Evaluation of Different Winter Road Conditions and Effectiveness of Winter Road Maintenance Operations

by

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Abstract

This study uses friction measurements of Real Time Traction Tool (RT3)-Curve to characterize different road conditions, evaluate the effect of winter maintenance operations, and identify influential parameters.

The reliability of RT3-Curve device was verified by a speed-dependency analysis. Evaluation of different road conditions showed that ice and snow reduced the dry surface friction considerably and friction decreased as more snow was accumulated. More traffic passes cause ice and moderate-to-heavy snow to become more slippery, while it causes higher friction over light snow.

Analysis of winter maintenance operations showed that plowing may not be beneficial for ice, but it is the critical operation for snow. Low sanding did not necessarily improve friction; however, medium and high sanding considerably increased friction over ice and snow. A regression analysis revealed that sand/salt quickly scatters off dry and icy roads due to high-speed traffic; however, salt was immediately effective for snow.

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List of Symbols and Abbreviations

μ	Friction Coefficient
Δt	Stopping Time
a	acceleration/deceleration
ABS	Anti-lock Braking System
AC	Asphalt Concrete
ASTM	American Society for Testing and Materials
BP, BPT	British Pendulum Tester
BPN	British Pendulum Number
CFT	Continuous Friction Tester
CIV	CRREL's Instrumented Vehicle
CRREL	Cold Regions Research and Engineering Laboratory
D	Stopping Distance
ERT	Etching and Replicating Technique
EWMC	Edmonton Waste Management Center
F	Friction Force
F_y	Side Friction Force
F_z	Normal Force
FS	Fresh Snow
g	Gravitational Acceleration (= 9.81 m/s2)

GEM	Grip Evaluation and Management
GPS	Global Positioning System
HFN	Halliday Friction Number
HMA	Hot Mix Asphalt
IRFI	International Runway Friction Index
IRRF	Integrated Road Research Facility
JWRFMP	Joint Winter Runway Friction Measurement Program
L_x, L_c	Side Friction Coefficient
LWFT	Locked-Wheel Friction Tester
m	Mass
MnDOT	Minnesota Department of Transportation
MTO	Ministry of Transportation of Ontario
N	Normal Force
NAC	Neunert Aero Corporation
NASA	National Aeronautics and Space Administration
PDO	Property Damage Only
PS	Packed Snow
RT3	Real Time Traction Tool
S	Slip Angle
SARSYS	Scandinavian Airport and Road System
SCRIM	Sideway-force Coefficient Routine Investigation Machine

SD	Standard Deviation
SR	Slip Ratio
STT	Speed × Traffic × Time
TWO	Traction Watcher One
U-G	Uniroyal-Goodrich
V	Vehicle Speed
V_1	Initial Vehicle Speed When Braking is Initiated
V_2	Vehicle Speed at Full Stop (=0 m/s)
V_W	Auxiliary Wheel Speed
VIF	Variance Inflation Factor
WS	Wet Snow
X	Parameter X, combination of time, traffic, and speed

1. Chapter 1: Introduction

1.1. Background

Annual collision reports published by municipalities and transportation agencies in cold regions show that slippery road conditions due to ice or snow contaminated roads during the winter result in higher number of collisions. For example, Figures 1-1, 1-2, and 1-3 show the number of collisions (both injury/fatality and property damage) in Edmonton, Alberta, in different months of 2010, 2011, and 2012, respectively (City of Edmonton 2011; City of Edmonton 2012; City of Edmonton 2013a). All three figures show that the total number of collisions increases during winter months (November to March). Further, in cold regions, such as many Canadian cities the winter is prolonged; therefore, city streets are prone to unsafe driving conditions and high number of collisions during a great portion of the year.

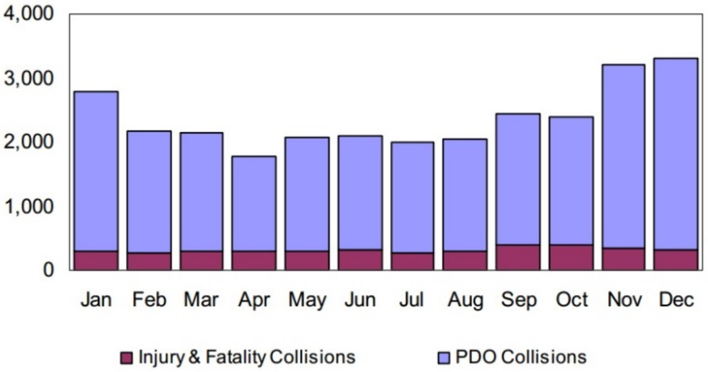


Figure 1-1. Number of fatal and injury collisions (Y axis) and property damage only (PDO) collisions per month in Edmonton in 2010 (City of Edmonton 2011).

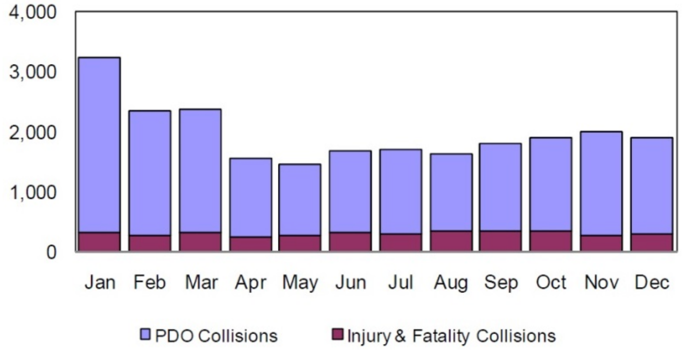


Figure 1-2. Number of fatal and injury collisions (Y axis) and property damage only (PDO) collisions per month in Edmonton in 2011 (City of Edmonton 2012).

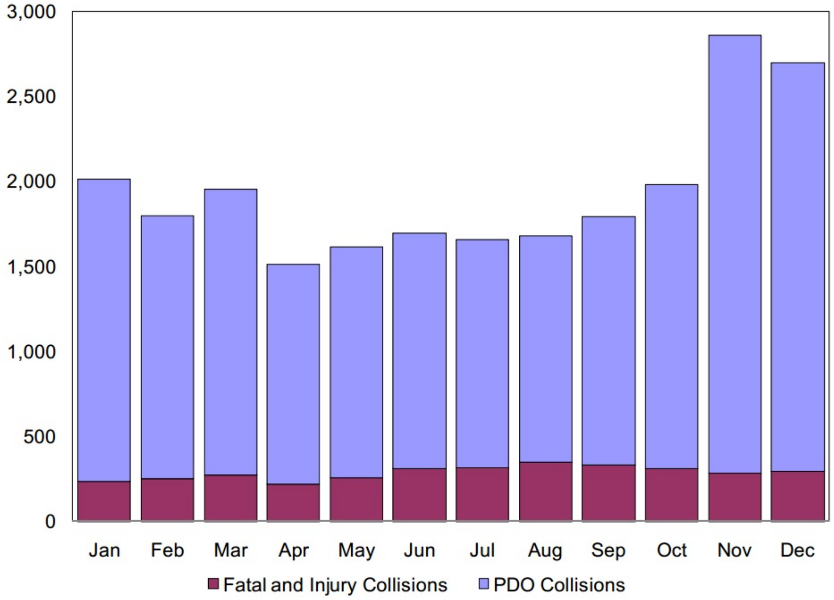


Figure 1-3. Number of fatal and injury collisions (Y axis) and property damage only (PDO) collisions per month in Edmonton in 2012 (City of Edmonton 2013).

Municipalities and transportation agencies in Canada perform various road winter maintenance operations. The most common winter maintenance operations are described as follows. De-icing mixtures are proactively applied to clear roads prior to forecasted storms in order to prevent the ice/snow from bonding to the road surface (C-SHRP 2000). During or after snowstorms, plowing operations are conducted to clear the snow from roads. Different municipalities have developed policies and guidelines to retain safe driving conditions to streets and highways based on prioritized plans. Specific criteria in terms of snow accumulation are in place for the winter maintenance crew on when to start the plowing operations. For example, the Cities of Edmonton, Winnipeg, and Montreal start plowing when 2.5-3 cm of snow has accumulated on the road, while the Cities of Calgary and Regina start plowing after 5 cm of snow accumulation; Cities of Ottawa, Toronto, and Saskatoon do not have a specific criterion and start plowing when the accumulation begins (2.5-8 cm). Comparing the ice and snow control policies in major Canadian cities revealed that metropolitan cities with larger road and highway network and population, such as Toronto, Ottawa, and Montreal are obligated to clear arterial routes to bare pavement condition in a short period of time after the snowstorm (two-three, two, and eight hours after the end of the snowstorm, respectively); however, cities smaller in size and population – such as Edmonton, Calgary, and Winnipeg – follow more flexible timetables allowing for 24-36 hours after the storm to achieve bare pavement surfaces. Another difference observation is the availability of storage areas along the streets and highways, in cities with heavy traffic and compact street network the city must plow, collect transport the plowed snow to storage/demolition plants, while other cities with multi-lane streets, boulevards, and streets with side ditches or side lanes reserved for plowed snow storage can leave the snow windrows along the streets (City of Toronto 2004; City of Calgary 2009; City of Edmonton 2010; City of Edmonton 2013b; City of Montreal 2013; City of Ottawa 2013a; City of Ottawa 2013b; City of Regina 2013; City of Saskatoon 2013; City of Toronto 2013; City of Winnipeg 2013; Nassiri *et al.* 2013).

Moreover, abrasive mixtures are applied to the road surface to bring temporary traction to slippery roads. The mixtures are comprised of common sand or rock chips as abrasives, mixed with salt or other de-icers. In recent sanding methods, the mixture is pre-wetted with brine or other de-icing chemicals and/or is heated prior to application. For instance, the City of Edmonton applies 412 kg/pass/km abrasive mixture pre-wetted with Calcium Chloride. This mixture is applied to intersections, hills, and corners (City of Edmonton 2010). It should be noted that the effectiveness of salt or brine highly depends on the ambient temperature. Salt becomes ineffective at temperatures below -18°C (Nixon et al. 2005; Goulden and Stuart 2009). That is why the abrasive mixture in cold cities mainly comprises sand and rock chips with small proportions of salt added based on the ambient temperature to keep the stockpiles from clumping. Edmonton and Winnipeg are examples of such cold cities with average annual temperatures of 2.4 and 2.6°C. On the other hand, warmer cities such as Ottawa and Toronto, with average annual temperatures of 6 and 7.5°C, mainly rely on salt and chemical de-icers to melt the ice and snow (Dunford and Haug 2007; City of Edmonton 2009; City of Toronto 2010; City of Winnipeg 2011; City of Ottawa 2013c; City of Ottawa 2013d).

Despite detailed and pre-approved municipal ice and snow control policies, the majority of winter maintenance policies depend on network size, ambient temperature, annual snowfall, available budget, and past experience instead of the actual physical condition of roads. Critical decisions regarding the amount and time of sanding are mainly made based on past experience and rules of thumb as described previously. Effective winter maintenance operations to retain safe driving conditions to city streets in a timely manner, and meet the public demand and satisfaction is the number one goal of municipalities and highway agencies during winter months. On the other hand, the negative social, aesthetic and environmental impacts of sanding and salting have become more and more evident in recent studies (Ramakrishna and Viraraghavan 2005; Nixon 2007). All of these factors have encouraged researchers to better understand the rubber tire and the road surface friction behaviour under winter conditions. Researchers have focused on evaluating different road conditions and the corresponding appropriate maintenance operation via performing laboratory and field experiments. The need for further research in this area is further discussed in details in the following section.

