Correlating Lab and Field Tests for Evaluation of Deicing and Anti-icing Chemicals: A Renewed Perspective

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Sponsoring committee: Winter Maintenance Committee

Word Count: 6216+ 5*250 = 7466
ABSTRACT

Numerous laboratory and field studies have been conducted to evaluate the performance of deicing and anti-icing products and their resulting friction coefficient of treated pavement. However, laboratory results often do not translate to the field performance due to varying temperatures, wind, traffic, etc. in actual field conditions. Also, the existing laboratory tests fail to address all the significant issues in the actual field environment or to provide actual performance of deicers to guide practitioners. This study sheds light on the challenges of developing a laboratory test that correlates the field test based on literature reviews and interviews from various agencies and practitioners. Recommendations for laboratory testing include the use of environmental chamber that can control and monitor air temperature, humidity, air speed and solar radiation. In addition, it is recommended to incorporate a plowing mechanism into the laboratory test to better simulate the field operations. Two friction-measuring devices were recommended that can be used both in laboratory and in field. In addition, it may be preferable to use a friction trailer if the necessary laboratory space can be obtained. For field testing, it is preferable to conduct the research in a controlled field environment. Recommendations from this study may assist in developing a test method that would closely mimic the actual performance.

Keywords: Deicer Performance, Ice melting, Ice penetration, Ice Undercutting, Friction Coefficient, Shear, Disbondment
1. INTRODUCTION

Deicer products are used to remove the ice once it has formed, while anti-icing products are used to prevent the formation of ice. Numerous laboratory and field studies have been conducted to evaluate the performance of deicing and anti-icing products and their resulting friction coefficient of treated pavement. Laboratory testing has been used extensively to quantify deicer or anti-icer performance because of ease and low cost to setup experiments and the relatively high reproducibility and transferability of results. However, laboratory testing often does not mimic the actual field conditions such as varying temperatures, wind, traffic, etc. which in turn does not provide the actual performance of the deicing and anti-icing products. Field testing is desirable over laboratory testing in terms of replicating the actual conditions. Yet it can be costly and difficult to reproduce because of ever changing conditions in the field environment where some variables are difficult to control or even to document. In this context, laboratory and field experiments need to be carefully designed to encompass all relevant variables so that better correlations can be developed.

While there are test methods that quantify deicer or anti-icer performance in the laboratory setting, results often do not translate to the field performance. There are many parameters in the real world that likely play a role in the effectiveness of deicer products used in winter maintenance. These include traffic, pavement type and condition, and meteorological conditions (as shown in Figure 1). The amount and type of traffic influence road conditions, as do pavement temperature, type, texture, and condition. Meteorological conditions that are important include air temperature, wind speed and direction, solar radiation, humidity, rate and type of precipitation, water content of snow, etc. Also important are the physical and chemical properties of deicers such as gradation (for solids), heat retention and emission properties, etc.

At this point in time, there is no laboratory test method for deicing or anti-icing performance and friction coefficient available that directly correlates with the performance and friction of deicer products in the field. As such, the existing laboratory tests can only provide a baseline to contrast various products under well-controlled conditions and the findings derived from such tests need to be used with caution.

The goal of this project was to utilize previous research to provide guidance on developing a laboratory test, tool or methodology that will quantify deicer and anti-icer performance and friction coefficient on pavement and correlate with results from the field. To accomplish it a literature review was conducted to provide direction for the design of laboratory and field tests. The objective of the literature review was to identify existing laboratory and field test methods for evaluating deicer and/or anti-icer (both referred to as deicer from this point forward) performance and pavement friction coefficient, and to provide guidance on which test methods may be used to develop a direct correlation. In addition, key individuals or experts from different department of transportation identified during the literature review were interviewed for additional information on previously conducted laboratory and field research, project costs, equipment design and cost, and important parameters and performance characteristics to consider. Based on information gathered in the literature review and interviews, recommendations have been made on meteorological parameters and performance characteristics to consider in laboratory and field testing as well as tools, equipment and methodologies to consider in future phases of this research.
2. TEST METHODS TO CHARACTERIZE DEICER PERFORMANCE

Deicer performance can be described in several ways, such as:

- melting and penetration ability (when used as a reactive strategy),
- anti-bonding ability (when used as a proactive strategy),
- time until bare pavement is achieved,
- persistence on the road,
- relative performance as compared with other products.

It is crucial to clearly define the term “deicer performance” based on prevailing user requirements prior to conducting laboratory and field research. This would enhance the usefulness of the data obtained from the laboratory and field testing. The performance measure or criterion is important in the context of measuring the effectiveness of winter road operations; however, currently there is still a lack of consensus on the subject. The more practical criteria may be the time until bare pavement is achieved or a certain level of friction is achieved; yet they are not as easy to measure as some other criteria.

It is also important to find the deicer performance in conjunction with other maintenance strategies such as plowing operations and abrasives spreading. Winter maintenance strategies can vary as a function of the local road weather scenarios, rule of practice, and other constraints. As such, a laboratory experiment that attempts to accurately predict field performance must be able to reasonably simulate plowing, deicing, and/or anti-icing, and the seemingly infinite number of
combinations of parameters (such as temperature, traffic levels, pavement condition, etc.) that could be present in the field.

In 1992 the Strategic Highway Research Program (SHRP) sponsored the development of the *Handbook of Test Methods for Evaluating Chemical Deicers* (referred to as SHRP Handbook from this point forward), which provided test methods for eight principal features of deicers, including deicing performance. Three types of test methods for deicing performance were created: Ice Melting Test for solid and liquid deicers (SHRP H-205.1 and H-205.2, respectively), Ice Penetration Test for solid and liquid deicers (SHRP H-205.3 and H-205.4, respectively), and Ice Undercutting Test for solid and liquid deicers (SHRP H-205.5 and H-205.6, respectively) \(^1\)

### 2.1 Ice Melting Tests

The SHRP Ice Melting Test (H-205.1 and H-205.2) measures the amount of ice melted by deicers over time. In this test, liquid or solid deicers are uniformly spread over the prepared ice and the melted liquid is removed for volume measurements \(^1\). The SHRP *Handbook* has a strict limit of temperature variation (±0.5°F) of the set temperature and also requires the ice surface to be melted and refrozen to produce smooth, uniform ice samples. The SHRP Ice Melting Test was modeled after tests conducted by McElroy et al. \(^2, 3, 4\). There are inherent difficulties presented by any ice melting test such as the inability to separate the entire melted portion from the remaining ice due to 1) entrapment within ice cavities and 2) absorption of brine on the ice surface and undissolved deicer particles. Other factors affecting reproducibility include the dependence on the rate of dissolution of solid deicers (which also depends on the particle size) and the amount of brine needed for reasonably accurate measurements. Thus, ice melting tests try to strike a balance between generating enough brine for accurate measurements and avoiding too much deicer, which may not represent a realistic application rate for highway operations \(^5\).

