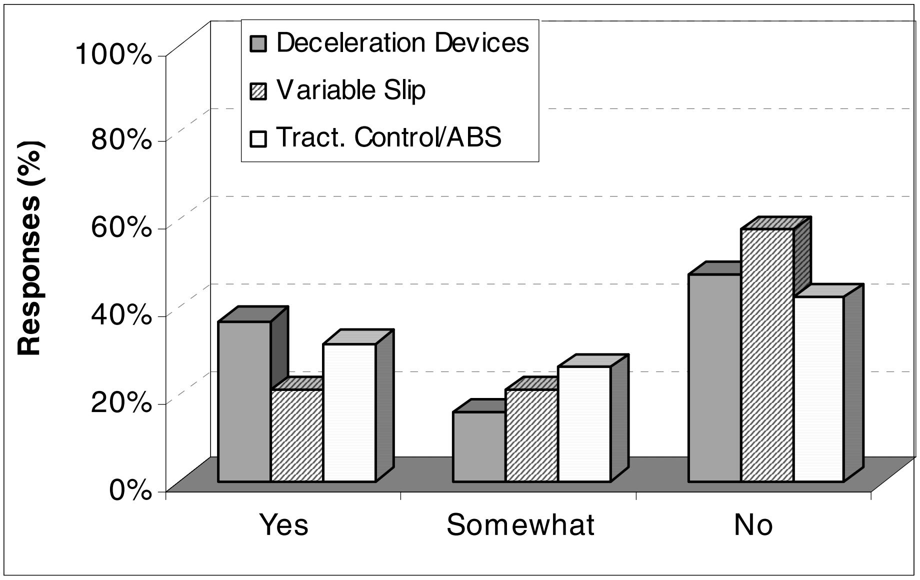

Figure 16. Respondent's familiarly with the friction measuring technologies

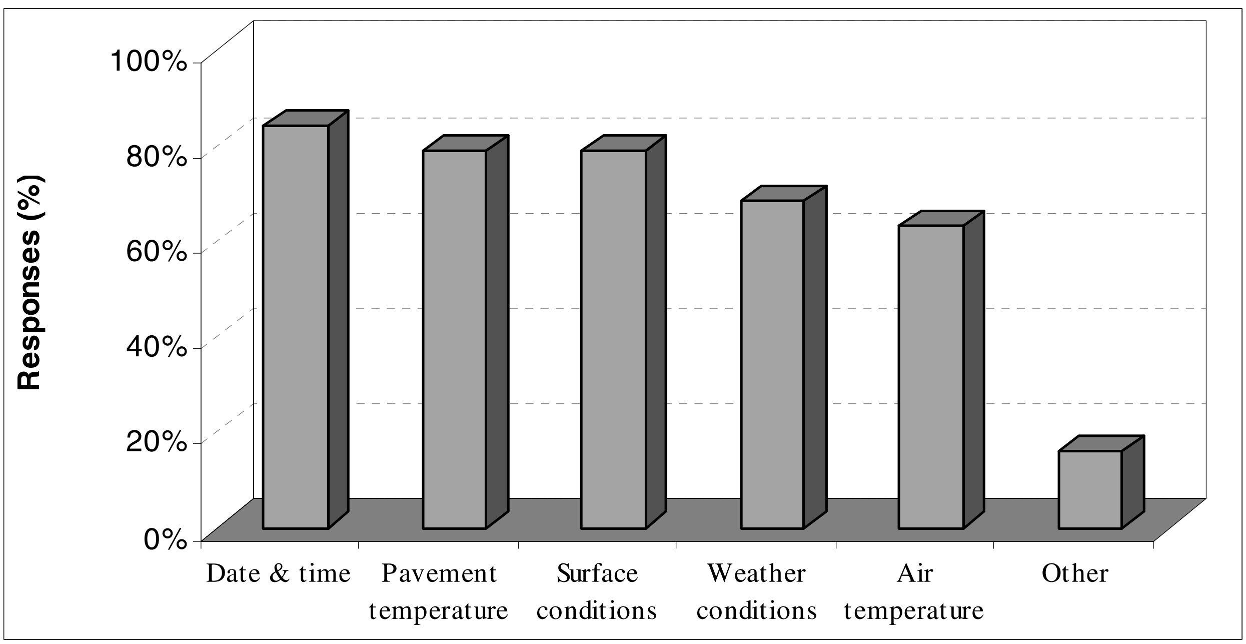

Figure 17. Other information needed to support winter maintenance operations

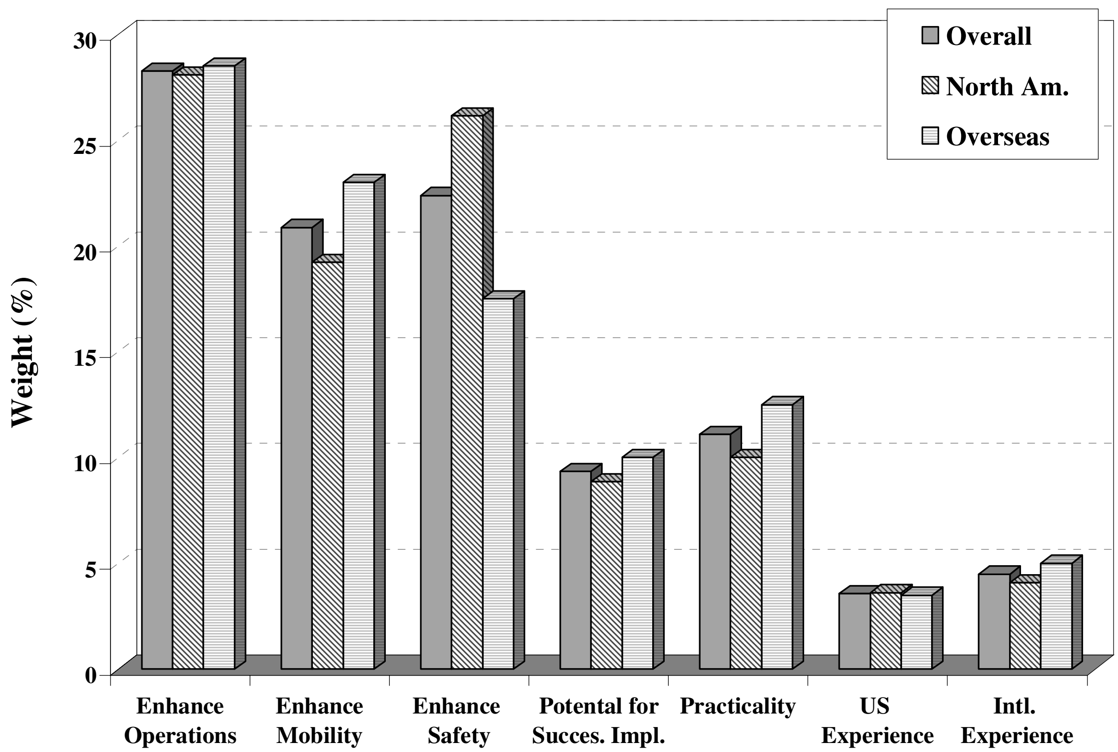

Figure 18. Scenario evaluation criteria relative weights

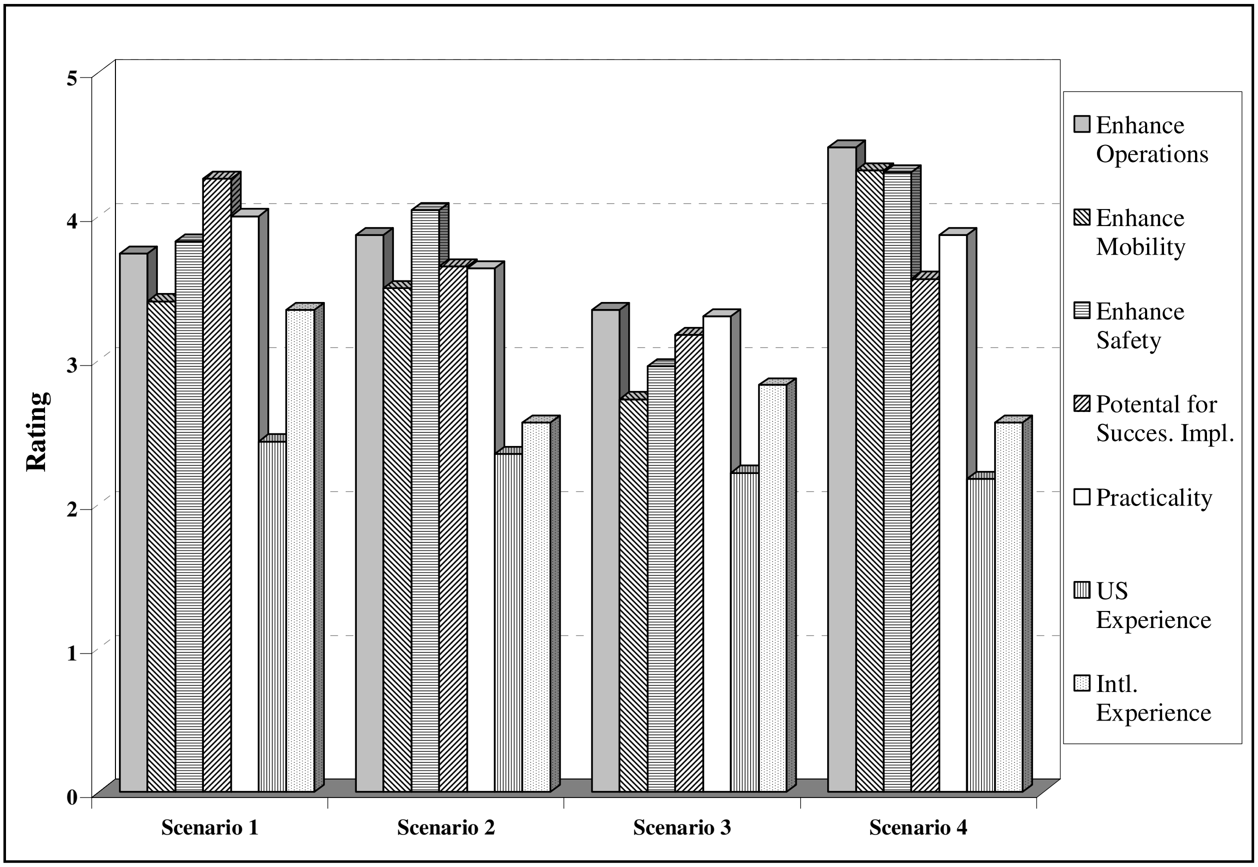