1.2. Research Impetus

In cold regions, a great portion of municipalities' annual budget is spent on winter maintenance operations to provide safe driving conditions throughout the winter. For instance, the winter road maintenance budget of the Cities of Edmonton, Winnipeg, and Montreal was $49 million (in 2008), $30 million (in 2012), and $145 million (in 2012), respectively (City of Edmonton 2009; City of Winnipeg 2011; Ville de Montreal 2014). This budget is used to cover the costs of plowing, sanding, snow removal, clearing sidewalks, and running snow storage sites. Yet, in some areas the quality of these operations is criticized by the public and experts, challenging the municipalities in satisfactorily meeting the public demand (CBC News 2014; Edmonton Sun 2014).

In addition to high costs, environmental impacts of winter operations include consuming unrenewable gravel and sand resources, also the amount of sand and salt applied to streets and highways. Sand, salt or other de-icing chemicals are carried by ice and snow melt-water into the surface runoff sewage pipeline system. Fines build up in pipes, clog and damage them. Also, Chloride, the main component of salt and other common de-icing chemicals, can cause corrosion in pipes. The salt and anti-icing chemicals can also infiltrate into the soil, stress and deteriorate roadside plants and vegetation, and seep into the underground water tables. When the chemicals enter running waters (surface or underground) they disperse rapidly, thus their future impact can extend to vegetation, land and aquatic habitants (Davis 2004; Ramakrishna and Viraraghavan 2005; Nixon 2007; Trahan and Peterson 2008; Betts *et al*. 2012).

Residual abrasives remain on the road well after the winter season, and bring discomfort to drivers and cyclists. Salt can accelerate vehicles' corrosion and sand can damage vehicles' bodies and break windshields. Residual abrasives also negatively impact cities' aesthetics.

The negative economic, environmental and social impacts of sanding and salting have been the motive for many researchers to evaluate the extent of the imposed pollution. Based on these studies, some countries – such as New Zealand and

Sweden, and some states in the United States such as Massachusetts and Minnesota have prohibited the usage of abrasive mixtures and/or have outlawed the use of de-icing chemicals. In addition, some studies have identified new methods or new materials – such as Safecote and IceBan Ultra M – that do not have negative impact on the environment; but they are not widely used yet (Burtwell 2004; Luker *et al.* 2004).

These moves have encouraged researchers in the area of Transportation Engineering to investigate winter maintenance operations in greater details in order to develop effective and optimized methods of clearing snow from the roads and providing traction.

Currently, decisions regarding winter road maintenance operations are made empirically and through visual observations of the snowplow operators, or based on pre-determined policies (Goulden 2011). This method of decision making is subjective and can be affected by the individual's experience and also the visibility conditions (Alqadi et al. 2002). No quantitative or objective measurement of the road physical condition is made before or after the treatments. The investigation of potential use of road friction as a road condition indicator first started with a great focus on runways safety during the winter in the 1970s (Nixon 1998; Al-Qadi *et al.* 2002). Several studies focused on better understanding the frictional interaction between the vehicles' tires and the road surface under winter conditions. A complete review of these studies is provided in Chapter 2. Due to the complexity of the road surface friction behaviour under different winter conditions and the numerous influential parameters on friction (such as the mechanism of friction measurement, ambient and surface temperatures, tire properties, winter contamination characteristics, and speed), past studies are only comparable to a certain extent. In addition, the number of studies that have focused on the influence of winter maintenance operations on road surface friction is very limited. The existing road friction measurement studies have used different types of devices, which function based on different mechanisms of measurement, and thereby their measurements can significantly differ from one to another. For instance, decelerometers have commonly been used to characterize surface friction; however, their measurements (vehicle's deceleration and stopping distance during braking) are heavily influenced by the Anti-lock Braking System (ABS) for different winter contaminations. Only a few studies have validated the accuracy of their measurements using different devices (Shoop 1993; Andrle *et al.* 2002; Hahn *et al.* 2002; Tokunaga *et al.* 2013).

In light of the discussion above, there is a need for controlled experiments that use reliable equipment, conducted on a variety of winter road conditions. Such an experiment should include different winter maintenance operations to evaluate their effectiveness and identify the influential parameters.

The current study aims the first steps towards optimization of winter road maintenance practices for winter road conditions. The research project, sponsored by the City of Edmonton, started with a comprehensive literature review upon existing ice/snow control policies in Canadian cities and various types of friction measurement devices. Surface friction is directly related to the driving condition and safety; thus friction measurements have long been used to enhance the airport runways' safety throughout winter season, but their application for winter maintenance purposes is still in the research phase. Previously-conducted studies that utilized friction measurements to evaluate winter road conditions were reviewed, and the devices that were used were compared. As a result, Real-Time Traction Tool (RT3)-Curve device was proposed to be purchased by the City of Edmonton, as its reliability was verified in several studies.

A series of controlled field experiments were then conducted on the University of Alberta's Integrated Road Research Facility (IRRF)'s test road under different winter conditions. The reliability and repeatability of the road friction measurement device is first established in the study. The study then focuses on each winter road condition and its influential variables in order to provide a better vision of the surface behaviour. In the next step, the effect of plowing and sand-salting on enhancing the road surface friction under ice, and different snow accumulations is investigated, and the parameters that potentially influence the result of these operations are analyzed.

1.3. Objectives

As discussed previously, the significance of road winter maintenance operations in cold regions necessitates a controlled field experiment to investigate the road surface friction under different wintery road conditions, and also evaluate the effectiveness of common winter maintenance operations on each condition. The ultimate goal of such studies is to assist transportation agencies to improve and optimize their winter maintenance actions and enhance the previously-discussed criteria in their policies. The main objectives of the current study can be summarized as follows:

- To investigate the reliability of road surface friction measurements using the Halliday Technologies' Real-Time Traction Tool (RT3)-Curve to identify various wintery conditions;

- To identify the influential variables, ambient conditions, and traffic pass, on friction behaviour of the winter contaminated surfaces; and

- To evaluate the effectiveness of common winter maintenance operations, plowing and sanding, on different wintery road conditions using road friction measurements.

1.4. Methodology

As part of a multi-phase research project, sponsored by the City of Edmonton, a broad literature review was conducted on tire-road friction behaviour and the potential use of friction measurements to quantitatively capture various winter road conditions. Further, different types of friction measurement devices and the results of laboratory and field experiments were reviewed to suggest the most appropriate device for use by the City of Edmonton.

In the next phase of the project, a relatively new friction measurement device, RT3-Curve, designed and manufactured by Halliday Technologies was proposed to be purchased and evaluated through controlled field experiments in Edmonton, Alberta. Friction measurements were conducted using this device, purchased by the City of Edmonton, on the University of Alberta's IRRF's test road. The Asphalt Concrete (AC) test road is located northeast of Edmonton, Alberta, and is the access road to Edmonton Waste Management Centre (EWMC). The test road was closed to traffic during the entire experiment season, providing controlled test conditions.

During the six test events conducted in winter 2012-2013, different road conditions including bare dry, dry with ice patches, ice, light, moderate, and heavily snow-covered surfaces were tested using the RT3-Curve. The collected data was then analyzed for each condition; and based on the recorded videos, photographs, and operator's notes, the sensitivity of the RT3-Curve to changes in road condition was investigated. Also, statistical parameters (minimum and maximum, first and third quartile, and average) friction values were established and compared for each condition. The effect of the number of passes of the test truck on ice and snow was also investigated for each lane for each condition.

On two of the test events, a snowplow and sand spreader truck was provided by the City of Edmonton stocked with the City's commonly used abrasive mixture. During these two events, first, measurements were made on the existing road conditions, followed by friction measurements performed after plowing and subsequently three levels of sanding. The entire data were analyzed to compare the operations' effectiveness in improving the surface friction. During the analysis, it was found that time, traffic pass, and traffic speed affect the surface friction. Since the extent of their effects could not be established independently, a regression analysis was conducted using a new parameter (*STT*) combining the three mentioned variables. The significance of *STT* in affecting the level of friction for each winter condition is discussed in detail.

1.5. Thesis Structure

This thesis is presented in the following organization:

- Chapter 1 – Introduction: In this chapter, a brief background on road winter maintenance operations and their significance in cold regions was provided. The main challenges associated with current practices that necessitate more comprehensive investigations were discussed. The objectives, methodology, and organization of the thesis were also described.

- Chapter 2 – Literature Review: In this chapter, information related to the application of friction measurements for winter maintenance purposes is discussed. Various types of friction measurement technologies are introduced, and the chapter continues with reviewing past studies that focused on winter surface friction measurements, and evaluating maintenance operations.

- Chapter 3 – Characterizing Driving Conditions for Various Winter Road Conditions Using Lateral Coefficient of Friction: In this chapter, the experiments performed on various wintery road conditions using the RT3-Curve are described. The collected data are analyzed to first, evaluate the device's sensitivity to changes in road surface condition, and second, to investigate the surface behaviour under different road condition. The effect of number of traffic passes on each condition's friction is also investigated.

- Chapter 4 – Using Lateral Coefficient of Friction to Evaluate Effectiveness of Plowing and Sanding Operations: In this chapter RT3-Curve measurements on the test road that were conducted after common maintenance operations on wintery road conditions are used to investigate the effectiveness of winter operations. These operations included plowing and applying three levels of low (100 kg/one-lane km), medium (250 kg/one-lane km) and high (420 kg/one-lane km) sand-salt mixture. After investigating the effectiveness of each operation, the effect of time since the application, traffic, and speed on friction is investigated through a multi-linear regression analysis.

- Chapter 5 – Conclusions: In this chapter, the research approach and the findings of the experiments are summarized. The findings of the experiments are highlighted and further topics are proposed for future research.

2. Chapter 2: Literature Review

2.1. Friction and Tire-Road Behaviour

Friction forces generate in any system that consist of a contact area between two objects. In a tire-road contact area friction occurs to resist the movement of the tire on the road, and this is a necessity for safe driving; otherwise, the tires continue to roll and will never stop. Dry pavements usually create enough traction for treaded tires; however, when the surface is contaminated with water, ice or snow, friction drops significantly. With less friction, the driver can lose control when stopping the vehicle (braking), collide with other vehicles, obstacles along the road, or slip into ditches. Basic laws of Physics state that the friction force (F) develops due to the normal force (N) applied onto the object from the surface, and the coefficient of friction (μ) of the surface is calculated using Equation 2-1 (Flintsch *et al.* 2012; Halliday *et al.* 2013).

$$\mu = \frac{F}{N} \qquad \textbf{Equation 2-1}$$

The amount of tire-road friction coefficient generally depends on four categories of variables (Al-Qadi *et al.* 2002; Shahin 2005):

- Tire Properties: Rubber composition, tire type (summer, winter, all-season tires), tire inflation pressure, and tire tread depth;
- Vehicle Properties: Speed, axle and tire load, braking system (including or the lack of ABS), and other factors;
- Surface Condition: 1. Surface micro- and macro-texture; 2. Winter contamination: wet, ice-covered (and ice type), snow accumulation (fresh snow, compacted snow, slush), sanded/salted surface;
- Environmental Variables: Ambient/surface temperature, relative humidity, dew point, wind speed.