Several authors performed SHRP Ice melting tests with a few modifications based on their applications. Nixon et al. \(^6\) performed the SHRP Ice Melting test to compare seven liquid deicers by varying water and deicer level at four different temperatures. The test helped in providing the best deicer for the different expected temperatures and also cost-effective deicer based on the volume of melted ice \(^6\). Shi et al. \(^7\) performed the SHRP Ice Melting Test by reducing the surface area (3.5cm radius) to limit the absorption rate as recommended by Chappelow et al. \(^5\). The test found that the rate of dissolution of solid deicers, which is dependent on the particle size and the amount of brine needed for reasonably accurate measurements, may have been a factor affecting reproducibility. Akin and Shi \(^8\) recommend the SHRP Ice Melting Test be implemented for liquid and solid deicers with brine volumes collected at only 20 and 60 minutes after application. Furthermore, brine volumes should only be reported to the nearest tenth mL, coefficient of variation to the nearest percent, and standard deviation to the nearest tenth mL to discourage inappropriate comparisons determined from this test method. A reference sample using 23% NaCl was recommended for all tests to determine acceptability of the test procedure. Gerbino-Bevins \(^9\) found out that SHRP Ice Melting test produced inconsistent results when compared with other similar research. It may be due to different sources of error while conducting the experiment and it may require few customized modifications to suit a particular application. Koefod et al. \(^10\) found reasonable comparisons of the SHRP Ice-Melting test between two laboratories when the test duration was extended to 5 and 7 hours. While this length of time is not as realistic for field applications, it does improve the reproducibility of the test significantly and may allow for a more realistic method of
comparing alternative deicers. Goyal et al. (11) developed an ice melting test before the SHRP Handbook was published. In this test, researchers used blotter paper to absorb and weigh the melted portion. The blotter method seems to be a reasonable method for brine collection for a time specified ice melting test. However, this test is not desirable for a continuous testing because the melted portion was not returned to ice samples. Another study conducted by Anti-icing materials laboratory (AMIL) modified the ice melting test by measuring deicer performance based on the time required to melt a certain amount of ice (12).

2.2 Ice Penetration Tests

The SHRP Ice Penetration Tests (H-205.3 and H-205.4), presented in the SHRP Handbook, were developed by Chappelow et al. (1) to test the ability of deicers to penetrate ice. The SHRP Ice Penetration Test was modeled after the studies conducted by McElroy et al. (3, 13) in Plexiglas® cavities which measure the depth a particle of solid deicer or 30 μL of liquid deicer penetrates a vertical cavity of ice over time. Dye provided the visual aid of the deicer penetration into the ice. Nixon et al. (5) performed the SHRP Ice Penetration Test on seven liquid deicers, and he does not recommend using this test because of the role of traffic in actual road conditions. The traffic might force the deicer into the ice or disperse from the road. Shi et al. (7) performed the SHRP Ice Penetration Test and discovered that, for solid products single pellets would have become physically wedged in the ice penetration apparatus. Akin and Shi (8) performed the SHRP Ice Penetration Test by inserting a small, cold metal tool instead of dye to measure penetration of deicer. The test method provided remarkably limited information for practitioners and also had inherently high variability due to the deicer/ice interface and the brine generation and penetration processes. Another study conducted by AMIL modified the ice penetration test by measuring deicer performance based on the penetration capacity as a function of time (13).

2.3 Ice Undercutting Tests

The third deicer performance test developed by Chappelow et al. (1) is the SHRP Ice Undercutting Test (H-205.5 and H-205.6) and is based on the ice undercutting test developed by McElroy et al. (14). In this test, ice is prepared on a textured surface (mortar substrate) by cooling slowly from the bottom to top. For testing solid deicers, drops of dye are added on the surface, and solid deicers were placed on the top of dyed area. For liquid deicers, small cavities are made on the ice surface, and liquid deicer solution (deicer mixed with dye) is filled in to those cavities (1). Shi et al. (7) performed the SHRP Ice Undercutting Test for solid and liquid products. Results from this test method provide insight and performance data that can be used to guide field applications. The authors do not recommend using this test method to evaluate solid deicers due to reproducibility issues. In addition, many deicers initially appeared to be undercutting and breaking the ice–concrete bond, but, in fact, the dye was moving across the surface of ice and only giving the appearance of undercutting.

Mauritis et al. (15) developed a laboratory test for solid deicers by using test tubes instead of dye to detect undercutting. The time for a deicer particle to penetrate and undercut ice in the bottom of a test tube was determined using an electrical circuit attached to the test tube. Akin and Shi (8) modified the Mauritis et al. (15) test method by comparing ice undercutting in smooth
and roughened test tubes. The test results for scratched and smooth test tubes were ultimately too variable and not repeatable enough for further development. Another study conducted by AMIL modified the ice undercutting test by measuring deicer performance based on the area of undercut as a function of time (16).