Figure 19. Average rating levels for each evaluation criteria

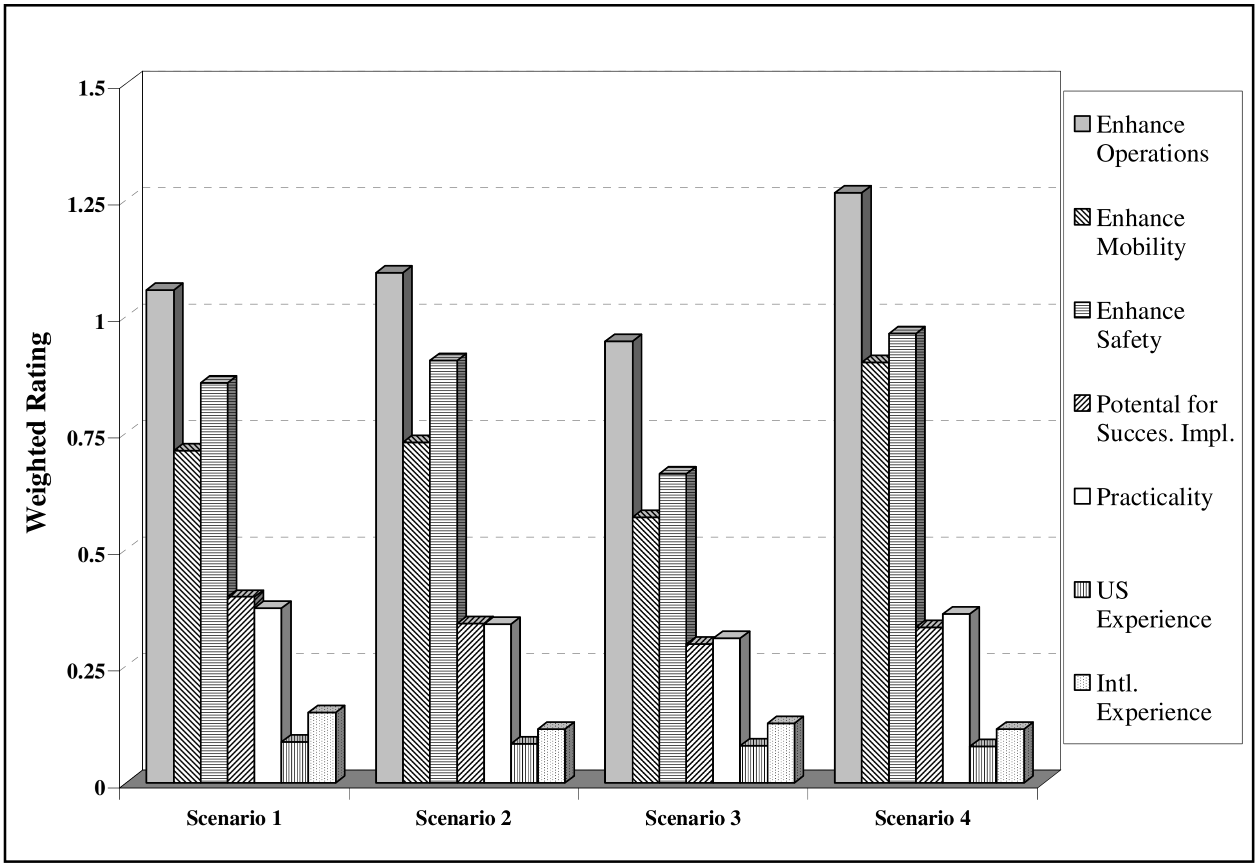

Figure 20. Weighted average rating levels for each evaluation criteria

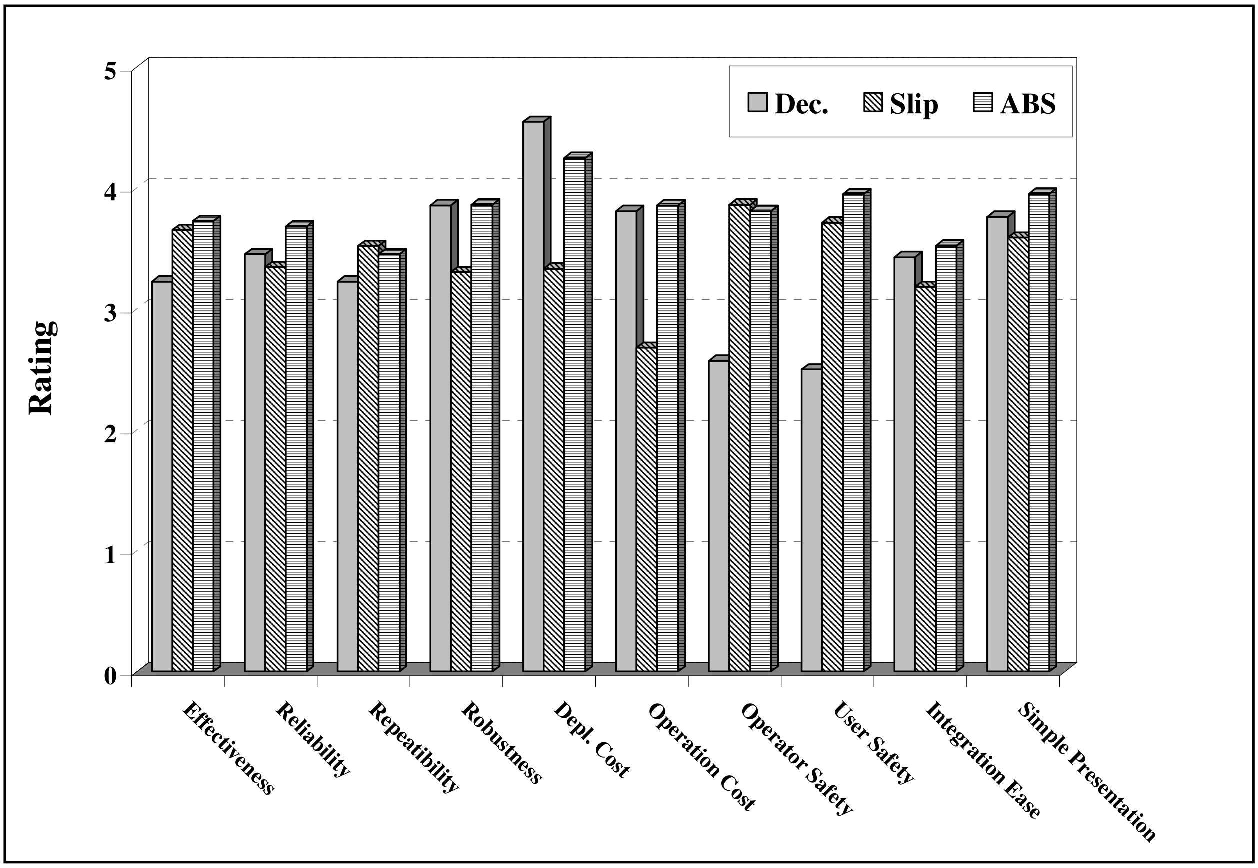

Figure 21. Friction measuring technology rating levels for each evaluation criteria

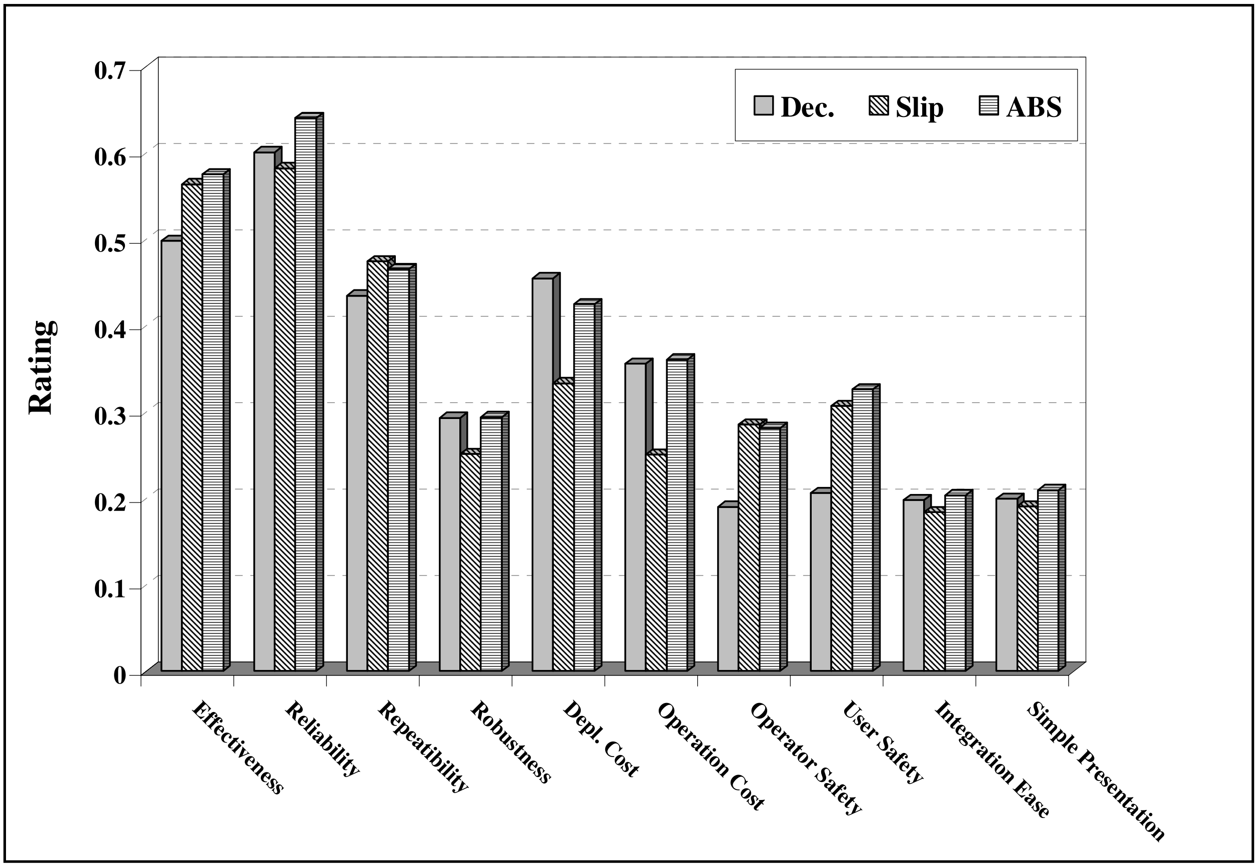

Figure 22. Weighted friction measuring technology rating levels for each evaluation criteria