Friction forces generally comprise of two major components: adhesion and hysteresis loss. Adhesion forces occur due to Van der Waals bonds between the tire rubber molecules and the pavement molecules, when they contact during driving. Although this interlock is weak and diminishes as the tire rolls, the adhesive force that resists the interlock break-down is a portion of the friction force (Ella *et al.* 2013). Adhesion is usually the dominant component of friction forces for bare and dry pavements.

The other portion of the friction forces is the deformation of tire rubber when rolling over the surface. While rolling, the rubber tire slightly flattens in the contact area, and also adjusts to the pavement roughness and irregularities. However, while rolling and unloading, relaxing does not occur fully and immediately because the rubber is a viscoelastic material. This continuous deformation and partial-relaxation result in some energy loss, namely the hysteresis loss, which is released in the form of heat. On a winter-contaminated pavement surface, the adhesion forces between the tire and the pavement are minimal and thereby the hysteresis loss is the main source of friction (Bowden and Tabor 1966; Klamp 1977; Persson 2000). In the winter, the tire and the pavement are both cold and therefore act more as solid elastic than viscoelastic and thus deform less and hence less friction is available. It is because of this phenomenon that winter tires are used in the winter. Winter tires are made of special rubber composition to allow for the rubber to remain as soft as possible even during winter's low temperatures (Walus and Olszewski 2011).

Different mechanisms occur in tire-ice and tire-snow (different accumulations) contact areas. The tire-road friction behaviour under these two types of winter conditions is very complicated. In this section, only a brief discussion on this topic is provided.

A common belief is that ice is the most dangerous surface for driving; however, this is not always the case. Tire-ice friction depends on the ice texture and the ice temperature. Friction is minimum on a smooth, shiny, and clean ice, but a rough and snow-contaminated ice provides better traction. In a microstructural study using etching and replicating technique (ERT), it was observed that the deformations caused in a rubber-ice contact area are mostly dislodging of the ice crystals and forming cracks in the ice surface. Small plowing tracks were also observed and were believed to be caused by small external particles such as dust on the ice surface (Klein-Paste and Sinha 2010b). Also, laboratory experiments have shown that at melting temperatures (-5 to 0°C), a thin film of melting water is formed under the moving wheel – due to the heat generated from hysteresis loss – which lubricates the ice surface and causes a more slippery surface, resulting in a significant drop in friction (Roberts 1981; Kietzig *et al.* 2010; Klein-Paste and Sinha 2010a; Klein-Paste and Sinha 2010b). On the other hand, at temperatures lower than -5°C, ice and rubber both act as solid elastic, thus more adhesion occurs in their contact area, resulting in greater friction (Roberts 1981; Klein-Paste and Sinha 2010a; Klein-Paste and Sinha 2010b).

Unlike the tire-ice condition, tire-snow has not been studied broadly, this is partially because controlled testing and simulation is not easily achieved for snow. Several external variables have found to be affecting the tire-snow friction including snow crystal type, temperature, snow density, liquid water content in snow, depth of accumulation, and traffic pass (Colbeck 1988).

There are three different mechanisms that affect tire-snow friction (in terms of either increasing or decreasing):

1. Plowing: In a solid-to-solid interaction, the tire treads plow a thin layer of the snow. This phenomenon mostly occurs when using winter tires, because this type of tires has special cuts in the treads (namely, sipes) which dig into the snow. The force initiated due to compressing and moving the snow helps the friction force in the tire-snow contact area (Nakajima 2003; Ella *et al.* 2013).

2. Melt water lubrication: Similar to ice, melt water is produced either due to ambient melting temperature, or as a result of the hysteresis loss of the moving wheel; additionally, moisture can come from snow itself, if there

is great liquid water content in the snow. The thin film of melt water lubricates the tire-snow contact area, and creates a more slippery surface (Nakajima 2003; Ella *et al.* 2013).

3. Capillary drag: When a thick layer of excessive melt water exists on top of the snow layer, capillary action drags the water into the tire treads. The force generated to resist this capillary action adds up to the total friction force (Colbeck 1992; Colbeck 1994).

All three mechanisms occur in snow in accordance to the thickness of existing film of water, as seen in Figure 2-1.

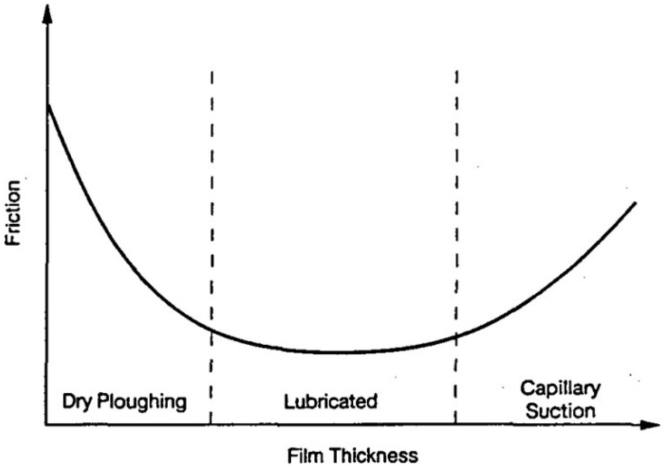


Figure 2-1. Effect of three mechanisms of plowing, melt water lubrication, and capillary drag on friction, and their occurrence possibility based on water film thickness (after Colbeck 1994).

Therefore, the dominance of each mechanism on friction value highly depends on speed, temperature, and contact area conditions. When driving at higher speeds, more melt water is produced, thus lubrication governs the friction value; whereas at lower speeds plowing is the main mechanism. Also, plowing, melt water lubrication and capillary drag are the dominant mechanism creating friction at low, medium and high temperatures, respectively (Colbeck 1992).

The early friction measurement studies focused on improving accident simulations, car racing, ski and sporting goods design, and runway safety and maintenance. Friction measurements devices used to simulate accidents or to enhance racing cars' technology mostly measure deceleration/acceleration, stopping time, and stopping distance (Nagurnas *et al.* 2007; Jamieson 2009; Muttart *et al.* 2011; Coralba 2014). Safe runways in the winter and providing sufficient traction for planes to land and take off is one of the most critical engagements of aviation transportation departments. Several complex friction measurement devices have been developed to capture surface friction at desired point locations on runways (Al-Qadi *et al.* 2002). Although each of these studies revealed some essential facts that are still valid today, using friction measurements for winter road maintenance seek other purposes.

The main purpose of using road surface friction under different winter conditions is to introduce friction measurements as a tool to conduct effective winter road maintenance treatments. This is achieved through measurements before and after treatments, when information about other influential variables is available (Nixon 1998; Al-Qadi *et al.* 2002). In addition, a simple cost-benefit study verified the potential benefit of using friction measurements for controlling applied de-icing chemicals (Nixon 1998).

Prior to field friction measurements, several research studies attempted investigating surface behaviour and tire-road friction in details. Laboratory studies usually use simple test setups in small scales to simulate the tire-surface contact area under different conditions. Although researchers are not able to completely evaluate the real driving conditions in laboratory tests, they have discovered several facts about the tire-surface interactions. In the following section, a summary of such laboratory research studies and their findings are described.

2.2. Laboratory Research Studies

One of the most common laboratory experiments used for measuring surface friction is the British Pendulum Tester (BP), shown in Figure 2-2. This laboratory device is used to measure friction based on the test method available in ASTM E303. A rubber pendulum is released from a certain height to slide over the testing surface. The swing length is correlated to friction properties of the surface, and reported in terms of British Pendulum Number (BPN) (ASTM E303-93; Hossain *et al.* 1997).

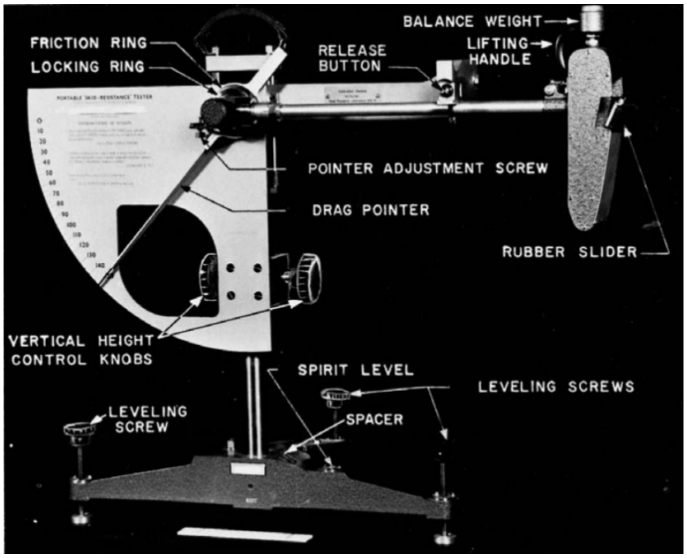


Figure 2-2. British Pendulum Tester, a common laboratory friction measurement device (ASTM E303-93).

In one laboratory study, BP was used to test three samples of bare ice, snow-contaminated ice and sanded snow-contaminated ice in a wide temperature range of -22 to 0°C. Results shown in Figure 2-3 imply that bare ice friction is highly temperature related; at melting temperatures of -5 to 0°C friction drops to a range of 0.05 to 0.25; while it was as high as 0.4 at low temperatures of -20 to -10°C. The other two surface conditions resulted in consistent friction values within the tested temperature range, but it was observed that snow contamination significantly reduced ice friction coefficient to 0.1, and even sanding such surface only increased the friction coefficient to 0.3 (even less than bare ice friction at low temperatures) (Klein-Paste and Sinha 2010a).

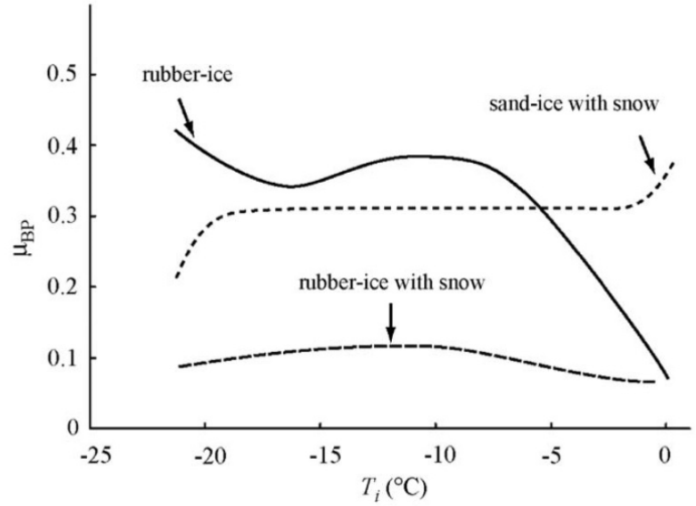


Figure 2-3. General trend observed for ice friction over a wide range of temperature (after Klein-Paste and Sinha 2010a).