The tests presented in the SHRP *Handbook of Test Methods for Evaluating Chemical Deicers* have been used extensively to characterize deicer performance. Many researchers have made modifications to the original test methods designed by Chappelow et al. (1, 5) to improve results. It is crucial to keep in mind the SHRP tests were not designed such that results could be directly translated to field performance; instead, the SHRP tests provide insight into relative performance between products. Table 1 summarizes the test details, pros, and cons of common test methods for deicer performance.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Purpose</th>
<th>Deicing or Anti-icing Attributes</th>
<th>How Experiment Incorporated or Simulated Various Parameters</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Chappello et al., 1992, *Chappello et al., 1993 | Ice melting test (SHRP 205.1-2) | NaCl (s) & CaCl2 (s); NaCl (l), CaCl2 (l), ethylene glycol (l) | 5, 15, 25°F (-3.9, -9.4, -15°C) | —                                                              | •Inexpensive, short testing time  
•Recommend running in triplicate  
•Can test liquids and solids  
•*Modified calculations for liquid products for greater accuracy. |
|                   | Ice penetration test (SHRP 205.3-4) | NaCl (s)& CaCl2 (s); NaCl (l), CaCl2 (l), ethylene glycol (l) | 5, 15, 20(s)/25(l)°F (-15, -9.4, -6.7/s)/-3.9(l)°C) | —                                                              | •Can test liquids and solids  
•Inexpensive, short testing time  
•Recommend running five replicates.  
•Can run side by side with a control. |
|                   | Ice undercutting test (SHRP 205.5-6) | NaCl (s)& CaCl2 (s); NaCl (l), CaCl2 (l), ethylene glycol (l) | solid 5, 25°F (-3.9, -15°C); liquid 5, 15, 20, 25°F (-15, -9.4, -6.7, -3.9°C) | Mortar substrate | •Inexpensive, short testing time  
• Recommend running five replicates.  
•Can test liquids and solids  
•Analysis made easier with use of digital images and computer analysis  
•Mortar only pavement type considered. |
| McElroy et al., 1990 | Deicers undercutting | Deicing, CaCl2 pellets, CaCl2 flakes, NaCl (2 products), KCl, pelletized urea, NaCl with traces of carboxymethocellulose, mixture of NaCl with KCl and urea, mixture of NaCl and urea, and CMA. | 0, 5, 10,15,20, 25 °F (-17.8, -12.2, -9.4, -6.7, -3.9 °C) | Concrete specimen according to ASTM specifications(ASTM C109-84), lightly broomed | •Each specimen accommodates 20 undercutting tests  
•Overlapping of undercutting area occurred due to high number of replicates per specimen. |
| Nixon et al., 2005 | Modified ice melting test and ice penetration test | NaCl brine (23%), CaCl2 brine, CMA, potassium acetate (KA), Ice Ban Ultra, Caliber M-1000, Mineral brine. | 0, 10, 20, 30 °F (-17.8, -12.2, -6.7, -1.1 °C) | —                                                              | •Test uses less water/ice and more deicer than SHRP 205.1-2 to achieve a greater amount of melt.  
•Test was run with five replicates.  
•No usable data was collected for 0 °F.  
•Ice penetration test not recommended for use as a quality control tool. |
| Goyal et al., 1989 | ice melting and ice penetration | Qwiksalt (NaCl, s) with PCI (corrosion inhibitor) and FreezGard (MgCl2, l) with | 23, 14, -0.4, -4°F (<5, -10, -18, -20 °C) | —                                                              | Humidity: high (90–100%) and low (5–20%) |

Table 1 Summary of Ice Melting, Ice Penetration and Ice Undercutting Test Methods.
<table>
<thead>
<tr>
<th>Tests</th>
<th>PCI</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ganjyal et al., 2007</strong></td>
<td>Ice melt</td>
<td>Sodium, calcium and magnesium levulinate</td>
</tr>
<tr>
<td>Traffic</td>
<td>32– -5.8°F (0– -21 °C)</td>
<td>Traffic: compacted snow/ice to 0.75 g/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>•Conducted laboratory and field testing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>•Only data collected was visual observations as digital images of melt.</td>
</tr>
<tr>
<td><strong>Shi et al., 2009 (CDOT)</strong></td>
<td>Modified ice melting test</td>
<td>NAAC, Peak SF, CMA, salt-sand, IceSlicer, NaCl (r,s),</td>
</tr>
<tr>
<td>Traffic</td>
<td>32, 23, -0.4 °F (0, -5, -18 °C)</td>
<td>Humidity: 26.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>•Test was run with three replicates.</td>
</tr>
<tr>
<td></td>
<td>Modified ice penetration test</td>
<td>NAAC, Peak SF, CF7, IceSlicer, NaCl (r,s), CDOT MgCl₂ blend (l),</td>
</tr>
<tr>
<td>Traffic</td>
<td>32, 10.4, -4 °F (0, -12, -20 °C)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>•Test was run with three replicates.</td>
</tr>
<tr>
<td></td>
<td>Modified ice undercutting test</td>
<td>NAAC, Peak SF, CMA, CF7, NAAC/NaFm blend, IceSlicer, NaCl (r,s),</td>
</tr>
<tr>
<td>Traffic</td>
<td>32, 21.2, 14, 3.2 °F (0, -6, -10, -16 °C)</td>
<td>Mortar substrate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>•Test was run with three replicates.</td>
</tr>
<tr>
<td>Akin and Shi, 2010</td>
<td>Modified ice melting</td>
<td>NaCl (r,s), MgCl₂ (r,s), CaCl₂ (r,s), NaCl (l), MgCl₂ (l), CaCl₂ (l)</td>
</tr>
<tr>
<td>Traffic</td>
<td>30, 15, 0 °F (-1.1, -9.4, -17.8°C)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>•Ran test in triplicate with an additional 23% NaCl control</td>
<td>•Does not predict anti-icing capability of products.</td>
</tr>
<tr>
<td></td>
<td>Modified ice penetration</td>
<td>NaCl (r,s), MgCl₂ (r,s), CaCl₂ (r,s), NaCl (l), MgCl₂ (l), CaCl₂ (l)</td>
</tr>
<tr>
<td>Traffic</td>
<td>30, 15, 0 °F (-1.1, -9.4, -17.8°C)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>•Not recommended as a method for comparing deicer performance.</td>
<td>•Results are highly variable.</td>
</tr>
<tr>
<td></td>
<td>•Results are highly variable.</td>
<td>•Gradation of solid deicers significantly affects results.</td>
</tr>
<tr>
<td></td>
<td>Modified ice undercutting test from</td>
<td>—</td>
</tr>
<tr>
<td>Mauritis et al. (1995)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td><strong>Mauritis et al. (1995)</strong></td>
<td>CaCl₂, MgCl₂, NaCl, and three types of CMA</td>
</tr>
<tr>
<td>Traffic</td>
<td>Range of 32 – -31 °F (0 – -35 °C)</td>
<td>—</td>
</tr>
</tbody>
</table>