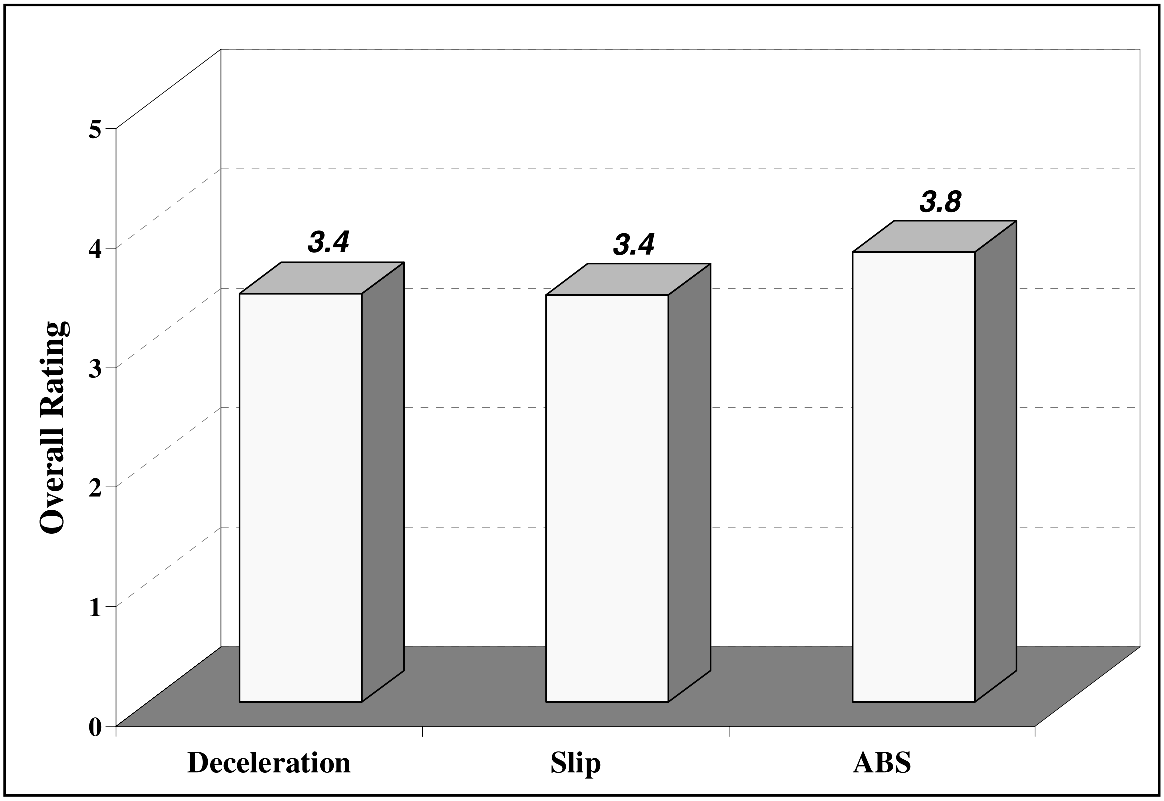

Figure 23. Overall average technology rating

LIST OF ACRONYMS

AAAE: American Association of Airport Executives

ACI: Airports Council International

ADT: Average Daily Traffic

ALPA: Air Line Pilots Association

ASFT: Airport Surface Friction Tester

ASTM: American Society for Testing and Materials

ATA: Air Transport Association

ATIS: Advanced Traveler Information Systems

CFME: Continuous Friction Measurement Equipment

CNRC: Canadian National Research Council

CRREL IV: Cold Regions Research and Engineering Laboratory Instrumented Vehicle

DBV: Diagonal Braked Vehicle

ERD: Electronic Recording Decelerometer

FAA: Federal Aviation Administration

FHWA: Federal Highway Administration

FinnRA: Finnish National Road Administration

HDB: Hokkaido Development Bureau

HMA: Hot-Mix Asphalt

IFI: International Friction Index

IMAG: Instrument de Mesure Automatique de Glissance

IRFI: International Runway Friction Index

ITTV: Instrumented Tire Test Vehicle

JWRFMP: Joint Winter Runway Friction Measurement Program (NASA, FAA, TC, CNRC)

LTPP: Long Term Pavement Performance

MnDOT: Minnesota Department of Transportation

NASA: National Aeronautics and Space Administration

NCHRP: National Cooperative Highway Research Program

OSCAR: Optimum Surface Contamination Analyzer & Recorder

PIARC: Permanent International Association of Road Congresses

PRA: Public Road Administration

RAA: Regional Airline Association

RCR: Runway Condition Rating

RFT: Runway Friction Tester

ROAR: Road Analyzer and Recorder

RUNAR: Runway Analyzer and Recorder

RWIS: Road Weather Information System

SAE: Society of Automotive Engineers

SALTAR: Salt Analyzer and Recorder

SAS: Scandinavian Airlines System

SCRIM: Sideway Force Coefficient Routine Investigation Machine

SFT: Saab Friction Tester

SHRP: Strategic Highway Research Program

TC: Transport Canada

TOC: Traffic Operations Centers

APPENDIX A: RESPONSES TO INFORMAL QUESTIONNAIRE

AT THE ROANOKE WORKING SESSION (OCTOBER 8, 2000)

Responses to a questionnaire provided to the knowledgeable sources at the working session.

Scenario (Be specific! How are friction measurements being used by your agency? Of the generic scenarios given, which one(s) are you attempting?).

1. Accident reconstruction- both from a vehicle and new pavement measurement is what cause the accident. Effects of liquid anti-icing on pavement, testing the various chemicals to determine if some have better qualities for friction.

2. Friction measurement is not done on operation-basis now in Hokkaido Development Bureau (HDB). It is only done on research-basis. From the results of research-basis friction measurement, we obtained co-relationship between the friction range and road surface classification for operations use. Scenario, which we are attempting, is near the first one.

3. With only one unit, Iowa is in the evaluation stage. Data is being gathered but only randomly checked to see if it looks reasonable and to insure the SALTAR unit is working.

4. Friction measurements are presently used only for winter maintenance-related research. These measurements have been made mostly to evaluate the performance of various devices against each other or against a SU device accepted as providing "good" measurements- i.e., K.J. Law use for measuring summer friction.

5. Scenario 1 has been used to a small extent in a few counties. Both scenarios1 and 2 will be implemented if appropriate tools are available.

6. For maintenance decision making, for policy-making, and for quality standards for contract documents

7. Research and development only at this time. Performance evaluations of alternative anti-icing, de-icing, and abrasive materials. Also, evaluation of friction as a quality assurance measure for winter operations.

8. We use a friction sensor to evaluate chemical friction properties under various conditions of temperature and humidity. This is for research and decision-making. For research, we assist chemical companies in their attempts to engineer better products.

Appropriated Techniques for Friction Measurements. (Specifically, what friction-measuring products have you tried or are presently using?)

1. Drag sled for research on anti-icing and accident reconstruction; Shotmarker (police) to reconstruct accidents; Accelerometer (police and engineers). Research for anti-icing and accident reconstruction.

2. Expensive bus-type, Saab friction tester, C-Trip type are tried and used for different research purposes.

3. Coralba for FHWA T&E-28 in 1995-1996, Norsemeter ROAR two winters 1997-1999, Norsemeter SALTAR on winter 1999/2000 and participated in NASA Summer 1999, test at Wallops Island and winter January 2000 tests at North Bay, Ontario

4. MNDOT has tried the K.J. Law, Norwegian ROAR and SALTAR (SALTAR did not function consistently and properly), English Griptester, Swedish BV-14, and Coralba. Coralba was used by E. Fleege in support of early SHRP studies.

5. We have tried both C-Trip (Coralba) and ROAR. ROAR is being used in scientific test with good results, but is too expensive to have a broad application. C-trip is burdened with some weaknesses that makes the instrument unlikely to be the tool asked for.

6. C-trip, digitrip; floating car monitoring equipment (Lampinen); Skiddometer; Paisler

7. Electronic Recording Decelerometer; Griptester; Tapley-Meter (mechanical accelerometer); Norsemeter RUNAR and ROAR MK II (presently in use); Pendulum device with full-scale tire; Fixed slip aircraft tire on instrumented tow bar in laboratory

8. We use a contant-velocity/12 lb. Drag sled pulled at 2 km/h with pull force measured via a 100 lb. Mettler-Toledo lad cell, sampled at 10 times per second and averaged of a typical 2 or 3 second pull. (Measures near peak f).

Domestic and International Efforts that are Supporting Your Implementation (Is a report or website posting available?)

1. Pacific Northwest Snowfighters Association; Forensic Dynamics, Inc.

2. Our website http://www2.ceri.go.jp/eng/ might help

3. Information from 1994 and 1998 FHWA/AASHTO/TRB Winter Scanning tours and papers presented at TRB annual meetings and International Symposium on Snow Removal and Ice Control Technology.

4. Norwegian test of ROAR and SALTAR (Jon Dahlon @ NPRA vs. other European devices, North Bay tests of various friction meters.

5. Not to my knowledge. Friction measurements especially on winter conditions are difficult. Perhaps someone should be taken an initiative to start an international project.