The temperature-dependency of ice-rubber friction was also observed as part of a laboratory experiment that investigated the effect of applying sand, rock salt, brine, sand-salt mixture, and sand-brine mixture on ice. Ice temperature was kept constant at four levels of -18, -12, -9.5, and -7°C; materials gradation, mixture ratio and application rate were the other variables included in this experiment. The tests on bare ice revealed that at lower temperatures higher friction is achieved (from PBN of 10 at -7°C to 16 at -18°C). Another observation was the slight decrease in PBN with more number of runs on the same ice surface, although after a certain number of runs no more declination was observed. When applying sand (no salt added), it was concluded that the sand temperature is also an affecting parameter: when using cold-stored sand, BPN ranged from 12 to 30 regardless of the sanding rate and gradation, because loosely-bonded sand particles are swept away by the swinging rubber pendulum. However, BPN ranged from 24 to 46 using warm-stored sand, and friction increased with larger top size aggregate and greater application rates. Both salt alone and sand-salt mixture tests showed that at temperatures less than -12°C, salt is ineffective and acts as sand, resulting in BPN from 15 to 30. Even at higher temperatures, salt did not improve the friction values; however it was able to melt the ice resulting in thinner samples. Sand-salt mixture was found to have better influence in friction in higher temperatures, resulting in BPN of up to 30 in all temperatures. Brine created a rough ice surface texture and its concentration was found to be most significant. An ice sample sprayed with brine resulted in BPN of between 15 and 24. Sand-brine mixtures were also found to perform better at higher temperatures (BPN up to 40). Finally the optimum workable treatment was suggested to be applying 183kg/lane-km of sand-brine mixture with 2:1 ratio and 25 percent brine concentration at temperatures higher than -12°C. At lower temperatures, application of 100kg/lane-km sand-brine mixture with 1:1 ratio and 2.5 percent concentration was recommended (Hossain *et al.* 1997).

Another project was performed for the Federal Aviation Administration by the U.S. Army Cold Regions Research and Engineering Laboratory in 1991. In this study a friction table was used to measure both static and dynamic friction coefficients in small scales. A friction table includes a fixed frame with the sample tire attached to it, while the ice surface block is moving in contact with the tire (See Figure 2-4). The tests were conducted at -10°C in order to compare different types of sanding materials and their gradation. The dynamic friction ranges on bare ice, loose-sanded ice, and frozen-sanded ice were 0.21-0.36, 0.13-0.15, and 0.29-0.46. Similar trends were observed for static friction coefficient ranges of 0.42-0.67, 0.21-0.28, and 0.44-0.65 on the same surfaces, respectively. It was concluded that sanded ice does not necessarily have higher friction. Loose sand on ice rolls under the tire and creates less bond and traction in the contact area than bare ice; the sand is also more prone to be scattered off the surface. However, frozen sand is stuck to the ice and provides more roughness, thus improves surface friction (Blaisdell and Borland 1992).

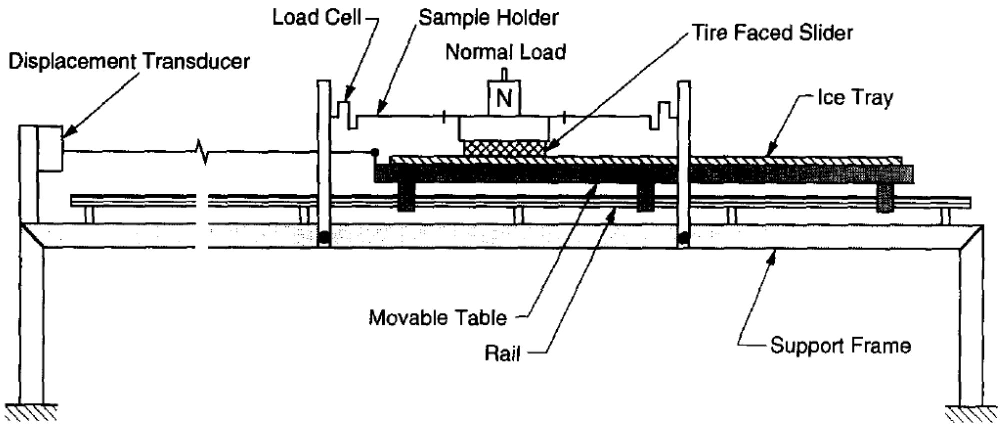


Figure 2-4. Schematic side view of a typical friction table used in laboratory studies (Blaisdell and Borland 1992).

A similar friction table equipped with ice and rubber samples were used in the United Kingdom to test tire-ice friction over a range of speed and temperature. It was concluded that over ice the lubricating melt water governs the friction values. At higher speed and temperature, more heat – thus more melt water – is generated, and lower friction values are achieved. Also, rubber material can influence the friction; stiffer rubber acts similar to glass and has less contact area with the surface, therefore less friction is produced (Skouvaklis *et al.* 2012).

The decrease in friction coefficient of ice at higher speeds was also observed for packed snow, in a laboratory study using two different types of tires. The reason for this decrease was explained to be greater heat generation at high speeds that lubricates the surface resulting in lower friction coefficient. The effect of tire type – with and without winter-special treads (sipes) – was investigated in this study, revealing that sipes help create more friction coefficient at higher speeds, while tires without sipes resulted in higher friction at very low speeds. Rubber-snow interaction is similar in both tires but sipes add plowing mechanism to the surface behaviour that creates more friction. The plowing mechanism found to be increasing at higher speeds (Ella *et al.* 2013).

Overall, each laboratory study revealed or verified certain facts regarding surface behaviour under winter contaminated conditions. However, real driving conditions cannot entirely be simulated in the laboratory. In addition to laboratory studies, several field experiments have also been conducted using different types of friction measurement devices. A brief introduction of different types of friction measurement devices is presented in the following section to compare their features and provide an overview of the proper device. Subsequently, prominent field experiments that used those devices to evaluate different wintery road conditions and winter maintenance operations are discussed briefly.

2.3. Friction Measurement Devices

Over the years, several advanced technologies have been evaluated for incorporation into winter maintenance decision making systems. One such technology that is still in research phases is road surface friction measurements. Friction measurements have been frequently used in runway condition evaluations, because sufficient surface friction is a critical parameter for airplanes safe landing and take-off. Friction measurement devices have been used in several research projects to characterize surface friction under different wintery conditions. They also have been developed in a more convenient mechanical system (e.g. covering shields and anti-freeze parts) for winter maintenance purposes.

For friction to become widely-used in winter maintenance operations, first the measurement device should be resistant to wear and break down in winter conditions and low temperatures. Additionally, the device must deliver continuous and real-time data to the plowing/sanding crew; so that they can make the right decisions regarding the time, amount and frequency of any winter maintenance application (Nixon 1998). Transportation agencies require an economic, operational, reliable, and easy-to-use tool to classify winter road conditions and understand the effect of winter operations on the measurements. Such a device can be used to test a variety of surface conditions as well as the friction before and after any type of operation. With that information available, the effectiveness of the operations on each condition can be evaluated. Besides, measurements can be performed along the road network, so that dangerous road conditions across the city are identified in a timely manner and treated with proper operations.

Generally, friction measurement devices can be divided into two main groups of decelerometers and wheel-based devices; though, some simple laboratory methods have also been developed to measure friction of a sample surface. The wheel-based group itself is categorized into four sub-groups of locked-wheel, fixed-slip ratio, variable-slip ratio, and side force devices. A description of each type of devices is provided as follows.

2.1.1. Decelerometers

Decelerometers are small, easy-to-use, and economical devices that can be mounted on the windshield of any vehicle (Al-Qadi *et al.* 2002). This category of devices calculates the vehicle's deceleration during a braking event and reports that as an impression of the coefficient of friction. When the vehicle's deceleration reaches a certain value (start of a braking event), the device records the speed and starts to measure the time it takes for the vehicle to come to a full stop. The stopping distance (as a function of speed and time) and deceleration (equal to the coefficient of friction) are reported in the output file. Newton's second law of motion is used in decelerometers as the main calculation principle as seen in Equations 2-2, 2-3, and 2-4.

$$\boldsymbol{a = \frac{V_2 - V_1}{\Delta t} = \frac{-V_1}{\Delta t}} \qquad \textbf{Equation 2-2}$$

$$\boldsymbol{D = \frac{V_1^2}{2a}} \qquad \textbf{Equation 2-3}$$

$$\boldsymbol{F = ma \rightarrow \mu . N = ma \ \& \ N = mg \rightarrow a = \mu g} \qquad \textbf{Equation 2-4}$$

Where, *a* is deceleration rate during braking (m/s^2), V_2 is the terminal speed when reaching a full stop (m/s), V_1 is the initial speed when braking begins (m/s), Δt is the stopping time (s), *D* is the stopping distance (m), *F* is the friction force (N), *m* is the total mass over each tire (kg), μ is the friction coefficient, *N* is the normal force applied to the tire (N), and *g* is the acceleration due to gravity which is equal to 9.81 m/s^2.

The Vericom VC4000 (Vericom Computers), MK3 (TES Instruments), Coralba-Mu, and Bowmonk/Tapley meter are some commonly-used decelerometers shown in Figure 2-5 (a to d).

(a) **(b)** **(c)** **(d)**

Figure 2-5. Commonly-used decelerometers, (a) Vericom VC4000 (Vericom Computers 2013), (b) MK3 (TES Instruments 2013), (c) Coralba-Mu (Shonx Motorsport 2013), and (d) Bowmonk (Sherwin Industries Inc. 2013; Wager Company 2013).

Despite their simplicity and practicality, they are associated with some drawbacks. The main issue when using decelerometers is the need for frequent braking which is not safe to perform in high-volume-traffic roads under winter road conditions (Al-Qadi *et al.* 2002). Decelerometers' other drawback is that the vehicle's characteristics (such as ABS, vehicle type, axle weight, and driving style) and road design (slopes and curves) can affect the data

2.1.2. Locked-Wheel Devices

Wheel-based devices generally use an auxiliary wheel mounted under or behind a vehicle. In locked-wheel devices, the extra wheel is fully locked via a braking system and slides on the road when the vehicle moves. Therefore, unlike the free rolling situation where the relative speed between the tire and vehicle – also referred to as the slip speed – is zero, for the locked wheel, slip speed increases until the vehicle has reached maximum speed. Another parameter, namely the slip ratio, better describes this behaviour. Both slip speed and slip ratio are calculated through Equations 2-5 and 2-6. Locked-wheel devices have a slip ratio of 100 percent and measure the sum of all resisting forces against tire movement (Hall *et al*. 2009).

$$\boldsymbol{S = V - V_W} \qquad \textbf{Equation 2-5}$$

$$\boldsymbol{SR = \frac{S}{V} \times 100 = \frac{V - V_W}{V} \times 100} \qquad \textbf{Equation 2-6}$$

Where, S is the slip speed (m/s), V is the vehicle speed (m/s), V_W is the extra wheel speed (m/s), and SR is the slip ratio (%) (Hall *et al*. 2009).

This category of devices is most common in the United States; ADHERA (by LCPC) and Dynatest 1295 are some of the widely-used examples of this category of devices (See Figure 2-6, a and b) (Nassiri and Bayat 2012).

(a) **(b)**

Figure 2-6. Common locked-wheel friction measurement devices, (a) ADHERA (Cerema 2013), and (b) Dynatest 1295 (Dynatest 2013).

It has been shown that these devices are associated with limitations in measuring the pavement friction. Some critical drawbacks include non-continuous data collection and unreliability of the data at curves, T-sections and roundabouts (Tokunaga *et al.* 2013). These devices are also not winterized. The locked-wheel testing system has also been criticized because it does not represent the behaviour of ABS in vehicles.