1 Notes: — indicates not available from reference, r indicates reagent grade product, s indicates a solid product, and l indicates a liquid product.
3. EUTECTIC AND EFFECTIVE TEMPERATURE

Eutectic temperature is the minimum temperature at which a deicer solution remains in liquid form. During the process of melting snow or ice, the deicer is diluted, which may cause the diluted solution to re-freeze when it experiences a temperature drop. Thus, the eutectic temperature can be significantly different from the effective temperature for a deicer, as the latter corresponds to a temperature at which the pavement turns icy and is a subjective term. ASTM D 1177 procedures used for engine coolants is followed to determine phase curves of deicers. Some organic proprietary additives, which act as cryoprotectants are added in the deicers to slow down the freezing process, but without lowering the freezing point of water. As Koefod puts it, cryoprotectants “fool the freezing point test”. Specific tests for effective temperature were not found in literature search, although effective temperatures may be theoretically calculated from a modified SHRP Ice Undercutting Test, but are more commonly reported from a consensus of field experience.

3.1 Differential Scanning Calorimetry (DSC) and Water Spray Endurance Test

The use of a differential scanning calorimetry (DSC) thermogram to quantify deicer performance was initially proposed by Shi et al. (7) based on work by Han and Bischof (17) who investigated freezing and thawing of salt brine in biological systems. The DSC thermogram can provide information on the characteristic temperature and the heat flow during the liquid/solid phase transition of a given deicer, which also shed light on a more realistic working temperature range than a deicer’s eutectic temperature. Additional details of the experiment can be found in Shi et al. (7). Akin and Shi (8) utilized the same methods as Shi et al. (7) for the DSC. They found that the warming cycle was preferred for data analysis because the cooling cycle data was sometimes interfered with by the supercooling effect.

The water spray endurance test (WSET) compares relative performance of aircraft deicing products and simulates deicing fluid behavior in freezing precipitation. The standard WSET, defined in SAE AS 5901, is performed in a climate controlled chamber. A fine mist of freezing water is sprayed on the deiced aluminum panel and the time taken for the formation of ice or slush is recorded as the WSET time. The high humidity endurance test is a modification of the WSET that uses moisture instead of freezing water to record high humidity endurance time. The WSET and high humidity endurance test methods may be modified to test pavement surfaces instead of aircraft materials.

4. SHEAR, DISBONDMENT, AND SCRAPING TESTS

Shear, disbondment, and scraping tests have been developed to realistically mimic field parameters, despite these tests are not being standardized. There are typically two methods of carrying out these type of tests, both of which attempt to disbond snow or ice that are bonded to pavement samples. One method applies a shear force to the entire snow/ice sample to determine the shear strength of the bond between the snow/ice and pavement. This is usually accomplished by placing a band, ring or box around the snow/ice and pulling until the snow/ice is sheared. This method was used by Ashworth et al. (18), Adams et al. (19), Tazawa et al. (20), Schweizer (21), and Cuelho (22). All the researchers uses these methods to test ice bonding on different pavement surfaces with few modifications. For example, Tazawa et al. (20) used single plane
shear test, impact tension test and compression test to clarify the bonding mechanism between ice and asphalt concrete. The results show that for a repellent-coated surface, either shear debonding strength or the energy from the impact tension could be used to evaluate the debonding resistance of the ice–asphalt concrete interface. Cuelho (22) used asphalt and Portland cement concrete pavement to evaluate bonding mechanism. Cuelho (22) found that at higher application rates, the snow did not bond to the pavement. At lower rates, the temperatures at which the snow shaved from pavement were compared to assess the relative performance of the deicers during different storm scenarios.

In addition to applying shear force to snow/ice, the other method involves scraping the snow/ice, similar to a plow on the road. Thus, a scraping force is usually reported with this method. This method was used by Kirchner (23), McElroy et al. (14), Bernardin et al. (24, 25) and Nixon and Wei (26). Anti-Bonding Endurance Test (ABET) was developed by the Anti-Icing Materials International Laboratory for Transport Canada to measure the effectiveness of deicers on concrete surfaces (24, 25). Droplets of freezing rain (precipitation) are applied over the substrate to form ice. The ice is then scrapped and the friction is measured. The precipitation duration times at which ice removal was successful make up the ABT (Anti-Bonding Time) range for a deicer. Nixon and Wei (26) used a scraping test to compare the effectiveness of various deicers on three types of ice (refrozen ice, atmospheric ice, and compacted snow ice) formed on concrete specimens. Tests on 108 ice samples without chemical treatment had 44 “successful” results in which ice bonding to the concrete was statistically significant (scraping and downward forces were both greater than zero with 95 percent level of confidence). With the chemical-treated specimens, zero-load samples due to poorly bonded ice were not distinguished from zero-load samples due to successful chemical performance.