6. No response

7. Joint Winter Runway Friction Test Program Transport Canada/Transportation Development Center studies

8. We are supported by Insurance Corporation of B.C., P.N.S. States, Chem Companies, and distributors/users.

Technological, Policy, or Customer (Social) Impediments to Implementation:

1. Which is the best device to use. Transferring the measurement to activity (maintenance) Legal ramifications of using the device to both start a maintenance activity and give info to the public

2. We are developing a Winter Road Maintenance Manual for HDB internal use.

3. Technological- no US winter friction standards. Equipment accuracy and reliability unknown; Policy- not yet developed; Customer response or reactions unknown

4. Research not enough advanced to address these questions.

5. Implementation still depends on the reliability and price of the friction measurement devices. If the price is acceptable and it mostly depends on what the road network owner decides.

6. Finnish Winter Maintenance Policy (1996) (also in English) and Winter Maintenance Methods (1992)

7. Must demonstrate that monitoring of operations requires this level of information. Must be accepted by maintenance contractors.

8. Technology- there seems to be no consensus about friction devices. Customer- a difficulty seems to be present in deterring what to do with the friction information,

Additional Research and/or Testing Required that May Lead to Implementation

1. Choosing a friction device; Model for transferring data to goals followed by maintenance activity

2. Low-cost measuring and collecting data system, also effective use of date (i.e., ITS technology should be developed.

3. Need to develop and conduct friction validation tests for equipment and correlate friction levels with driver behavior and driver training needs.

4. Development of a consistent measure of frictions for operators, managers, and public.

5. There should be an international standard or reference of how to measure friction under winter conditions.

6. No response

7. Low cost and reliable equipment; Automated interpretation of data; Industry-wide, sanctioned standards

8. We are starting "new" research on friction related to roadway contamination. This may lead to information sharing with decision-makers.

Are Friction Measures in Winter Maintenance Cost Effective? What is the minimum set of Direct Benefit factors for use in Cost/Benefit consideration?

1. Yes, it potentially can reduce material usage as we often put material out "just to be safe" when we may not need to. It may also reduce accidents that carry large social costs.

2. No now, but don't know in the future. It depends on lowering cost and developing effective use of data. Benefit from using data (by ITS technology) will increase in the near future. You should take into account.

3. Cost effectiveness of established technologies such as RWIS and anti-icing are uncertain and very difficult to quantify. Friction will encounter the same difficulties. The many variables such as weather, driver skills, accident analysis, inaccurate databases complicate cost/benefits analysis.

4. Objective measure is/will be very difficult. Attempt to measure effect of friction measurement on changes in operator practice in Concept Vehicle Study has been inconclusive at best. Factors could include reduced salt (chemical) and sand amount reductions in equipment material and labor costs from reduced number of passes given better friction information.

5. Depends on the effort put into the friction measurement system and what the effects really are.

6. No response.

7. Will it reduce cost of operations to the contractor or to the contracting agency? Will it help to automate operations?

8. They could be very cost effective. If, for example, the roadway is at a suitable level of friction, it would be imprudent to apply additional material to increase an already adequate road friction level.

Responses to a few draft scenarios provided by an International knowledgeable source

Scenario 1: Winter maintenance patrol vehicles are dispatched to travel over part of the road system after winter maintenance activities have been performed, making either periodic or continuous measurements of roadway friction. If some or all these measurements do not meet approved friction levels-of-service, then the winter maintenance decision-maker is equipped with the requisite information needed to recall the maintenance fleet and re-treat those sections of the road that require additional effort to meet the specified friction condition. This technique of using friction measurements for decision support is already enjoying some success in the Scandinavian countries.

Appropriate Techniques for Friction Measurements:

JHC (Japan Highway Corporation) decides the operations more "synthetically" the decision maker, police officer, patrols by himself and decides what to do based on his "feeling and experience." Sometimes, the images by ITV camera, weather data, and road condition data collected and transmitted by road administrator support his decision.

Prior Domestic and International Efforts that Support Domestic Implementation:

(1) "A Golden Curve" for Winter Road is possible? Note: J.J. Henry of Penn. State University has succeeded in setting up "a golden curve" for summer road. In case of summer road, the road roughness decides everything along with the thickness of water film. In case of winter road, what determines the friction coefficient? Air temperature, road surface temperature, in-ground temperature, moisture, density of snow, residual of chemicals, and so many factors have influence on the friction co-efficient. I think it is possible to set-up such a curve for artificially designed and resin-coated road. But, I am not sure it is possible for actual winter roads. The aim of the joint calibration test in this September is to examine the golden curve for such an artificial winter road as the first step. After that, we are to carry out joint calibration tests on real winter roads. Meanwhile, we should investigate more quantitatively and more precisely what are the influential factors on friction co-efficient of winter road.

(2) The relationship between friction and level-of-service in terms of traffic safety and traffic efficiency. Note: In the past, several papers discussed the relationship between friction co-efficient and accident rate. I think it still remains unreliability on the friction co-efficients that were measured after accidents, because winter road surfaces are very unstable and fragile. Sometimes, it is too late to measure it after accidents. I suppose what makes this problem difficult is that we have to treat the range of 0.0 to 0.3 or 0.4 of friction co-efficient. A little difference in friction co-efficient has a large influence on the stopping distance. We have to estimate the friction co-efficient at accidents very carefully. At the same time, during these ten years, both automobiles and tires have changed a great deal in terms of the interaction with road surface: Many vehicles equip the ABS as the standard. Studless tires, which are featured by the flexible read structure and have quite different friction characteristics, are 100% used in Japan in winter season. At this symposium, I made a presentation concerning how to estimate friction co-efficient at accident using a reconstruction technique. In early 90's, we conducted a series of field survey in order to quantify the influence of the regulation of stud tire on saturation flow rate at signalized intersection and formulated it. I'll give you a few related papers with some comments. They are written in Japanese.

Scenario 2: Friction measured by winter maintenance patrol vehicles is used to support advisories to winter maintenance vehicle operators of appropriate (or optimal) application rates for spreading snow and ice control materials for the specific conditions being measured. In this scenario, relatively few vehicles are collecting friction data. These data are transmitted to a central location for consideration, and an "average" or representative value for snow and ice control material spreading is determined. This value is transmitted to the entire winter maintenance fleet and is used by operators to manually adapt their snow and ice control material spread rates.

Appropriate Techniques for Friction Measurements:

We do not have a criterion on how frequently we should measure the friction co-efficient. But, the experiences on an expressway where we measured it every 0.1 m and a mountainous road on a pass where we measured it every 1 km indicated very low correlation even between successive points.

Prior Domestic and International Efforts that Support Domestic Implementation:

We should have a criterion and a definition of how to measure friction co-efficient: many points per km and how many times per hour.

Scenario 3: As in the previous scenario, friction measured by winter maintenance patrol vehicles is used to support advisories to winter maintenance vehicle operators of appropriate (or optimal) application rates for snow and ice control materials. Patrol vehicles, equipped with GPS or other type of automatic vehicle location technology, transmit the friction information to a control center where the information is processed. The data can be clustered and different application rates determined for different zones or regions. An "average" or representative value for snow and ice control material spreading is transmitted to the winter maintenance fleet in that zone or region.

Appropriate Techniques for Friction Measurements:

If my knowledge is correct, such a remote-sensing system has not adopted in Japan yet. At present, in-vehicle sensor determine the concentration and amount of chemicals while measuring temperature, concentration of residual, and so on.

Prior Domestic and International Efforts that Support Domestic Implementation:

(1) I think the information of friction co-efficient is point-based even if it is averaged over a certain length. We should develop the technique to interpret the information of ITV camera's images.

(2) I suppose on such a system, the time lag between sensing and applying is also another significant factor we should consider. The precision of prediction must be reliable. Note: I think the short-term prediction of friction co-efficient is essential technology in winter maintenance system as well as in winter information system because road conditions in winter vary rapidly with time. At the last symposium in Reno in 1996, I made a presentation on this subject. Considering the nonlinearity and unsteadiness, we built a prediction model named "Neuro-Korlman Filtering" method. The model is successful in reconstructing the actually measured data but not successful in predicting the friction co-efficient even 30 minutes ahead in the transition period when road condition changes drastically due to sunshine and morning peak traffic.

Scenario 4: Friction measuring devices on individual winter maintenance vehicles would control, in an automated fashion, one or more of the of the winter maintenance functions of the vehicle including, for example, the application rates of snow and ice control materials and down pressure on forward and under-body plows. In this specific scenario, all winter maintenance vehicles that are capable of spreading snow and ice control materials are equipped with an independent friction measuring capacity. However, it should be noted that a measured friction alone cannot and should not completely control the snow and ice chemical delivery process. Other factors (pavement temperature and forecasted weather conditions) will also need to be incorporated.

Prior Domestic and International Efforts that Support Domestic Implementation:

Same as the Scenario 1. Now we are engaged in another study to find a synthetic index that is closely related to friction co-efficient but stable and easy to handle. This study has just begun. We are trying to define such a index combining weather data, road condition data, winter maintenance application data, and so on.

APPENDIX B: QUESTIONNAIRES

Questionnaire 1: To be submitted to winter maintenance operation personnel

Questionnaire 2: To be submitted to national and international knowledgeable sources.

NCHRP 6-14

FEASIBILITY OF USING FRICTION INDICATORS TO IMPROVE WINTER MAINTENANCE OPERATIONS AND MOBILITY

PURPOSE OF THE QUESTIONNAIRE:

Friction measurements have been used in some Scandinavian countries as decision support tools and quality assurance measures for winter maintenance activities. Focused on the *operational* needs and requirements for the *highway* winter maintenance, NCHRP has initiated a project to evaluate the feasibility of using friction indicators to improve winter maintenance operations and mobility. A detailed analysis of the available information relative to the use of friction indicators to enhance winter maintenance operations resulted in proposing four scenarios in which friction indicators can be applied to winter maintenance operations decision-making, operation performance evaluations, and motorist information. Based on your field experience and knowledge, your collaboration is requested to assist in evaluating the proposed four scenarios (see attachment). This will help us refine these scenarios, identify the most promising friction measuring techniques for winter maintenance operations, and define possible technological impediments to domestic implementation of the proposed scenarios, and thus possibly recommend further research or testing that may serve to overcome the identified impediments.

Please complete the following request for information and return the completed questionnaire by **September 20, 2001**.