2.1.3. Fixed-Slip Ratio Devices

Studies have shown that the tire-road friction coefficient does not remain constant during braking and will increase with more slip ratio until a critical slip ratio after which friction coefficient either remains constant or decreases with greater slip ratio. The critical slip ratio represents the time that ABS locks the tires in a braking event. Several studies have shown that both the maximum friction coefficient and critical slip ratio depend on the road condition (See Figure 2-7) (Alvarez *et al.* 2005; Fay *et al.* 2007; Sui and Johansen 2010; Villagra *et al.* 2011; Flintsch *et al.* 2012).

Based on the finding that the maximum friction coefficient is achieved at a slip ratio range of 10 to 20 percent, fixed-slip ratio devices were developed (Shahin 2005; Fay *et al.* 2007). In this category of wheel-based devices, the extra wheel is partially locked so that friction is always measured at the critical slip ratio.

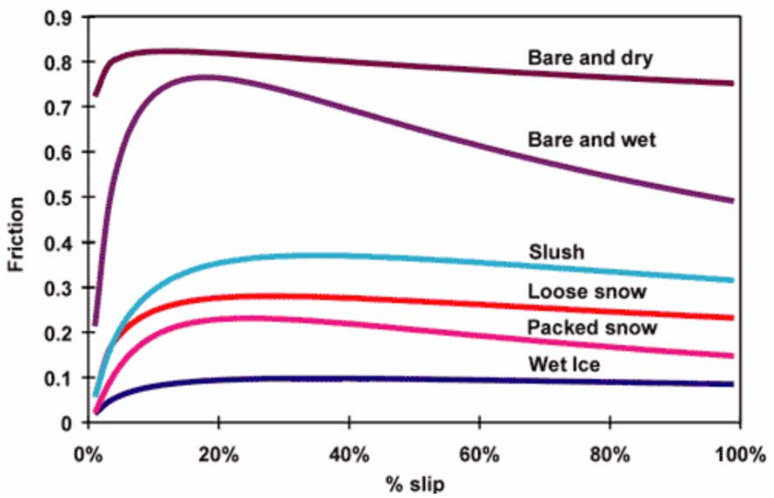
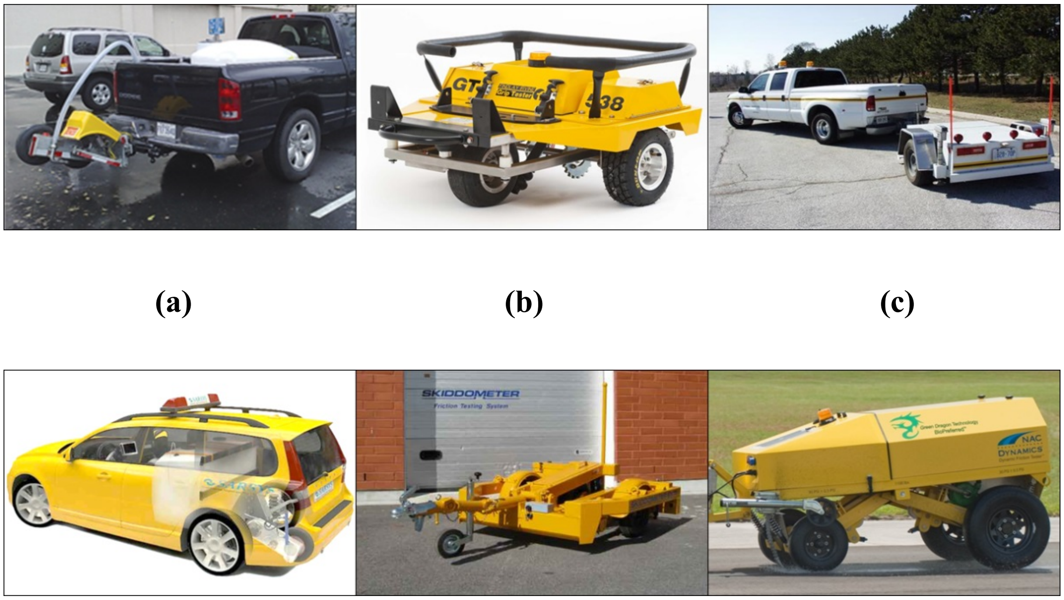


Figure 2-7. Friction coefficient versus slip ratio for different road conditions (Fay *et al.* 2007).

The Traction Watcher One (TWO), Griptester (by Findley Irvine), Dynatest 6875H, SAAB Friction Tester (by Scandinavian Airport and Road Systems, SARSYS), Skiddometer BV-11, and Dynamic Friction Tester (by Neunert Aero

Corporation, NAC) are examples of fixed-slip ratio devices shown in Figure 2-8 (a to f).



(a) **(b)** **(c)**

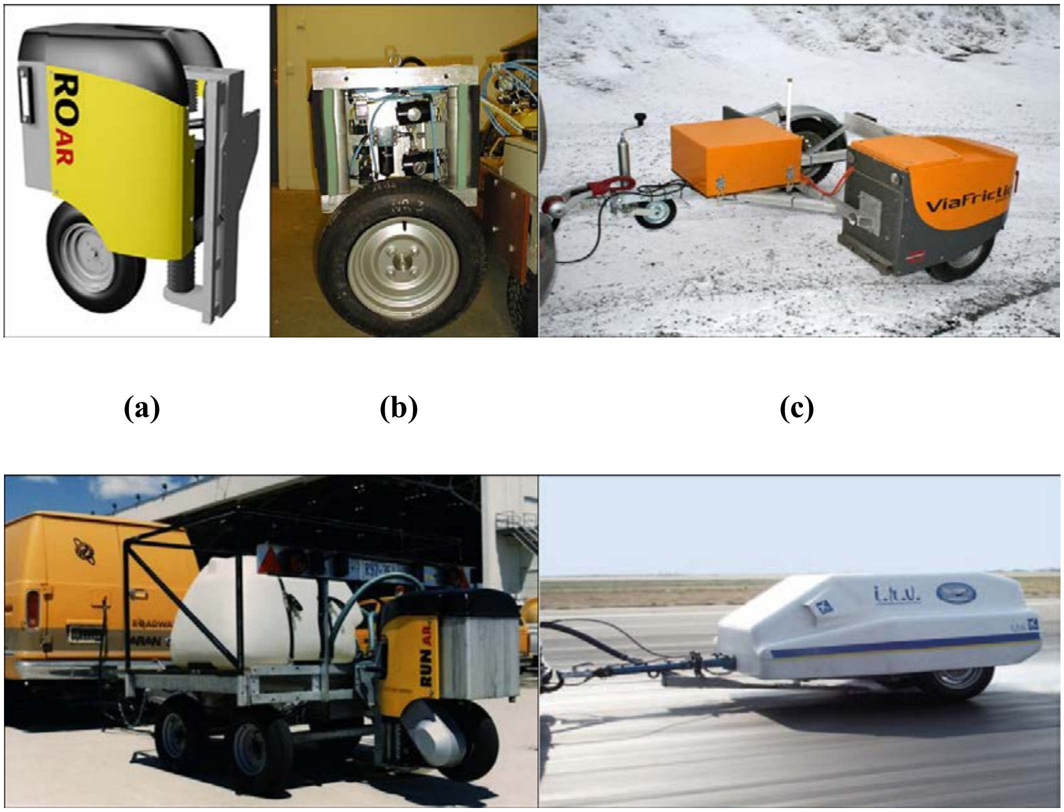
(d) **(e)** **(f)**

Figure 2-8. Common fixed-slip ratio devices, (a) Traction Watcher One (TWO) (Infrastructures 2013), (b) Griptester (The Rich Works 2013), (c) Dynatest 6875H (Ontario Ministry of Transportation 2013), (d) SAAB Friction Tester (Airport International 2013), (e) Skiddometer BV-11 (Airport Technology 2013), and (f) Dynamic Friction Tester (PRWeb 2013).

2.1.4. Variable-Slip Ratio Devices

As seen in Figure 2-3, the maximum friction coefficient is achieved at the critical slip ratio, which varies depending on the road conditions; thus, when using fixed-slip ratio devices on different road conditions, the maximum friction coefficient is not always recorded. This is the reason for the development of variable-slip ratio devices. These devices function based on similar principles as fixed-slip ratio devices; however, they are able to measure friction at all desired slip ratios (Nonstad [undated]).

Some examples of variable-slip ratio devices are ROAR (by Norsemeter), SALTAR, ViaFriction, RUNAR, and IMAG, shown in Figure 2-9 (a to e).



(a) (b) (c)

(d) (e)

Figure 2-9. Common variable-slip ratio devices, (a) ROAR (Inopave 2013), (b) SALTAR (Center for Transportation Research and Education 2013), (c) ViaFriction (ViaTech 2013), (d) RUNAR (BMT Fleet Technology Limited 2010), and (e) IMAG (Airports and Airforces Bases Engineering Department 2004).

The main advantage of this category of wheel-based devices is the continuous recording of friction at various slip ratios. However, they are relatively expensive and require complicated data processing and analysis.

2.1.5. Side Force Devices

The last group in the category of wheel-based devices is side force devices, which include an auxiliary wheel set at a fixed angle from the direction of travel. Due to this angle, also referred to as the yaw angle, side friction forces are applied to the measuring tire and are measured by a load cell. The side force is then converted to a friction value via device-specific correlations.

The most common side force devices include British Sideway-force Coefficient Routine Investigation Machine (SCRIM), Mu-Meter (yaw angle = 7.5), and Real Time Traction Tool (RT3) (by Halliday Technologies) (yaw angle = 1.5), shown in Figure 2-10 (a to c).

(a) **(b)** **(c)**

Figure 2-10. Common side force devices, (a) SCRIM (CIEN 2013), (b) Mu-Meter (Pavemaintenance 2013), and (c) Real Time Traction Tool (RT3) Curve (Halliday Technologies 2013).

Side force devices simulate the driving conditions at curves and while making turns. Because of the small yaw angle, these devices are very sensitive to changes in road conditions (Engstrom *et al.* 2009).

Each category of friction measurement devices has its own advantages and disadvantages, as revealed in different field experiments. Field friction measurement experiments seek investigating tire-road friction changes under real driving (and/or braking) conditions. The following section shortly describes related field studies, their purposes, and their results.

2.4. Field Experiments Research Studies

2.1.6. Comparing two or more friction measurement devices

With the development of different types of friction measurement devices, several experiments have been conducted using these devices on actual winter road conditions. Some experiments used two or more devices along with each other to compare them based on their results and operational features; some studies also developed prediction models to correlate the values obtained from different devices to each other.

For instance, in Canada, the Joint Winter Runway Friction Measurement Program (JWRFMP) was an extensive study to establish an index for different wintery conditions. This project was supported by Transportation Canada and National Aeronautics and Space Administration (NASA) in 1997 with 18 different friction measurement devices including Griptester, IMAG, Mu-Meter, ROAR, RUNAR, Saab, SALTAR, Skiddometer BV-11, and Tapley meter. The project focused on runway safety and the International Runway Friction Index (IRFI) was developed based on the collected data (Yager *et al.* 2002).