The review of literature related above indicates that direct interfacial shear testing has been commonly used in the laboratory for assessing the undercutting and disbondment characteristics of deicers and anti-icers. However, the literature does not show general agreement on the degree to which environmental parameters may influence results. Environmental parameters such as humidity, long and short wave radiation and wind were not considered in those tests. See summary Table 2 for individual test purpose, attributes, experimental factors incorporated, and pros and cons.
Table 2 Summary of Shear, Disbondment and Scraping Tests.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Purpose</th>
<th>Deicing or Anti-icing; Attributes</th>
<th>How Experiment Incorporated or Simulated Various Parameters</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashworth et al., 1989</td>
<td>Interfacial shear strength tests of ice formed on pavement</td>
<td>Anti-icing, concentrated solution of South Dakota Deicer No.2 (SD2), CMA, and NaCl.</td>
<td>Laboratory chamber at 23 and 5°F (-5 and -15°C); distilled water poured in Teflon rings to simulate freezing rain; on Portland cement concrete (PCC) substrates</td>
<td>• Each substrate accommodating two specimens allows eight test without opening the chamber door. • Four deicer application rates (100, 200, 300, 400) were considered and compared. • Reference tests are conducted to make sure substrates are clean.</td>
<td>• Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice. • One type of pavement</td>
</tr>
<tr>
<td>Adams et al., 1992</td>
<td>Residual anti-icing properties</td>
<td>Anti-icing, concentrated solutions of NaCl and CMA</td>
<td>Laboratory chamber at 24.8°F (-4°C); Natural aged snow, sieved; on smooth limestone and granite coupons compressed snow with 31 psi for 10 minutes</td>
<td>• Natural snow more realistic than ice, but aged snow is different than fresh snow</td>
<td>• No macro texture • Air and pavement were at same temperature • Only considered snow, no ice.</td>
</tr>
<tr>
<td>Cuelho, 2010</td>
<td>Anti-icing application rates</td>
<td>Anti-icing, NaCl, CaCl₂, MgCl₂, Potassium acetate, ag. by-product</td>
<td>Air (A), Pavement (P) Storm 1: A23°F (-5°C), P32°F (0°C); Storm 2: A14°F (-10°C) P 14°F (-10°C); Storm 3: A30°F (+1.1°C), P32°F (0°C); Natural aged snow, sieved 0.04 in.; on asphalt and Concrete pavement, surface ground smooth; compressed snow at 80 psi for 5 minutes</td>
<td>• Natural snow more realistic than ice, but aged snow is different than fresh snow • Different air and pavement temperature</td>
<td>• No macro texture—lower application rates than field • Bond force not measured—just temperature when snow sheared</td>
</tr>
<tr>
<td>Bernardin et al., 1996, 1998</td>
<td>deicers anti-icing properties</td>
<td>Anti-Bonding Endurance Test, liquid runway deicers: urea-ethylen-glycol based, acetate of potassium based and FRIGOL</td>
<td>climatic chamber at 23°F (-5°C) and substrate at 26.6°F(3°C); Freezing rain; on concrete plates, molded aluminum plates, polymer concrete and an epoxy-resin coated aluminum plate.</td>
<td>• Air and pavement were at different temperature • Weight is added to scraper to simulate the action of the plow trucks in airports.</td>
<td>• Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice. • Tests not reproducible because the concrete substrate absorbs part of the deicer and some of the precipitation.</td>
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<tr>
<td>Nixon and Wei, 2003</td>
<td>Scraping resistance of</td>
<td>Deicing, Solid NaCl, solid CaCl₂, and 27.3 percent by weight liquid</td>
<td>Controlled cold room, temperatures at 30.2, Refrozen ice, atmospheric ice, and compacted snow ice; on concrete specimens prepared</td>
<td>• More realistic by using three types of ice.</td>
<td>• Only one type of pavement was tested.</td>
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<tr>
<td>Study</td>
<td>Methodology</td>
<td>Findings/Considerations</td>
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<td>Muthumani, Fay, Akin, Wang and Shi, 2011</td>
<td>Different types of ice on the pavement under different de-icing chemical application: NaCl, using an Iowa DOT concrete mix design; compressed snow under 83 psi for 10 minutes</td>
<td>• Only one deicer application rate of 1760 lbs per lane mile was considered, which is very heavy compared with usual application rate of 300–400 lbs/lane mile.</td>
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<td>McElroy et al., 1990</td>
<td>Deicers undercutting and disbondment characteristics: Deicing, CaCl₂ pellets, CaCl₂ flakes, NaCl (2 products), KCl, pelletized urea, NaCl with traces of carboxymethocellulos, mixture of NaCl with KCl and urea, mixture of NaCl and urea, and CMA. Controlled temperatures: 0, 5, 10, 15, 20, 25 °F (-17.8, -15, -12.2, -9.4, -6.7, -3.9°C)</td>
<td>Freezing chamber produced ice with surface partially melted with a metal iron; on concrete specimen according to ASTM specifications (ASTM C109-84), lightly broomed. • Each specimen accommodates two disbondment blade tests • Disbondment test was not standardized. • Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice.</td>
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<tr>
<td>Kirchner, 1992</td>
<td>Undercutting and disbondment characteristics: Deicing, pellets of equal weights of CaCl₂, NaCl, KCL, pelletized urea, CMA</td>
<td>Controlled temperatures: 0, 5, 10, 15, 20, 25 °F (-17.8, -15, -12.2, -9.4, -6.7, -3.9°C)</td>
<td>Freezing chamber produced ice, surface partially melted with a metal iron; on lightly broomed concrete slab • Only considered one type of ice, could be more realistic if consider refrozen ice, atmospheric ice, and compacted snow ice.</td>
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<td>Tazawa et al., 1992</td>
<td>Interfacial bonding between ice and asphalt concrete: Anti-icing, water repellent agents: organic polysiloxane boned with special metal; dimethyl polysiloxane; denatured polysiloxane; silicone water repellent agent; silane; fluoride contained resin; oleic acid; sorbitan ester; mixture of higher fatty acid, zinc naphthenate, polyvinyl resin ester, penetration promoter, solvent and diluents; pulverized silicone polymer; treated hydrophobic silica powder. Temperature normally tested at 9.5, 5, 0.5°F (-12.5, -15, -17.5°C), some test at 14 and -4°F (-10°C and -20°C).</td>
<td>Ice produced in a refrigerator; on asphalt concrete • Three types of tests for measurement of debonding strength • Only one type of ice is considered.</td>
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<td>Schweizer, 1998</td>
<td>Behavior of alpine snow under shear to understand slab-avalanche formation</td>
<td>Controlled cold room, temperatures at 23°F (5°C), 14°F (-10°C), and 5°F (-15°C).</td>
<td>Natural alpine snow</td>
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5. FRICTION

Friction between vehicle tires and a road surface is responsible for keeping the vehicle on the road during braking, accelerating and turning the vehicle. Friction plays even a bigger role during winter conditions when roads surface are icy. The presence of snow and ice can reduce friction to such levels that “almost any braking or sudden change of direction results in locked-wheel sliding and loss of vehicle directional stability” (27). Winter maintenance operations such as anti-icing, plowing, deicing, and sanding are aimed at restoring the pavement friction coefficient to safe levels.