Name: ____

Current Position/Title: ______________________________________

Agency: ____

Address: ____

____

City: ______________________ State: ________ Zip: __________

Telephone: __________________ Fax: ______________________

Email: ______________________________

If you have any questions, please contact:

Dr. Imad L. Al-Qadi
200 Patton Hall
Blacksburg, VA, 24061-0105
Tel: 540 231 5262, Fax: 540 231 7532
e-mail: alqadi@vt.edu

Thank you in advance for your help and cooperation with this project

Proposed Winter Maintenances Scenarios

Scenario 1: Friction Measurements from a Winter Maintenance Patrol Vehicle

Friction measurements are used to provide information to support winter maintenance decision-making in a simple, qualitative way. For example, a winter maintenance supervisor's or monitoring vehicle is dispatched to travel over portions of the road system, during and after winter maintenance, making either periodic or continuous measurements of roadway friction. Friction information collected is presented to the patrol vehicle operator in simple, qualitative terms (e.g., a green, yellow, or red surface friction condition). If some or all of these measurements do not meet approved friction levels-of-service, then the decision-maker can call the maintenance fleet to re-treat those road sections. Additionally, appropriate application rates for ice control materials for the monitored conditions can be relayed to the entire winter maintenance fleet. Individual operators may use this information to manually set their ice control material spread rates.

Scenario 2: Friction Measurements by Winter Maintenance Snowplow/Spreader Vehicles

Friction measurements are collected by snowplow/spreader vehicles equipped with independent friction measurement devices, and are used to control the vehicle's maintenance functions such as material application rates and underbody plow downpressure.

Scenario 3: Recorded, Archived Friction Measurements by a Winter Maintenance Patrol or Snowplow/Spreader Vehicles

Winter maintenance patrol or snowplow/spreader vehicles measure the friction and record it for use in post-snow-fighting periods to assess the effectiveness of the winter maintenance. Data are referenced by a manually recorded milepost or by global positioning system (GPS) coordinates.

Scenario 4: Recorded, Archived, and Real-time Transmitted Friction Measurements from a Winter Maintenance Patrol or Snowplow/Spreader Vehicles

Friction measurements and location are transmitted in near-real-time from the winter maintenance patrol or snowplow/spreader vehicles to a central office where the information is processed. This information is used, along with Roadway Weather Information System data, for dispatching snowplow/spreader vehicles to existing and anticipated trouble spots, and for selecting ice control material application rates for different storm periods. The information (or a summary) can be made available to both private and commercial road users with warnings regarding sections of roadway where surface friction may be inadequate for safe mobility.

1. Is your job directly related to winter maintenance?

☐ Yes ☐ No ☐ Somewhat

Comments:

2. Does your Agency use any type of friction measurement to support winter maintenance operations?

☐ Yes ☐ No ☐ Do not know

If Yes, please specify what type of equipment and how it is used: ___________________________________

____

____

____

Comments:

3. If Yes, please identify any possible deficiencies in the process and discuss what should be done to correct them.

____

____

____

____

4. Are you familiar with the following friction measurement devices that can be used under snow and ice conditions?

Deceleration Devices (e.g., Coralba)	☐ Yes	☐ No	☐ Somewhat
Variable Slip Devices (e.g., SALTAR)	☐ Yes	☐ No	☐ Somewhat
Traction Control and Anti-Lock-Brake (ABS) Devices	☐ Yes	☐ No	☐ Somewhat

Comments:

5. The use of friction measurement would improve winter maintenance operations in my jurisdiction or setting.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

6. What would you consider to be a reasonable cost for a friction measurement device to be mounted on a winter maintenance supervisor's vehicle?

☐ <$5,000 ☐ $5,000-$10,000 ☐ $10,000-$15,000 ☐ $15,000-$20,000 ☐ >$20,000

Comments:

7. What would you consider to be a reasonable cost for a friction measurement device to be mounted on a snowplow/spreader?

☐ <$5,000 ☐ $5,000-$10,000 ☐ $10,000-$15,000 ☐ $15,000-$20,000 ☐ >$20,000

Comments:

8. Devices that require locked wheel braking (as in the Coralba) may be used on a heavy winter maintenance vehicle if proven reliable and cost effective.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

9. A simple indication of the pavement friction (e.g., a green, yellow, or red surface friction condition) may help field supervisors to make a decision on re-treating a particular roadway section.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

10. A simple indication of the surface friction (e.g., a green, yellow, or red surface friction condition) may help on the selection of appropriate application rates for ice control materials.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

11. A simple qualitative friction measurement of ice- or snow-covered pavement (e.g., a green, yellow, or red surface friction condition) may assist snowplow/spreader operators in selecting appropriate ice control material application rate and/or downpressure on underbody snowplows.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

12. Would equipping winter maintenance fleet vehicles with friction measuring devices be beneficial?

Maintenance supervisor's vehicles	☐ Yes	☐ No	☐ Do not know
Snowplows	☐ Yes	☐ No	☐ Do not know
Spreaders	☐ Yes	☐ No	☐ Do not know

Comments:

13. Recording and storing friction data may be beneficial for future uses such as assessing the effectiveness of the winter maintenance activities after snowstorm periods.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

14. It may be cost-effective to install a GPS or other automatic vehicle location device to automatically record the location of the surface friction measurement (considering costs of the equipment necessary to downlink and display the data).

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

15. What would you consider to be a reasonable cost for an automatic vehicle location device to record the locations of the measured surface friction?

☐ <$1,000 ☐ $1,000-$2,000 ☐ $2,000-$5,000 ☐ $5,000-$10,000 ☐ >$10,000 ☐ Do not know

Comments:

16. Can you identify other uses for a database containing records of surface friction measurements and locations collected during the winter maintenance operations?

☐ Yes Please describe: ____

☐ No ____

____

____

Comments:

17. Please indicate any information that should be collected in addition to surface friction and location.

☐ Date & time ☐ Air temperature ☐ Pavement temperature ☐ Surface conditions

☐ Weather conditions

☐ Others: ____

____

____

18. Records of friction measurements and locations, similar to the thermal maps that have been used in winter maintenance practice, could be used to develop spatially averaged maps of surface friction state during snow fighting periods.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

19. It is useful for road users to have access to maps of average and minimum surface friction states during storm and snow fighting periods though the Web, printed material, or other appropriate source.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

20. It is useful to collect and analyze real-time records of friction measurements and location at a data control center.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

21. Real-time friction measurements, along with Roadway Weather Information System (RWIS) data, can be used to allocate snow fighting resource in real-time.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

22. It is beneficial to incorporate near-real-time surface friction records into existing winter maintenance or traffic management practices.

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree ☐ Do not know

Comments:

23. In addition to friction measurements, several factors may be considered in the winter maintenance decision-making process. Please rate the importance of each of the following factors (in the rows) using a scale from 1 to 5 (1 being not important and 5 being very important) with respect to actions based on the proposed scenarios (in the columns).

	Maintenance fleet recalls to re-treat road sections not meeting the specified friction condition	Operation strategy selection (material application rates and down pressure on underbody plows)	Operational decisions (effectiveness of storm fighting, inform users, resource allocation, etc.).
Surface Type			
Surface Temperature			
Forecast Air Temperature			
Expected Storm Duration			
Precipitation Type			
Precipitation Intensity			
Wind Speed (drifting)			
Accident reports			
Others:			

Comments

24. Please add any information that may be of benefit to this project, including the effectiveness, reliability, repeatability, and robustness of the devices you are familiar with.

NCHRP 6-14

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Please complete the following request for information and return the completed questionnaire by *September 20, 2001***.**

Name: ____

Current Position/Title: ______________________________________

Agency: ____

Address: ____

____

City: ________________________ State: __________ Zip: __________

Telephone: ____________________ Fax: ____________________

Email: ___________________________

If you have any questions, please contact: Dr. Imad L. Al-Qadi
200 Patton Hall
Blacksburg, VA, 24061-0105
Tel: 540 231 5262, Fax: 540 231 7532
e-mail: alqadi@vt.edu

Thank you in advance for your help and cooperation with this project

Evaluation Criteria

The following criteria have been selected for rating the proposed scenarios for the use of friction measurements to improve winter maintenance operations decision-making, operation performance evaluations, and motorist information. These criteria are independent of the scenarios, and it is requested that you provide a percentage weight for each criterion that represent the relative importance of each criterion in the final evaluation of the scenarios. The total of all weights should add to 100% (e.g., in the case of two criteria, A and B, if A is 70%, B should be 30%). Please fill the table below.

Scenario Evaluation Criterion	Weight (%)
Potential to enhance winter maintenance operations (benefit to DOT)	
Potential to enhance user mobility (benefit to road users)	
Potential to enhance roadway safety	
Implementation feasibility	
Implementation practicality	
Prior domestic experience	
Prior international experience	
Total	**100**

Similarly, please assign a weight to each of the selected criteria for evaluating the most promising technologies for friction measurements under winter condition.

Technology Evaluation Criterion	Weight (%)
Effectiveness	
Reliability	
Repeatability	
Robustness	
Deployment cost	
Operational cost	
Operational safety	
Road User safety	
Ability to be integrated into an agency's operation	
Ability to be presented in a simple format	
Total	**100**

A - Winter Maintenance Scenario Evaluation

Scenario 1: Friction Measurements from a Winter Maintenance Patrol Vehicle

Friction measurements are used to provide information to support winter maintenance decision-making in a simple, qualitative way. For example, a winter maintenance supervisor's or monitoring vehicle is dispatched to travel over portions of the road system, during and after winter maintenance, making either periodic or continuous measurements of roadway friction. Friction information collected is presented to the patrol vehicle operator in simple, qualitative terms (e.g., a green, yellow, or red surface friction condition). If some or all of these measurements do not meet approved friction levels-of-service, then the decision-maker can call the maintenance fleet to re-treat those road sections. Additionally, appropriate application rates for ice control materials for the monitored conditions can be relayed to the entire winter maintenance fleet. Individual operators may use this information to manually set their ice control material spread rates.