Another study was performed in Japan, comparing the friction measurements by an accelerometer, Locked-Wheel Friction Tester (LWFT), and Continuous Friction Tester (CFT) over artificially-made dry, wet, compacted-snow-covered, and thin-ice-covered surfaces. The CFT, shown in Figure 2-11, is a side force friction measurement device developed by Halliday Technologies, and it measures friction in terms of Halliday Friction Number (HFN) ranging from 1 to 114. The average values obtained using CFT were 101, 101, 53, and 40 for dry, wet, compacted snow, and thin ice road conditions. The accelerometer were used in braking events over each road condition and resulted in friction coefficients of 0.53, 0.53, 0.28, and 0.19 for the same road conditions, respectively. The LWFT was also used to measure friction during braking events resulting in friction coefficients of 0.83, 0.49, 0.22, and 0.15, over the same road conditions, respectively. The study concluded that CFT had the most reliable results and due to its continuous measurements, reflected the road condition changes; whereas the devices with braking mechanisms only deliver spot measurements (Tokunaga *et al.* 2013). The main drawback of this study is that the LWFT, a locked-wheel device, was used as the reference device. As mentioned in Section 2.2, this mechanism has limitations and cannot represent driving and braking conditions of recent vehicles.

Figure 2-11. Continuous Friction Tester (CFT), a side force friction measurement device, used in a study in Japan (after Tokunaga *et al.* 2013).

The verification of the accuracy of friction measurement devices is a necessity; therefore these devices should be tested in real conditions. Several research studies have focused on evaluating different devices. These studies and their findings are summarized in the following section.

2.1.7. Evaluating different winter road conditions

Currently, the use of friction measurements for winter operations is not in operational phases, and only research projects are conducted in this area. Some of these projects were sponsored by transportation agencies to evaluate the feasibility of using friction measurements widely in winter maintenance programs. These projects attempted to evaluate different road conditions and investigate the logic behind the changes in surface friction due to winter contaminations.

For example, Alberta Transportation's pilot project in 2005 included friction measurements on winter road conditions in March and April, as well as summer conditions in May (used as reference values). Halliday Technologies' RT3 device was used in the project due to its reliability and consistent results, it was concluded that friction has the potential to be added to departmental performance measurements (Alberta Infrastructure and Transportation 2005).

The Ministry of Transportation of Ontario (MTO) is also one of the agencies with several friction measurement studies to evaluate snowy conditions. In 2008, statistical models were developed to relate snow-covered surface friction measurements (using TWO) to weather data (Fu *et al.* 2008). In 2013, more details on weather information and snow properties were investigated by RUNAR's friction measurements along a snowplow route. Friction was found to be varied along the route, due to varied snow accumulation caused by snow drifting and changes in the adjacent vegetation condition. The snow cover was then estimated based on RWIS data, which was correlated to friction measurements at an acceptable confidence level (Perchanok 2013).

A project conducted by the Minnesota Department of Transportation (MnDOT) compared the friction coefficients obtained by a decelerometer and a ROAR friction measurement device. The decelerometer resulted in friction coefficients of 1.0, 0.96, 0.7, 0.6, 0.4, and 0.22 over bare dry concrete, bare dry asphalt, loose snow-covered surface, dirt road, gravel surface, and ice, respectively. A similar test was performed with ROAR from dry asphalt to gravel where a sudden drop in friction coefficient from 0.85 to 0.4 was observed. Both devices were reported to be sensitive to road conditions (Hahn *et al.* 2002). Despite decelerometers' practicality, fixed-slip ratio and variables-slip ratio devices have become more popular in research projects, due to their advantages compared to the locked-wheel devices and decelerometers. Therefore, many researchers have attempted to measure friction on winter roads using these types of devices.

For example, in a project in Sweden, Skiddometer BV-11 was used to measure friction at highway speed (90 km/h) on different road conditions during winter 1986 and 1987. Bare dry (μ = 0.93) and bare wet (μ = 0.80) surfaces resulted in the highest friction coefficients among all tested conditions. On road sections with both bare dry and ice spots, friction coefficient ranged from 0.11 to 0.9. Snow and ice conditions were categorized into hard and loose snow/ice and they resulted in the friction coefficients of 0.27 and 0.16, respectively (Wallman *et al.*1997).

Satisfactory results from variable-slip ratio devices have encouraged researchers to step forward into classifying the values for simpler interpretation of result. An experiment with SALTAR mounted on a snowplow truck in Iowa, United States, was conducted and friction was measured in braking events along the route of the snowplow. Five categories of Good (μ>0.5), Acceptable (0.4<μ<0.5), Slippery (0.25<μ<0.4), Very Slippery (0.15<μ<0.25), and Hazardous (μ<0.15) road conditions were introduced. Results indicated that friction coefficient on packed snow, ice patches, and drifting snow were less than 0.15 (reported as "Hazardous"); whereas, streets that were treated with de-icing chemicals had "Good" level of friction (Friction coefficient of greater than 0.5). The device found not to operate properly at low temperatures and winter conditions. Comparing SALTAR's friction values with ROAR's speed-dependent measurements in the same conditions revealed that SALTAR is designed for low speeds of around 30 km/h (Andrle *et al.* 2002).

Side force devices are another successful category of friction measurement devices, as they can continuously measure friction and their results have proved to be reliable through several experiments. A series of field experiments were performed using a side force friction measurement device developed by the United States' Cold Regions Research and Engineering Laboratory (CRREL). The device is called the CRREL Instrumented Vehicle (CIV), and is shown in Figure 2-12.

Figure 2-12. The Cold Regions Research and Engineering Laboratory (CRREL) Instrumented Vehicle (CIV) side force friction measurement device (Coutermarsh and Shoop 2009).

In 1993, CIV's friction coefficient results were compared to SAAB (fixed-slip ratio = 12 percent) and Uniroyal-Goodrich (U-G) friction measurement devices. Ice contaminated with loose snow, rough ice, snow-covered surface, and bare asphalt were tested with all three devices. The friction coefficient values from SAAB and CIV at 12-percent slip ratio were almost the same. The same average friction coefficients were measured by CIV and U-G at slip ratio range of 25-75 percent. Overall, the maximum friction coefficients of 0.12, 0.15, 0.32, and 0.64 were obtained by CIV for smooth ice with snow, rough ice, fresh snow, and dry asphalt surfaces, respectively (Shoop 1993; Shoop *et al.* 1994).

Later in 2009, the CIV was used to test snow at various densities and accumulations along with ice in two winter seasons, and the results are shown in Figure 2-13. Packed snow resulted in the highest friction coefficient of 0.4; however, when only 0.5 cm of fresh snow was added to packed snow, friction coefficient dropped to 0.36. Wet snow and 5cm of snow both resulted in the same maximum friction coefficient of 0.3, but for fresh snow, the maximum friction coefficient is achieved at higher slip ratios. More fresh snow on the ground resulted in lower friction coefficients, for instance, 15 cm of fresh snow had a maximum friction coefficient of 0.22. Ice and 22 cm of fresh snow resulted in the lowest friction coefficient of 0.14, yet for ice, this maximum is reached at very low slip ratios (approximately 5 degrees). This study concluded that the device is reliable with great sensitivity to road conditions and it could be used to evaluate different conditions (Coutermarsh and Shoop 2009).

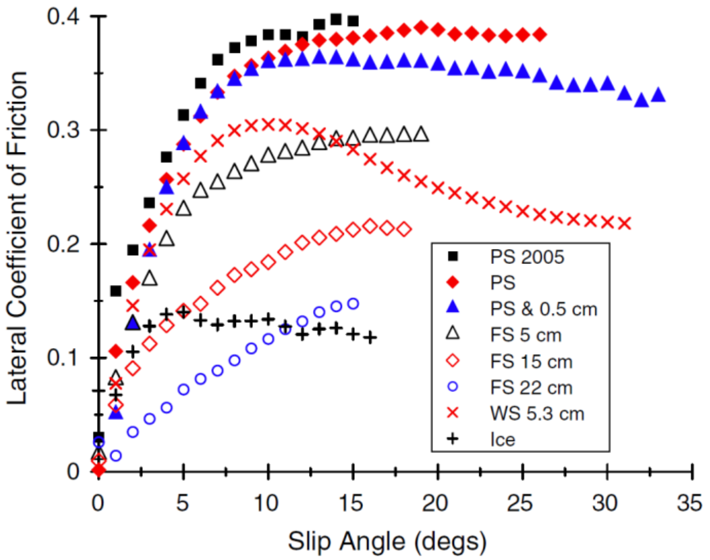


Figure 2-13. Lateral coefficient of friction over slip angle range for a variation of road conditions including packed snow (PS), fresh snow (FS), wet snow (WS), and ice (after Coutermarsh and Shoop 2009).

In another study using CIV in Montana, a similar trend was observed for packed and unpacked snow with friction coefficients of around 0.36 and 0.24, respectively. Ice also resulted in the lowest maximum friction coefficient of 0.11 (Phetteplace *et al.* 2007). Yet, the main issue with CIV is that it is not a common device and its availability is limited to some specific areas. Also, the bike tire used in this device might not have the same material composition or tire properties as that of passenger cars.

One comprehensive study in Sweden, tested RT3, TWO, Coralba-Mu, and ViaFriction on rough snow-contaminated ice (namely old system ice), Zamboni-polished ice (namely polished ice), and blade-roughened snow-contaminated ice (namely new system ice) at 30, 50, and 70 km/h. Comparing all runs at 50 km/h by different devices, ViaFriction, Coralba, and TWO showed small changes in friction over the three ice surfaces. The average friction coefficients were 0.27, 0.22, and 0.30 by ViaFriction, and 0.29, 0.12, and 0.27 by Coralba, and 0.21, 0.17, and 0.24 by TWO on old system ice, polished ice, and new system ice, respectively. RT3, however, resulted in friction values of 66, 32, and 53 (in terms of HFN) over the three ice surfaces, respectively, implying considerable difference between the surfaces. The study also included ambient temperature and speed as part of analysis, and they concluded that weather information cannot predict friction as it is not the only affecting parameter. Also, ViaFriction was highly speed-dependent in measurements; whereas the other devices' collected friction values were not correlated to speed. At the end, the study concluded that TWO and RT3 showed acceptable repeatability among others. TWO were not sensitive enough to the road surface texture, while with RT3's data, one can clearly distinguish between different road surfaces (Engström *et al.* 2008). Despite the comprehensive experiments and results in this project, friction was investigated only over ice, and other contaminations were not considered.

Overall, reliable results have been concluded from some of the above mentioned studies that provide the ranges of friction coefficients for each road condition. In addition, some other studies have stepped forward to evaluate the winter maintenance operations and their effectiveness on each road condition; these studies are summarized in the next section.

2.1.8. Evaluating winter maintenance operations

Road measuring devices have been used in other studies to attain a better understanding of common winter maintenance operations. To achieve this objective, friction measurements were conducted after each type of operation and they were then compared to untreated surfaces' friction values.

As an example, from 2009 to 2011, the City of Edmonton initiated a study using a decelerometer to measure friction coefficients and stopping distances for arterial streets under different winter conditions. The different road conditions included freshly-sanded, bare dry, residual snow, and packed snow. The changes in friction with respect to when the sand was applied were also investigated. According to the study, friction dropped considerably for a road section where ice or snow was allowed to accumulate. Sanding/salting improved friction on icy/snowy and snow-packed conditions, and friction improved significantly within one to five hours after the application of sand/salt. The study concluded that friction data had a strong potential to be used in optimizing sanding and salting procedures (Goulden 2011).