The air transportation sector in the United States and some highway agencies in European and Asian countries have made significant contributions to research in the field of friction. A NCRHP project produced a guide for pavement friction (27) that comprehensively examined friction measuring equipment and briefly discussed the complications posed by the effects of winter weather and maintenance activities. A Swedish-based literature review also examined friction and its correlation to traffic safety (28). Al-Qadi et al. (29) examined the feasibility of measuring friction specifically during winter conditions to improve operations.

Measures of friction can be described in various terms such as friction coefficient ($\mu$), coefficient of static friction ($\mu_s$), coefficient of kinetic friction ($\mu_k$), etc. The International Friction Index was developed in an effort to harmonize the reporting of frictional properties of pavement surfaces—it requires measurement of pavement friction and pavement texture. The International Runway Friction Index also represents a harmonization effort and was one result of the Joint Winter Runway Friction Measurement Program that involved extensive testing of 42 different friction measuring devices (30).

The friction between a vehicle and road depends on a variety of factors (Table 3). Winter maintenance activities are focused on improving the friction, but operators have no control over the pavement, vehicle, or tire characteristics. The pavement frictional characteristics during a winter event will probably change with time based on temperature, precipitation, and level of traffic—not to mention the changes produced by plowing, anti-icing, deicing, etc. A friction measurement must be scrutinized in terms of the measuring device, the specific tire, and the specific operating conditions under which it was measured (31).

<table>
<thead>
<tr>
<th>Pavement Surface Characteristics</th>
<th>Vehicle Operating Parameters</th>
<th>Tire Properties</th>
<th>Environment</th>
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</thead>
<tbody>
<tr>
<td>• Macrotexture</td>
<td>• Slip speed</td>
<td>• Tread pattern design and condition</td>
<td>• Climate</td>
</tr>
<tr>
<td>• Microtexture</td>
<td>• vehicle speed</td>
<td>• Inflation pressure</td>
<td>• Wind</td>
</tr>
<tr>
<td>• Material properties</td>
<td>• braking action</td>
<td>• Rubber composition and hardness</td>
<td>• Temperature</td>
</tr>
<tr>
<td>• Unevenness</td>
<td>• Driving maneuver</td>
<td>• Footprint</td>
<td>• Water (rainfall, condensation)</td>
</tr>
<tr>
<td>• Temperature</td>
<td>• turning</td>
<td>• Load</td>
<td>• Snow and Ice</td>
</tr>
<tr>
<td></td>
<td>• overtaking</td>
<td>• Temperature</td>
<td>• Contaminants</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Anti-skid material (salt, sand)</td>
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<td></td>
<td></td>
<td></td>
<td>• Dirt, mud, debris</td>
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</tbody>
</table>

Note: Critical factors are shown in bold
5.1 Field Methods and Equipment Used to Measure Friction

There are several commercial options available to measure friction on roads or on airport pavements. Most devices utilize an extra wheel that is either installed on a vehicle or towed behind a vehicle. Slip speed is a critical factor in friction measurements because the friction changes as the slip speed changes. The ratio of the slip speed to the vehicle speed is the slip ratio, reported as a percentage. The critical slip ratio for dry and wet roads is usually in the range of 10 to 20 percent, but no such range can be provided for snowy or icy roads (29). The devices used for measuring friction in the field include: Stopping distance, Deceleration devices, Locked-Wheel Devices, Fixed-Slip Devices, Variable-Slip Devices and Side-Force Device. Due to space limitations, hereby we present only one working method for measuring field friction.

Deceleration Devices: A short record of deceleration with a normal vehicle for only about 2 seconds can provide a mean friction value. This is a common method for winter roads because a normal vehicle can be used, a full stop is not required, and several measurements can be taken along a stretch of road. Other advantageous include availability of a standard method (ASTM E2101), easy instrumentation for data collection (27) and better correlation to stopping distance (30). The repeatability and reliability of this type of friction measurement received mixed reviews in the literature, with Al-Qadi et al. (29) offering good reviews with sufficient training and Wallman and Astrom (28) citing low precision and high dependence on vehicle and tires.

5.2 Laboratory Methods and Equipment Used to Measure Friction

In general, techniques and equipment used to measure friction in the laboratory tend to look and operate much differently than devices used in the field. While some standardized equipment is available, several friction measuring devices have been custom designed and built for specific research projects. Simple devices usually include a metal block with a rubber pad on the bottom that is pulled across the surface. The ratio of the force needed to pull the block (initiate movement) divided by the weight of the block is the coefficient of static friction. The devices used for measuring friction in the laboratory include: Drag Sled, In Road Friction Sensor, Scraper and Friction System, Simple Skid Friction Measurement Device, and Bench-top Tribometer. Portable methods that can be used in the laboratory and field include: British Pendulum Tester, Handheld Tribometer, and Dynamic Friction Tester. Table 4 provides information about laboratory tests that used friction as the performance measure—there are relatively few cases when compared to the higher use of ice melting, ice penetration, and shear tests. Below is the working method of one of the laboratory testing friction measuring device (due to space constrain all other devices are not discussed in this section).