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Question	Scenario	5	4	3	2	1
1. How would you rate the potential of the scenarios to enhance winter maintenance operations (benefit to DOT)?	Scenario	5 (very useful)	4	3	2	1 (not useful)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
2. How would you rate the potential of the scenarios to enhance user mobility (benefit to road user)?	Scenario	5 (very useful)	4	3	2	1 (not useful)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
3. How would you rate the potential of the scenarios to enhance roadway safety?	Scenario	5 (very useful)	4	3	2	1 (not useful)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
4. How would you rate the possibility of a successful implementation of the scenarios?	Scenario	5 (highly probable)	4	3	2	1 (not likely)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
5. How would you rate the practicality of the scenarios?	Scenario	5 (very practical)	4	3	2	1 (not practical)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
6. How would you rate the existing US experience with these types of operations?	Scenario	5 (extensive)	4	3	2	1 (no experience)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐
7. How would you rate the existing international experience with these types of operations?	Scenario	5 (extensive)	4	3	2	1 (no experience)
	1	☐	☐	☐	☐	☐
	2	☐	☐	☐	☐	☐
	3	☐	☐	☐	☐	☐
	4	☐	☐	☐	☐	☐

B - Friction Measurement Technology Evaluation

Question	Technology	5 (very familiar)	4	3	2	1 (not familiar)
1. Are you familiar with the following technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	5 (very effective)	4	3	2	1 (not effective)
2. How would you rate the effectiveness of these technologies in providing the information needed for the four scenarios being evaluated?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	5 (reliable)	4	3	2	1 (unreliable)
3. How would you rate the reliability of these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	5 (repeatable)	4	3	2	1 (not repeatable)
4. How would you rate the repeatability of these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	5 (robust)	4	3	2	1 (not robust)
5. How would you rate the robustness of these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	<$5,000	$5,000 - $10,000	$10,000 - $15,000	$15,000 - $20,000	> $20,000
6. What is a reasonable cost for the deployment on a supervisor's vehicle of a friction measurement device based on these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

Question	Technology	<$5,000	$5,000 - $10,000	$10,000 - $15,000	$15,000 - $20,000	> $20,000
7. What is a reasonable cost for the deployment on snowplow/spreaders of a friction measurement device based on these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

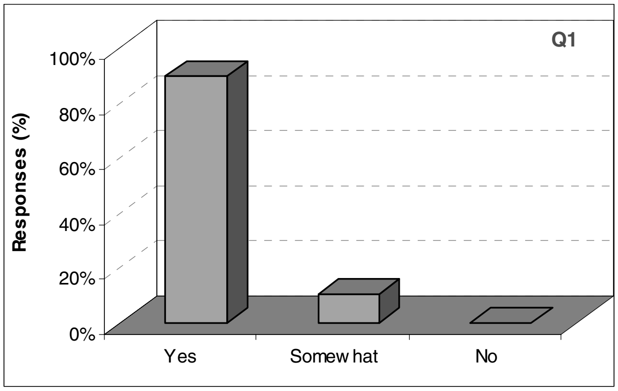
Question	Technology	5 (inexpensive)	4	3	2	5 (expensive)
8. How would you rate the operation cost of these technologies?	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

B - Friction Measurement Technology Evaluation **(cont.)**

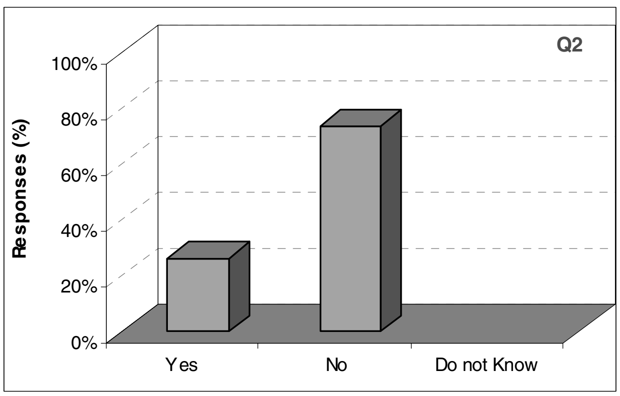
9. How would you rate the equipment operator safety of the technologies under the operational constraints of the scenarios being evaluated?	Technology	5 (safe)	4	3	2	1 (unsafe)
	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐
10. How would you rate the roadway user safety of these technologies?	Technology	5 (safe)	4	3	2	1 (unsafe)
	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐
11. How would you rate the possibility of integrating these technologies into an agency's operation?	Technology	5 (easy)	4	3	2	1 (difficult)
	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐
12. How would you rate the possibility of presenting the friction data in a simple format for these technologies?	Technology	5 (easy)	4	3	2	1 (difficult)
	Deceleration	☐	☐	☐	☐	☐
	Variable Slip	☐	☐	☐	☐	☐
	Traction Control/ ABS	☐	☐	☐	☐	☐

APPENDIX C: QUESTIONNAIRE 1 RESULTS

1. Is your job directly related to winter maintenance?



2. Does your Agency use any type of friction measurement to support winter maintenance operations?



3. If Yes, please identify any possible deficiencies in the process and discuss what should be done to correct them.

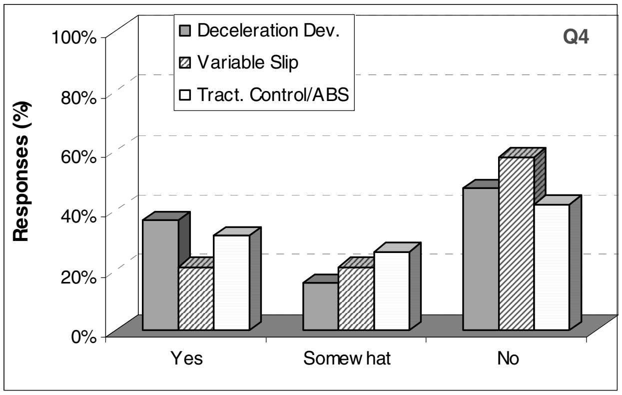
✓ Am not familiar enough to give good info. Can provide contact names of friction equipment experts if desired.

✓ Our primary use of these devices is for research and development.

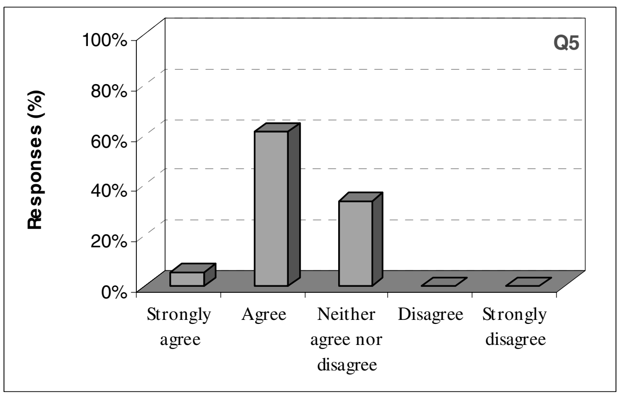
✓ Locked wheel is too expensive and unwieldy for Winter Ops work. The Coralba can work if proper training and calibration is achieved.

✓ Dependability, no support break down. When good, it works good.

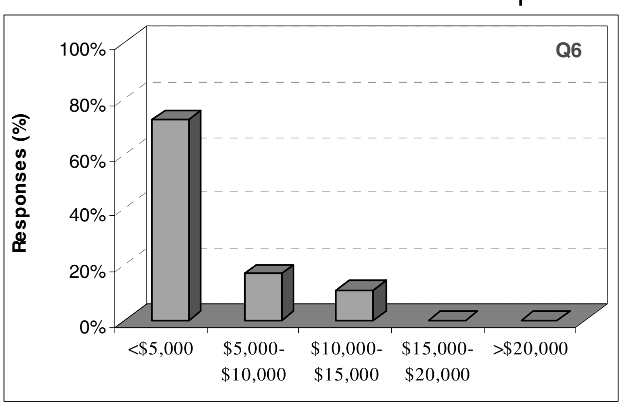
4. Are you familiar with the following friction measurement devices that can be used under snow and ice conditions?



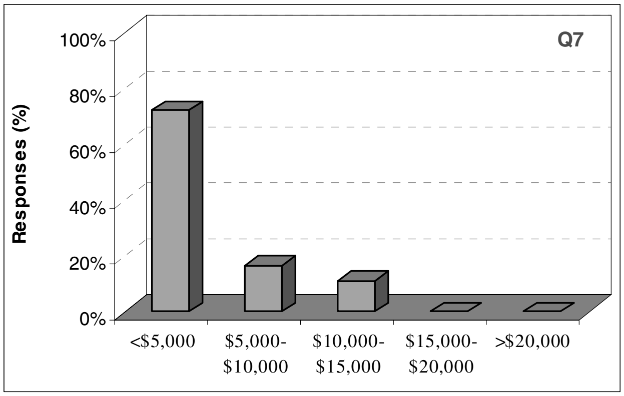
5. The use of friction measurement would improve winter maintenance operations in my jurisdiction or setting.



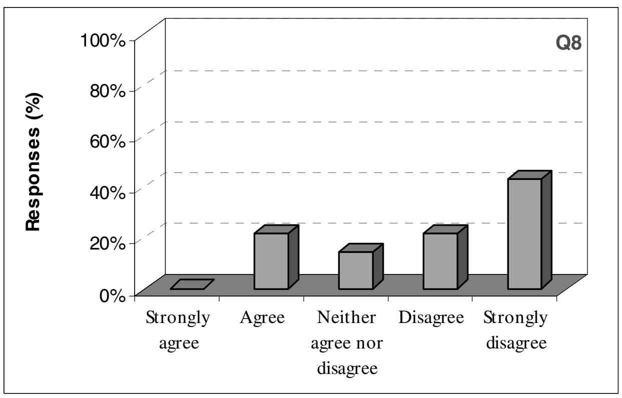
6. What would you consider to be a reasonable cost for a friction measurement device to be mounted on a winter maintenance supervisor's vehicle?