Different methods of applying sand-salt mixtures are another area of research in Norway and other countries. The effectiveness of each method can be investigated through friction measurements. In 1999, four types of friction measurement devices – C-my (a decelerometer), ROAR, OSCAR, and Kofriks (a side force device) – were used to compare sand application methods on wintery roads. Tests on untreated wintery roads resulted in friction coefficients of approximately 0.2 with or without traffic. As seen in Figure 2-14, when applying dry sand, the friction coefficient increased by 0.1. The other method, applying warm-wetted sand, did not have any significant influence immediately; yet it was the most effective within an hour from application and increased friction to around 0.6. However, with 300 vehicle passes sand was scattered off the road, resulting in a lower friction coefficient of approximately 0.4 (Vaa 2007).

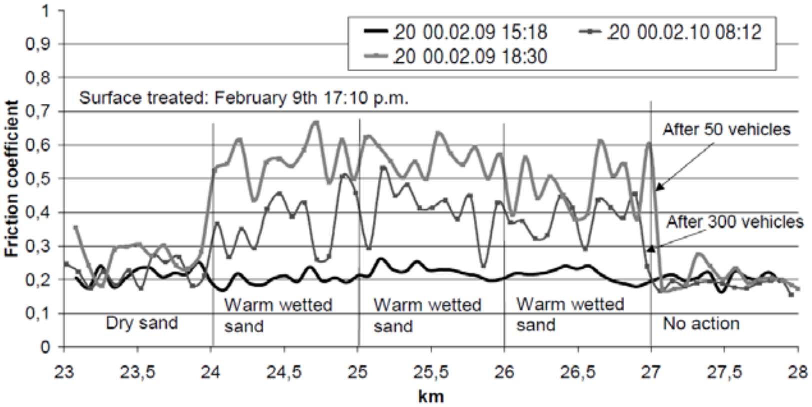


Figure 2-14. The variation of friction coefficient along the road section treated with different methods of sand application (Vaa 2007).

Another study compared similar methods of sand application on wintery conditions using ROAR and OSCAR friction measurement devices. Among the three methods of applying dry sand, hot sand, and warm-wetted sand, it was concluded that the warm-wetted sand results in greatest improvement in surface friction. This method was shown to make sand to remain longer on the road due to better bonds with the surface; therefore, it is also more environmentally-friendly because of less total sand consumption (Dahlen and Vaa 2007).

These studies were able to identify the difference between sanding methods based on the level of friction improvement, time lapse after application, and traffic pass over sanded areas. However, the road conditions were not identified specifically; thus a comparison between the effectiveness of the mentioned sanding methods on different road conditions could not be achieved. Further, sanding methods were evaluated at one application rate, whereas, several other winter maintenance practices and their frequency and rate of applications require such investigations.

2.5. Summary of Findings

Past studies have shown the potential of surface friction measurements to characterize different road conditions. Friction is also the essential parameter that provides sufficient tire-road traction, thus safe driving conditions. It should be noted that friction relies on tire, vehicle, surface and environmental factors; the mechanisms creating friction in the tire-road contact area also differs in different road conditions. Therefore, extensive studies are required to investigate the effect of each variable by controlling the mentioned variables.

Laboratory studies use rubber pendulum and small-scale samples (usually ice) to measure friction under controlled laboratory conditions. Since most of these experiments were performed at controlled temperatures, the effect of temperature on rubber-ice friction was able to be investigated thoroughly. It has been concluded that ice is more slippery at melting temperatures (-5 to 0°C). Further investigations of this phenomenon revealed the existence of a thin film of melt water over the ice, creating a more slippery surface than ice at very low temperatures. The melt water is produced at high temperatures and speeds, and a similar phenomenon occurs in rubber-snow contact area.

To better understand the actual road friction conditions in winter, field experiments have been performed. Utilization of friction measurement devices is advantageous in evaluating different road conditions in actual driving conditions. Although different types of measurement mechanisms and devices have been developed, they are all still in research phase and need further research before they can be implemented on network levels to assist municipalities and highway agencies in their decision making for winter maintenance operations.

The review of literature provided in this chapter shows that consistent ranges of friction coefficient were captured for each road condition; with bare dry pavement showing the highest friction, and ice and snow friction interchangeably showing the least friction, depending on their surface properties. Several experiments performed on snow showed that snow density and accumulation significantly influence the surface friction. Sand was observed to be effective in improving ice and snow friction; however, the application method was found to be critical. Applying warm-wetted sand was found more influential on friction than dry sand; because dry sand remains loose on the surface and is scattered off the road by traffic pass.

The studies in this area have discovered many influential variables in the tire-surface behaviour when driving in wintery conditions; however, each case was conducted in a specific environmental condition, with one or several equipment that might not even represent the conditions accurately. Also the number of available studies in this area is limited. Additional research is required to verify and expand the findings of these studies to address a wider range of winter road conditions. Contributions to comprehending surface behaviour in wintery conditions, influential variables (and the way they influence friction), and winter road treatments can be investigated in further studies that have overcome the previous limitations.

The extreme winter conditions in Canada and the significance of winter maintenance operations has led to several evaluation projects by highway agencies and municipalities. Such projects are able to help enhance the effectiveness of winter operations. More efficient and effective winter operations could optimize costs, time, and efforts; increase public satisfactory and comfort; and eliminate environmental hazards caused by excessive sand/salt consumption.

The current thesis presents the findings of a research project conducted by the University of Alberta and sponsored by the City of Edmonton to evaluate the application of friction measurements for optimizing winter maintenance operations. After the literature review phase in 2011, RT3-Curve was proposed to the City of Edmonton as the most suitable friction measurement device. RT3 has proved to be reliable, easy to use, and compatible to wintery conditions and low temperatures (as low as -26°C) (Tilley *et al.* 2008). RT3-Curve was designed and manufactured by Halliday Technologies located in Ohio. Phase II of the project included friction measurements on the University of Alberta's IRRF test road under different conditions in winter 2012-2013. The description of the tests and the results are presented in the following chapters.

3. Chapter 3: Characterizing Driving Conditions for Various Winter Road Conditions Using Lateral Coefficient of Friction[1]

3.1. Introduction

Winter-contaminated roads are directly correlated to high numbers of collisions during the winter months in cold reigns. Returning the roads to safety in a timely manner to avoid collisions and facilitate mobility is a major challenge faced by municipalities in cold regions (Fu *et al.* 2005; Usman *et al.* 2012; Andrey *et al.* 2003; Brown and Baass 2007). To provide safe driving conditions, municipalities and highway agencies perform a variety of winter operations every year, such as applying abrasive mixtures and snowplowing. Currently, decisions regarding where, when, how much, and how frequently road winter treatments should be executed are made empirically. However, these decisions should ideally be made to result in the application of the optimum amount of abrasives at the proper location and time (Erdogan *et al.* 2007). In order to select the most appropriate and effective treatment, driving conditions on various types of winter-contaminated roads must be understood. To date, few studies have focused on quantitative characterization of the effect of different winter contaminants on tire-surface friction to truly represent winter driving conditions for a light vehicle (truck).

Auxiliary wheel(s), typically towed behind a vehicle, have been used to measure the in-situ friction levels of pavements and runways. Slip Ratio (*SR*), defined as the relative speed of the vehicle with respect to the measuring wheel's speed to the vehicle's speed, is a critical parameter when using wheel-based friction measuring systems. While the first generation of these measuring systems was comprised of fully-locked measuring wheels (*SR* = 100%), they evolved into

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[1] A version of this chapter has been submitted to ASCE Journal of Cold Region Engineering, Authors: Sahar Salimi, Somayeh Nassiri, Alireza Bayat.

partially-locked wheels at a fixed SR to simulate vehicles' new braking behavior with the Anti-Lock Braking System (ABS). In a project conducted in 1993, one fixed-SR device (SAAB friction meter) was implemented to measure the tire friction of an asphalt concrete (AC) runway under various conditions of bare, packed snow, smooth ice, rough ice, and snow-contaminated ice. Based on the measured friction coefficient (μ), the conditions were arranged from the most slippery to the most tractive as follows: snow-contaminated ice, smooth ice, rough ice, snow, and bare asphalt (Shoop 1993). While application of fixed-SR devices, such as the Griptester, grew in popularity for quality assurance of newly constructed runways and different types of pavements, only a few experiments implemented this type of device for winter-contaminated roads (Comfort and Dinovitzer 1997). For instance, one study in Sweden with SAAB Surface Friction Tester collected data during ice and snow conditions. The median friction coefficient was reported at 0.05, 0.15-0.25, and 0.8-0.9 for frozen-rain-covered, ice/snow-covered, and bare dry surfaces, respectively. Results of this study also showed correlations between friction and temperature (Wallman *et al.* 1997). Validity of the fixed-SR systems' measurements for winter contaminated surfaces has been criticized; studies have shown that the critical SR at which maximum friction is present between the tires and the surface does not coincide for different winter contaminants such as ice versus snow (AlQadi *et al.* 2002; Hall *et al.* 2009). As a result, the fixed-SR system does not simulate the true stopping behaviour of a braking vehicle with the ABS system. Another criticism made regarding this system of measurement, which is perhaps more critical when used on dry surfaces, is that the partially locked wheel is prone to substantial wear and tear as a result of frictional heat. Wear in the tire treads results in varying surface area and consequently compromises the friction measurements (Don Halliday, personal communication, 23 October 2013).

To overcome the need to lock the measuring wheel(s) and to alternatively use a free rolling wheel for measurements, side-force friction measuring devices were developed, where the tire-road friction is simulated during cornering and turning. For this mechanism, the lateral friction force (side force) applied onto the measuring wheel(s), set at a fixed slip angle with respect to the wheel or vehicle's longitudinal axis, is measured. This mechanism was tested in Shoop (1993)'s experiment discussed previously, using the Cold Region Research and Engineering Laboratory (CRREL) Instrumented Vehicle (CIV) to characterize the tire-road friction under different winter conditions. The average peak friction coefficients were found to be 0.12, 0.15, 0.32, and 0.64 for snow-contaminated smooth ice, rough ice, snow, and bare asphalt, respectively. Coutermarsh and Shoop (2009) repeated the experiment in 2005 with the CIV, where fresh snow, wet snow, packed snow, packed snow topped with 0.5-cm of fresh snow, remixed snow, and ice were included in the experiment. Maximum friction coefficients recorded were 0.22, 0.3, 0.4, 0.36, 0.24, and 0.14 for the mentioned winter conditions, respectively. The study also showed that friction drops as snow depth increases. Real Time Traction Tool (RT3) is another side-force measuring device that was used in an experiment on a frozen lake in Sweden to characterize tire-ice friction for different ice types and textures. Different ice types of Zamboni-polished, artificially-rough using a metal teeth blade, and snow-contaminated slightly-rough were included in the experiment. The RT3 friction coefficient showed great sensitivity to the ice texture, as the average friction value of each run varied from 71.5 for the snow-contaminated, slightly-rough ice to minimum of 28.25 for the Zamboni-polished ice (Engstrom *et al.* 2008).

As mentioned previously, the number of studies that applied rubber tire friction measurements to characterize the effect of winter contaminants on driving conditions is limited, as opposed to the large body of literature focused on ski and snow frictional mechanisms. Additional investigation is required to expand the findings of the studies reviewed above to address a wider range of winter road conditions. Further studies in this area will shed light on the actual tire-ice and tire-snow friction mechanisms and will contribute to the knowledge of winter road treatment and maintenance. The current paper presents the findings of a series of experiments conducted in winter 2012-2013 using an RT3-Curve unit, where a variety of winter road conditions were captured. The main objective of this paper is to present the friction coefficients for different road conditions encountered by drivers in cold regions and explain the possible causes of friction loss during these conditions.