Scraper and Friction System: The Anti-icing Materials International Laboratory (AMIL) at the University of Quebec at Chicoutimi designed and built a Scraper and Friction System (SFS) to research deicing and anti-icing of runway pavements. A pavement surface is exposed to freezing rain and then plowed with the scraper. The scraper is then removed and the friction coefficient measurement block is installed. The bottom of the metal block has a 0.2-in-thick rubber pad supplied by NASA that conforms to ASTM E501. The scraper and friction block are pulled very slowly at 0.016 mph, which is less than 0.3 feet per second (24).
6. PREVIOUS CORRELATION OF LABORATORY AND FIELD DATA

Many laboratory tests have been conducted to assess performance of deicers, some of which mimic field conditions better than others. However, correlations between laboratory performance and field performance are not addressed in most of the studies that were reviewed and only a few studies were found that involved both laboratory and field tests. There is good reason to believe that many existing laboratory tests do not accurately predict field performance, as illustrated recently by Alatyppö and Jutila (32). Alatyppö and Jutila (32) reported on the relative performance of a new airfield deicer (50 percent betaine solution) to two reference deicers (50 percent potassium formate solution and solid NaCl) in laboratory and field tests. Three laboratory tests were performed: SHRP H-205.1 (SHRP Ice Melting Test), SHRP H-205.3 (SHRP Ice Penetration Test), and a new test that combines these two. The laboratory tests showed that potassium formate had twice as much deicing efficiency as betaine (trimethyl glycine, manufactured in Finland by Danisco Animal Nutrition), and sodium chloride had twice as much efficiency as potassium formate. Thus, from the laboratory tests conducted at 21 and 28°F (-6.1 and -2.2°C), it appeared that betaine was not going to be an effective deicer.

Regardless, field tests on a runway were undertaken using betaine and potassium formate (NaCl is not used on runways and was not included in the field test). Two performance measures were used: ice thickness and runway friction. In both cases, betaine and potassium formate performed very similarly and better than predicted from results in the laboratory—“i.e., the results of the field tests correlate in no way with the results obtained from the laboratory tests” (32).

Operational use of betaine at two airports since 2005 and a third since 2007 has shown betaine to be an effective and efficient deicer. This stresses the need for more realistic laboratory tests and correlation factors that can be used to predict field performance.

7. INTERVIEW RESPONSES

Key individuals were identified and interviewed to gain their insights on their areas of expertise. Information sought in the interview process included, but was not limited to, lessons learned from laboratory and field research, project costs, equipment design and cost, etc. Provided below are brief summaries of some of the interviews conducted.

8.1 Laboratory and Field Tests to Characterize Deicer Performance

Charlie Pizino works for the Midwest Research Institute (MRI) and he did not think that the SHRP tests can directly correlate with field tests, but did state that the laboratory tests may provide some guidance in developing and interpreting field tests. He suggested one way to get close to this would be a gradual scale up- starting with laboratory research, followed by research conducted outside on a sidewalk, then a parking lot, and finally on a street section. In his opinion, it is possible to quantify the identified parameters, at least in a relative way, but it is impossible to design one laboratory test that will be able to test for all of the parameters. This is also true for a field test. Jim McGraw and Allen Gallistel work for MnDOT and conduct the laboratory testing on deicing/anti-icing products. MnDOT uses the SHRP ice melting capacity test method to initially evaluate products (they use it as screening tool) such as rejecting very poor deicers during laboratory testing. They suggest that one route for field testing would be to
survey the drivers while using a specific chemical, measure the times, and collect the data and then try and correlate this with the laboratory data.

Wilf Nixon of the University of Iowa has extensive experience conducting laboratory and field research on deicers. When asked if laboratory and field data collected for deicer performance could be correlated he replied with a qualified yes, and suggested that the tests can tell you something about how chemicals perform, but went on to say that the definition of performance is important. Regarding his experience with scraping tests in the laboratory, he said low scraping speeds were not realistic and highly variable compared to actual plowing speeds. He is skeptical that one test can be developed to adequately test all parameters/variables to predict field performance. For field testing he recommends having two ways to measure each parameter. Arlene Beisswenger of the Anti-Icing Materials International Laboratory (AMIL) at the University of Quebec at Chicoutimi was involved in the development and testing of airport pavement anti-icers. Overall, she cautions that laboratory test results will not match field tests due to scaling effects. Instead, she says laboratory tests are better for comparison testing, unless you specifically look at the relationship between laboratory and field testing.

8.2 Friction

Tim Leggett and Gerald Sdoutz of Forensic Dynamics, Inc (FDi) routinely conduct friction tests on pavement treated with anti-icers. Their drag sled device works well for wet or icy conditions, but they haven’t used it on snow or slush, which they think would just be plowed from the surface by the locked tire. FDi had a few other suggestions for new friction testers that can simulate traffic and measure friction, equipment that can be used in a large laboratory and in the field for better correlations. Max Perchanok of the Ontario Ministry of Transportation (MTO) has participated in several winter projects that involved friction measurements. MTO has three different friction trailers: a Traction Watcher One, a SCRIM, and a Halliday RT3. His suggestion is to mimic all the relevant parameters (sunlight, humidity, temperature, traffic, etc.) in order to predict how a deicer will react in the field. Video cameras are very useful for field testing. Tom Yager of NASA Langley Research Center was involved in the Joint Winter Runway Friction Program that produced the International Runway Friction Index (IRFI). Regarding laboratory testing, Mr. Yager recommended to look into the Dynamic Friction Tester because it gives friction readings over a wide range in speeds and can be used in the laboratory and field. It can be used on dry and wet pavement, but its reliability on snow or ice is uncertain.

8. RECOMMENDATIONS

A four-step approach is recommended for developing a laboratory test method that aims to correlate deicer performance in the laboratory with field performance, as shown in Figure 2. The key parameters to be tested need to be identified and agreed upon prior to the design of the experiments. The first recommendation is that the laboratory and field test methods be designed at the same time so that the statistical analysis for correlating the laboratory and field data is planned and key hypotheses are identified before any experimental testing begins. The next recommendation is to use a statistical design of experiments (e.g., uniform design or factorial design schemes) to minimize the number of experiments needed to explore a large unknown domain of factors that affect deicer performance and friction coefficient of treated pavement and to capture their complex interactions.
Figure 2. Recommended approach for developing a laboratory test method that could correlate with field deicer performance.

9.1 Identified Testing Parameters

There are many potential parameters that could be important to consider in laboratory and field testing of deicer performance. The key parameters for consideration are:

- Temperature—air and pavement
- Relative humidity
- Traffic
- Pavement type—asphalt and concrete
- Melting rate of deicers
- Uniformity of Snow/Ice

To quantify the identified parameters the following sections provide recommendations on test methods that can be used in the laboratory.

Air temperature and relative humidity can be controlled and monitored using an environmental or cold chamber. Pavement temperature can be controlled independent of air.
temperature using a heating/cooling table. Temperature sensors will need to be embedded in all pavement samples for accurate pavement temperature readings.