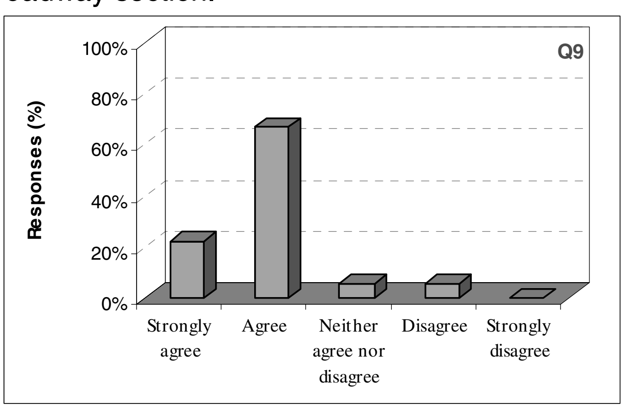
7. What would you consider to be a reasonable cost for a friction measurement device to be mounted on a snowplow/spreader?



8. Devices that require locked wheel braking (as in the Coralba) may be used on a heavy winter maintenance vehicle if proven reliable and cost effective.

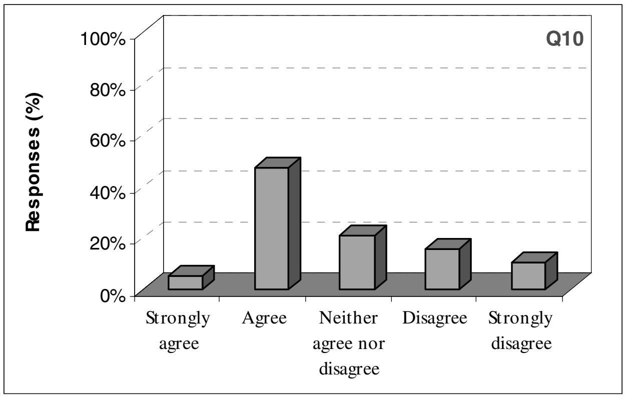


9. A simple indication of the pavement friction (e.g., a green, yellow, or red surface friction condition) may help field supervisors to make a decision on re-treating a particular roadway section.

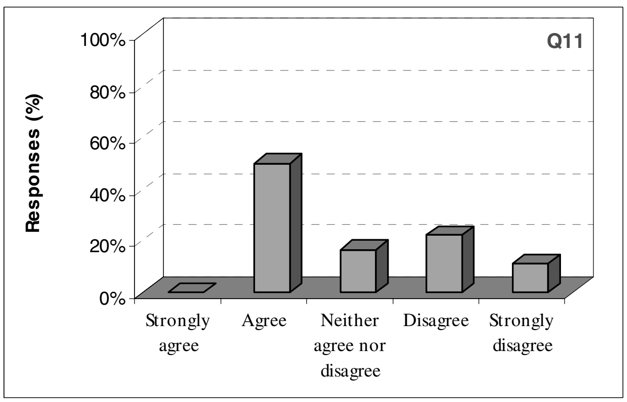


10. A simple indication of the surface friction (e.g., a green, yellow, or red surface friction condition) may help on the selection of appropriate application rates for ice control

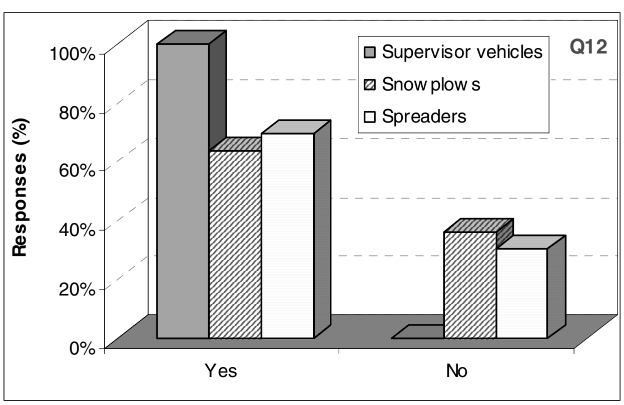
materials.



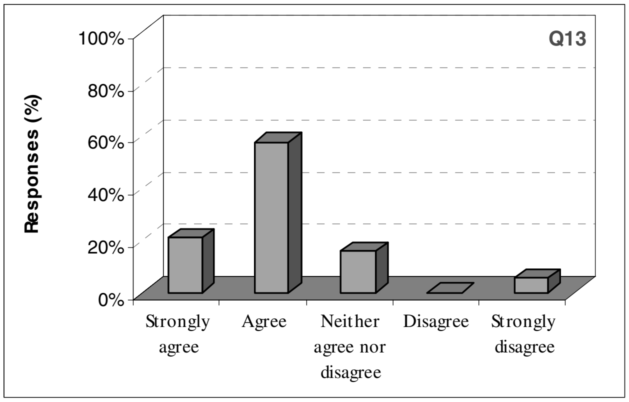
11. A simple qualitative friction measurement of ice- or snow-covered pavement (e.g., a green, yellow, or red surface friction condition) may assist snowplow/spreader operators in selecting appropriate ice control material application rate and/or downpressure on underbody snowplows.



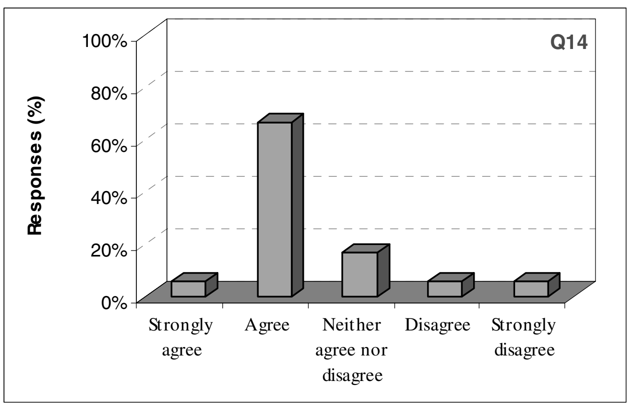
12. Would equipping winter maintenance fleet vehicles with friction measuring devices be beneficial?



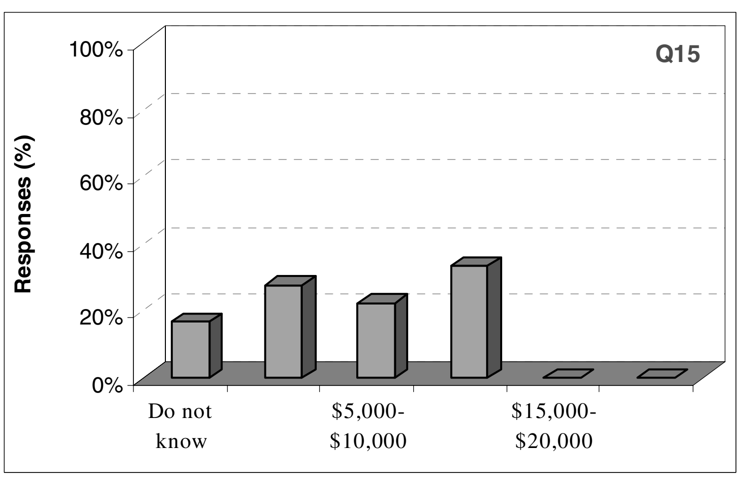
13. Recording and storing friction data may be beneficial for future uses such as assessing the effectiveness of the winter maintenance activities after snowstorm periods.



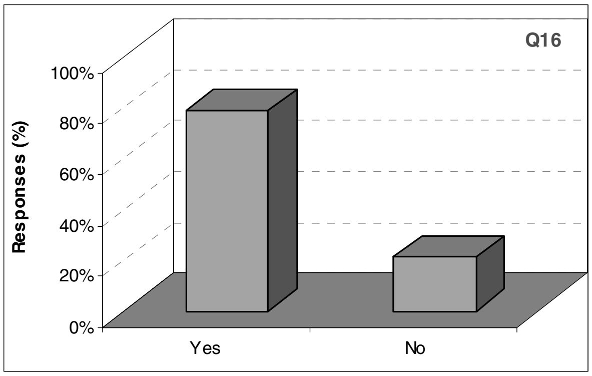
14. It may be cost-effective to install a GPS or other automatic vehicle location device to automatically record the location of the surface friction measurement (considering costs of the equipment necessary to downlink and display the data).



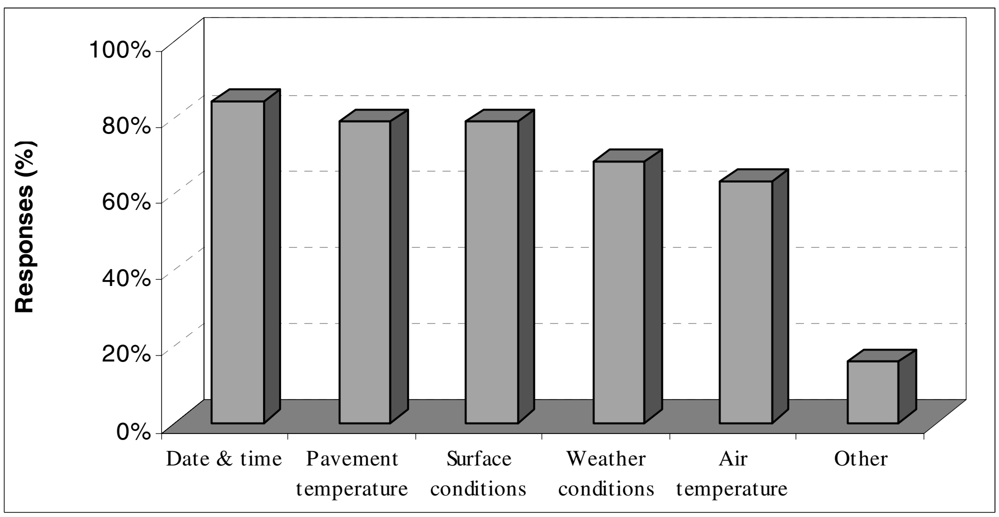
15. What would you consider to be a reasonable cost for an automatic vehicle location device to record the locations of the measured surface friction?



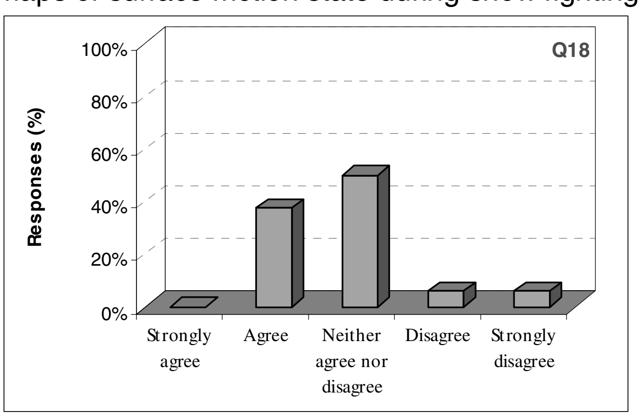
16. Can you identify other uses for a database containing records of surface friction measurements and locations collected during the winter maintenance operations?