Traffic presents a more difficult parameter to bring into the laboratory. Only one case of trafficking in the laboratory was found while reviewing literature (33) and one can argue that it only minimally simulated traffic considering the following: 1) the speed was slow—it was manually operated; 2) only a single tire was used, and 3) it was applied in a back-and-forth motion. Regardless, the research results indicated traffic is important and it seems appropriate to include some level of traffic simulation in this new laboratory experiment. A motorized system will most likely better simulate traffic than a manually pushed system.

The two most common pavement types are asphalt and concrete, and it is recommended to conduct testing on both types in the laboratory and field. Once the laboratory experiment is designed, built, and validated, ongoing testing using more specific pavement substrates can be conducted. For instance, samples could be removed from actual roads and used in the laboratory test. This will allow testing on open-graded asphalt, dense-graded asphalt, tined concrete, old rough concrete, etc.

Melting rate of the deicers can be determined using the SHRP Ice Melting Test (H-205.1 and H-205.2) and/or the DSC. Previous work by Akin and Shi (8) found that results from a modified SHRP Ice Melting Test correlate well with DSC results. Using one or both methods would provide the necessary information for correlating laboratory and field deicer performance. The DSC is preferred because it provides the characteristic temperature of the deicer in addition to ice melting capacity. The characteristic temperature is the warmest temperature at which ice crystals begin to form in the presence of each deicer.

Uniformity of snow/ice on pavement surfaces may be difficult to achieve but is very important when comparing samples. Field testing of tire performance conducted in New Zealand required uniform winter driving conditions to be created in the field and was achieved using snow grooming equipment (personal communication with Dr. Jordy Hendrix, NIWA). The SHRP Handbook provides a method on how to make uniform ice on a concrete mortar surface for the ice undercutting test. It is strongly recommended to take the time to develop a standard method of creating a uniform snow/ice surface prior to laboratory testing. Additionally, testing should initially be conducted using fresh snow and aged snow to determine whether the changes that snow undergoes during storage are significant.

The key testing parameters need to be identified and agreed upon prior to the design of the experiments. It is recommended that the laboratory and field test methods be designed at the same time so that the statistical analysis for correlating the laboratory and field data is planned and key hypotheses are identified before any experimental testing begins. It may be necessary to use a statistical design of experiments (e.g., uniform design or factorial design schemes) to minimize the number of experiments needed to explore a large unknown domain of factors that affect deicer performance and friction coefficient of treated pavement and to capture their complex interactions.
9.2 Identified Laboratory and Field Test Methods

It is recommended to conduct laboratory testing in a cold room or environmental chamber of sufficient size to contain large equipment and be able to measure and control air and pavement temperatures, humidity, wind, and solar radiation at a minimum. For evaluation of anti-icer performance, it is recommended to incorporate a plowing mechanism into the laboratory test to better simulate the field operations. The knowledge gained from this work (particularly the scraping tests) should be utilized to design such a plowing mechanism and possibly the sensing of plowing force in both the laboratory and field tests.

At least two devices have been identified to be potentially useful for measuring friction: the Dynamic Friction Tester (ASTM E 1911) and the Vaisala Remote Road Surface State Sensor (DSC111). The Dynamic Friction Tester was selected based on recommendations from use in the field and the small required pavement surface area for testing, which will allow for testing in the laboratory and field using the same piece of equipment. This will also allow for direct correlations to be made between laboratory and field friction coefficient data collected. The small size will also allow several friction tests to be taken over the test surface. While several interviewees mentioned this device would be worth trying, little has been reported about its use on roads during winter conditions; so preliminary testing should be performed on loose snow, compacted snow, ice, slush, etc. The DSC111 is a non-contact device that provides a measurement of grip based on a spectroscopic analysis of the road surface. This device can be used in the laboratory and field to provide direct correlation between the two environments. Because of the pervasiveness of friction trailers used in the field, it would be beneficial if one can also be used in the laboratory to provide a more spatially continuous measure of friction coefficient. However, the smaller space generally available in a laboratory could be a barrier. None of the interviewees, despite their extensive experience, were able to firmly recommend a friction trailer that would be appropriate for use in the laboratory. It is recommended that a mathematical method for handling noisy data and for mining the friction data be determined prior to the start of any friction testing.

It is recommended to conduct field testing for deicer performance in a controlled field environment so that the number of variables can be reduced and as much control as possible can be applied to the existing conditions. The field testing location should have both concrete and asphalt pavement surfaces, RWIS or the equivalent ability to monitor meteorological parameters, pavement temperature sensors (for both pavement types), the ability to create a uniform snow/ice surface, and traffic the snow/ice pavement surface.

9. CONCLUDING REMARKS

The literature review identified test methods that have been used to quantify deicer performance and friction in the laboratory and field. Based on information gained from the literature review and interviews, the following recommendations are provided for developing a laboratory test method that quantifies deicer/anti-icer performance and correlates with field performance.

The parameters identified as being important to evaluate include: air and pavement temperature, humidity, traffic, pavement type (asphalt and concrete), melting rate of deicers, and uniformity of snow/ice. While most of these parameters can be easily monitored in the laboratory and field, trafficking samples in the laboratory and creating uniform snow/ice in the laboratory and field will be the most difficult to simulate.
Recommendations for laboratory testing include using an environmental chamber that can control and monitor air temperature, humidity, air speed and solar radiation. For evaluation of anti-icer performance, it is necessary to incorporate a plowing mechanism into the laboratory test to better simulate the field operations. Two friction-measuring devices were recommended that can be used in both the laboratory and field: the Dynamic Friction Tester and the Vaisala Remote Road Surface State Sensor (DSC111). In addition, it may be preferable to use a friction trailer if the necessary laboratory space can be obtained. For field testing, it is preferable to conduct the research in a controlled field environment.

ACKNOWLEDGEMENTS
The researchers thank the Wisconsin Department of Transportation and Clear Roads program for the funding support. They also thank the personnel who participated in the interviews. Finally, the authors would like to thank Dan Williams for his assistance in the review of the report.
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