17. Please indicate any information that should be collected in addition to surface friction and location.

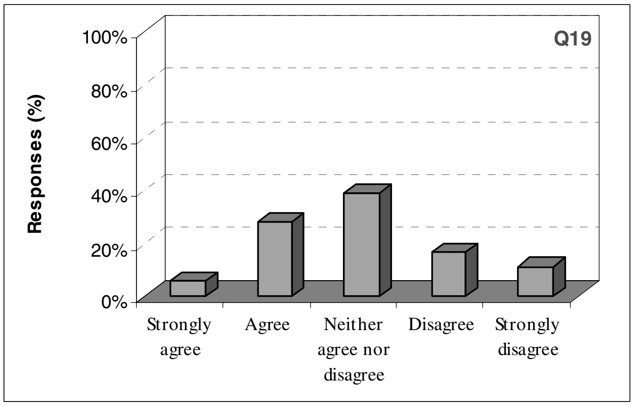


18. Records of friction measurements and locations, similar to the thermal maps that have been used in winter maintenance practice, could be used to develop spatially averaged maps of surface friction state during snow fighting periods.

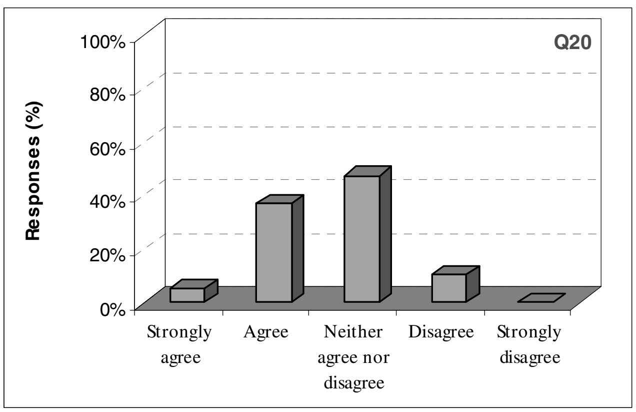


19. It is useful for road users to have access to maps of average and minimum surface friction states during storm and snow fighting periods though the Web, printed material,

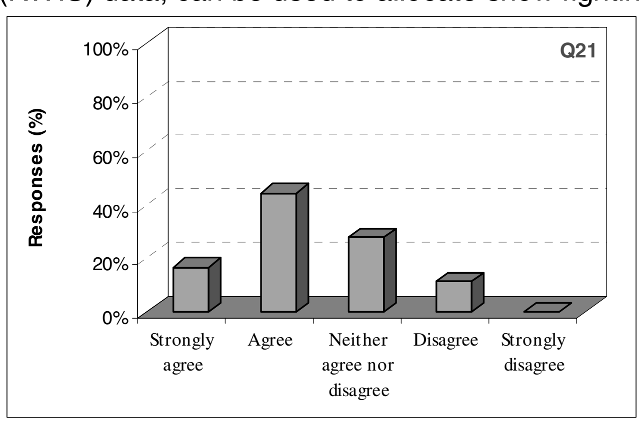
or other appropriate source.



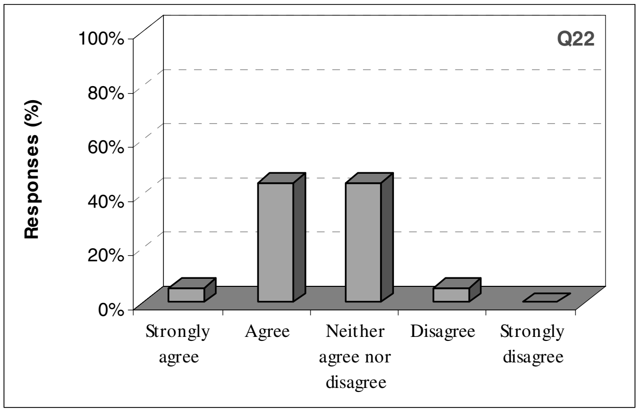
20. It is useful to collect and analyze real-time records of friction measurements and location at a data control center.



21. Real-time friction measurements, along with Roadway Weather Information System (RWIS) data, can be used to allocate snow fighting resource in real-time.



22. It is beneficial to incorporate near-real-time surface friction records into existing winter maintenance or traffic management practices.

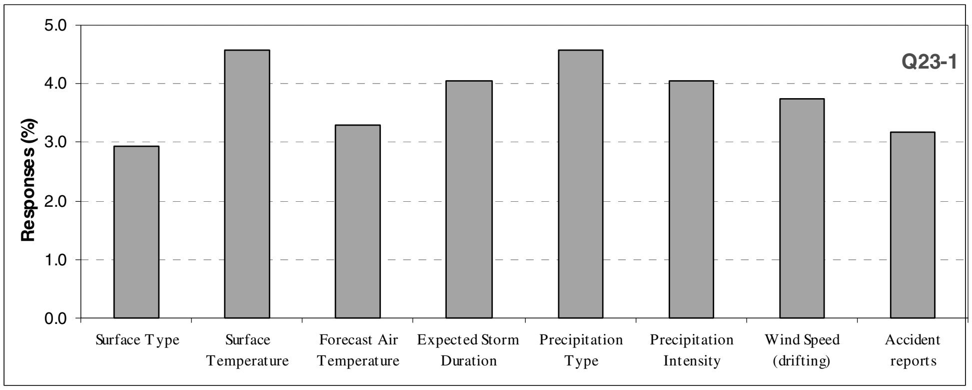


24. Please add any information that may be of benefit to this project, including the effectiveness, reliability, repeatability, and robustness of the devices you are familiar with.

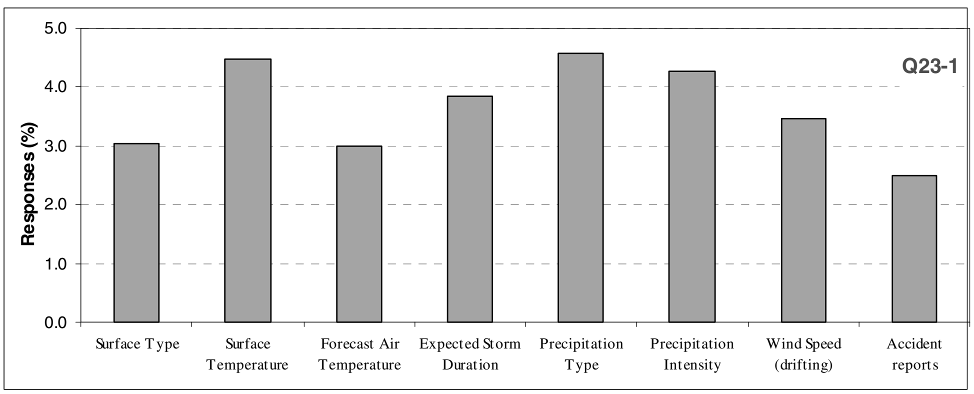
- ✓ Any type of equipment or product we use depends greatly on the wise and knowledge of the operator. If they are well trained with what they are using the will be effective.
- ✓ I think we need to work toward low cost units that can provide friction measurements to provide maintenance forces, law enforcement and the public. Also should consider putting these units on over the road trucks/law enforcement vehicles to provide 24-hour a day data information
- ✓ Our research and development of the MDSS project could provide some useful information and algorithms for maintenance practices. The folks who contributed to the Joint Winter Runway Friction Project could provide very pertinent information with regard to friction measuring devices.
- ✓ Don't have enough in hand experience with this type of test equipment to be able to offer any good comments.
- ✓ We here in Marquette County are willing to try any or all tools to help us make decisions for highway safety. Always willing to try something new. Please Contact.
- ✓ The measurement of friction is of value only if the program is reactive in nature. Once the friction is gone the game is lost. It's main value is in the area of quality control and quality assurance.
- ✓ Reliability is a problem. No parts or service experts available.
- ✓ Coralba was difficult to use unless traffic was light and conditions exact (no curves or grades)

23. In addition to friction measurements, several factors may be considered in the winter maintenance decision-making process. Please rate the importance of each of the following factors (in the rows) using a scale from 1 to 5 (1 being not important and 5 being very important) with respect to actions based on the proposed scenarios (in the columns).

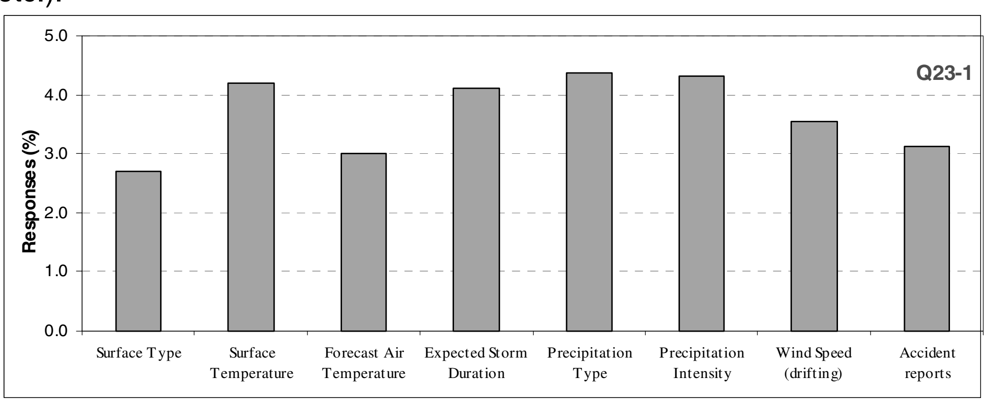
Maintenance fleet recalls to re-treat road sections not meeting the specified friction condition



Operation strategy selection (material application rates and down pressure on underbody plows



Operational decisions (effectiveness of storm fighting, inform users, resource allocation, etc.).



Others: Terrain (mountain or desert), Expected pavement temperature.