3.2. Background

Tire-road friction forces are generally created through two major mechanisms of adhesion and deformation (hysteresis loss). Adhesion is formed through Van der Waals bonds created at a molecular level at the contact area between the tire and the pavement. These bonds are weak and are formed, stretched, and eventually broken with every roll of the tire on the pavement (Ella *et al.* 2013). For general tire-road friction, adhesion affects friction at micro-texture levels and contributes to tire-road friction forces, especially on dry and clear road surfaces. Besides adhesion, tire-road friction forces are created due to hysteresis losses of the rubber tire. The tire continually conforms to the pavement's surface roughness and irregularities and also flattens at the contact area with the pavement. Because of its viscoelastic properties, the tire does not fully rebound and relax upon unloading, resulting in an energy loss known as hysteresis loss. The process of deforming and partial relaxing continues as the wheel moves forward; this is known to be the main source of energy loss and heat generation between the two surfaces (Bowden and Tabor 1966; Klamp 1977; Persson 2000).

Presence of winter contaminant on the road surface results in a decline in the tire-surface friction. Adhesion between the tire treads and the road surface decreases in the presence of winter contaminants; the hysteresis loss is also reduced in this condition because the pavement surface inequalities cannot be realized by the tire. Further, during the winter, the cold tire exhibits more elastic than viscous behaviour, thereby the hysteresis losses are also reduced (Walus and Olszewski 2011). The topic of tire-road friction alone is complicated; the addition of ice and snow on the surface results in different friction mechanisms that complicate understanding of the topic further.

3.2.1. Tire-Ice Friction

It is commonly believed that ice is the most dangerous surface condition for driving; however, this belief is not valid for any type of ice. Apart from tire properties, tire-ice friction depends on several other variables, such as the ice texture (rough versus smooth, clear or snow-contaminated, and so forth) and the ice temperature. Experiments have shown that at very low temperatures (<-5°C) both the ice and rubber tire act as stiff and rigid materials, thus creating a great adhesion at their contact area (Klein-Paste and Sinha 2010a; Klein-Paste and Sinha 2010b; Roberts 1981). Conversely, when exposed to higher ambient temperatures (melting temperatures), a thin film of water covers the ice surface, acting as lubrication and creating a slippery surface. This phenomenon has been confirmed by laboratory experiments, where a significant drop was observed in the friction coefficient at temperatures ranging from -5 to 0°C (Klein-Paste and Sinha 2010a; Klein-Paste and Sinha 2010b; Roberts 1981). Lubricant water can also be created due to the sudden heat loss (hysteresis loss) resulting from the tires passing over the ice (Roberts 1981 and Kietzig *et al.* 2010a; Klein-Paste and Sinha 2010b).

3.2.2. Tire-Snow Friction

Tire-snow friction has not been studied to the same extent as tire-ice friction, since snow is a more complicated material to investigate compared to ice. Tire-snow friction can depend on many variables, such as prevailing snow crystal type, temperature, density, and liquid water content (Colbeck 1988). The primary mechanisms resulting in tire-snow friction have been as plowing (or solid-to-solid interaction), melt water interaction, and capillary drag. When the tire runs on snow, the top layer of the snow is scraped off; phenomenon known as plowing, which is predominantly seen with winter tires, which enhances the frictional forces as shown in Figure 3-1 (a). Winter tires' special tread cuts, called "sipes", dig into the snow as the tire rolls on the snow; this snow-compressing force is part of the frictional force created at the contact area. Additionally, when the tire runs over snow, frictional heat can melt a thin snow layer; the melt water considerably reduces friction by acting as lubrication [Figure 3-1 (b)] (Ella *et al.* 2013; Nakajima 2003). Capillary drag forces are created when more heat is generated at the tire-snow contact area or when the snow is wet, resulting in a thicker film of melt water. Depending on speed, temperature, and the contact area conditions, the dominant mechanism varies. At high velocities, melt water interaction governs the friction coefficient value; whereas, at lower speeds, the plowing mechanism is dominant. At low, medium, and high temperatures plowing, melt water interaction, and capillary drag, respectively, are the governing tire-snow mechanisms influencing the friction coefficient (Colbeck 1992).

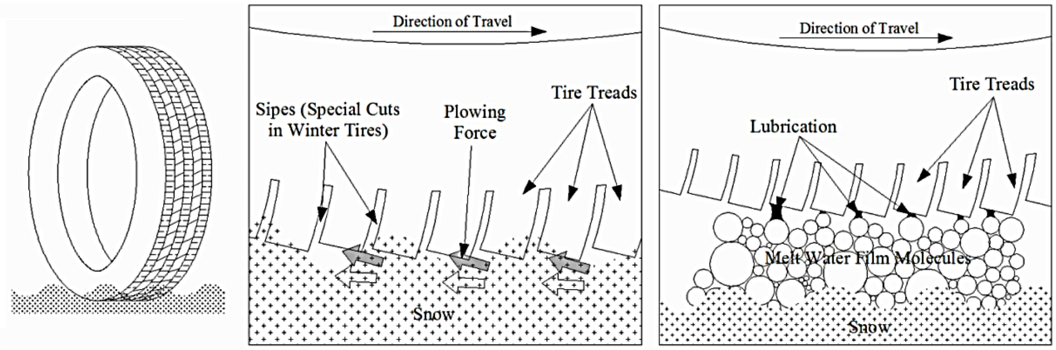


Figure 3-1. (Left) Plowing mechanism; (Right) lubrication act by a film of melt water.

3.3. Description of Test Equipment

As discussed previously, the equipment used in this study is a side-force friction measuring device, which functions based on lateral friction force or the so-called side friction force measurements. The lateral friction force at the tire-road contact area depends on several variables, including the properties of the tire, road, and vehicle, along with the weather conditions. For this type of road friction measuring device, the test wheel is maintained at a fixed angle from the direction of travel, known as the yaw or the slip angle, as seen in Figure 3-2 (Wallman and Astrom 2001).

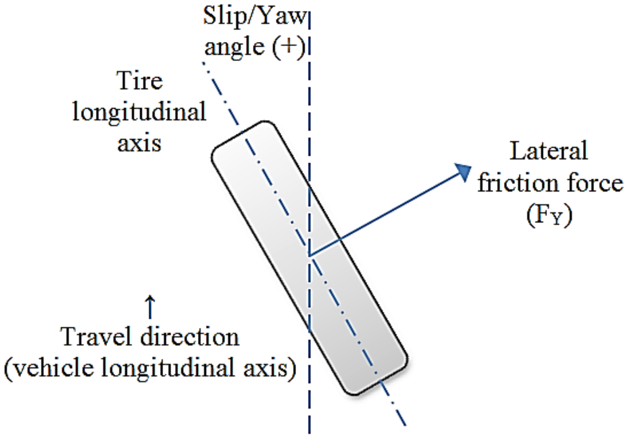


Figure 3-2. Principle of lateral friction force (plan view).

The lateral friction force (F_Y) applied perpendicular to the tire's longitudinal direction is measured by a load cell and is divided by the vertical load (F_Z) on the tire to establish the lateral friction coefficient (L_x) using Equation 3-1 (Engstrom *et al.* 2012; Al-Qadi *et al.* 2002).

$$\boldsymbol{L_x = \frac{F_Y}{F_Z}} \qquad \textbf{Equation 3-1}$$

The lateral friction coefficient is an essential parameter in vehicle dynamics that can characterize the road condition, particularly when cornering and turning, which is especially critical in winter conditions. RT3-Curve, the machine used in this study, is a towed-behind, side-force friction measuring device with two measuring wheels and a third wheel used to direct the trailer when the measuring wheels are not operating (Figure 3-3, right). The yaw angle for the RT3-Curve is set at 1.5 degrees, as schematically presented in Figure 3-3, left.

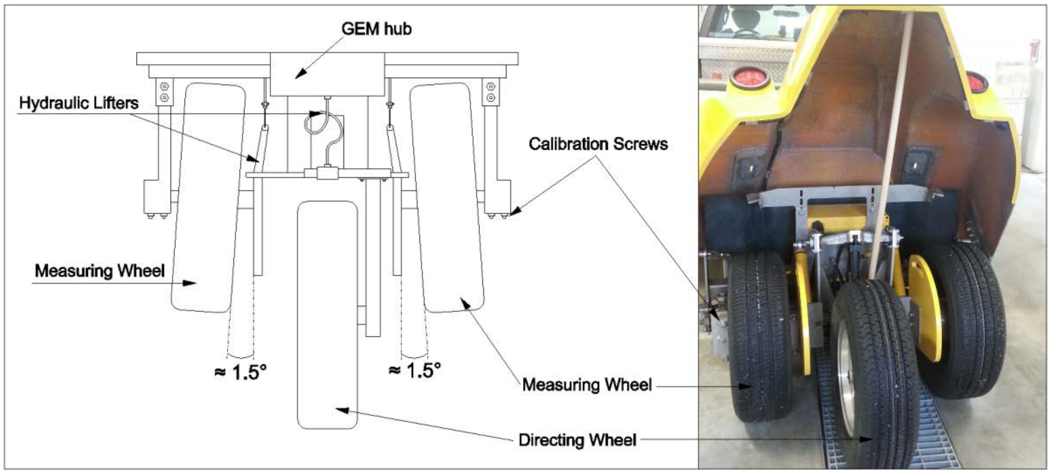


Figure 3-3. (Left) schematic plan view of the RT3-Curve; (Right) picture of the RT3-Curve trailer.

The vertical load on the RT3-Curve's measuring wheels is applied through a hydraulic system. The lateral friction coefficient is reported as the Halliday Friction Number (HFN) in the range of 0 to 114. The machine is accessorized with several features to facilitate operational applications. One of its main features is a control panel placed inside of the vehicle, which is used to run the machine as well as to display the HFN values in real-time at the desired frequency. To provide a quick evaluation of the road conditions, three colored lights (green, yellow, and red) characterize the HFN values. For HFN values of 71-114, the green lights illuminate, indicating safe driving conditions. Yellow lights illuminate for HFN values of 51-70, indicating that driving requires caution, and red lights illuminate for HFN values of <50, denoting unsafe conditions that require immediate treatment. A smartphone's Global Positioning System (GPS) is used to assign geographical coordinates to each HFN measurement. For this study, the HFN data (at 1 HFN precision) and the vehicle's speed, coordinates, and kilometers were collected at three-second intervals for green conditions and one-second intervals for yellow and red conditions. Data points are also projected in real-time in their corresponding colors on Google Earth and Open Street Maps.

3.4. Experiment Details

3.4.1. Test Road

Aside from winter road conditions, a number of external factors, such as tire properties, road surface type and texture, vehicle model and specifications, and device features, can affect the values obtained from a friction measurement device (Nixon 1998). To keep the external variables constant, the tests for this study were performed on one test road, which is part of the University of Alberta's Integrated Road Research Facility (IRRF). The 500-m, two-lane AC test road is the access road to the Edmonton Waste Management Center (EWMC) that was constructed in summer 2012 and has not been opened to traffic yet. The 300-m center portion of each lane was used for the friction measuring tests, leaving 100 m for gaining speed, stopping, and turning at each end. The RT3-Curve trailer was mounted on a Ford F150 owned by the City of Edmonton and operated by their designated driver.

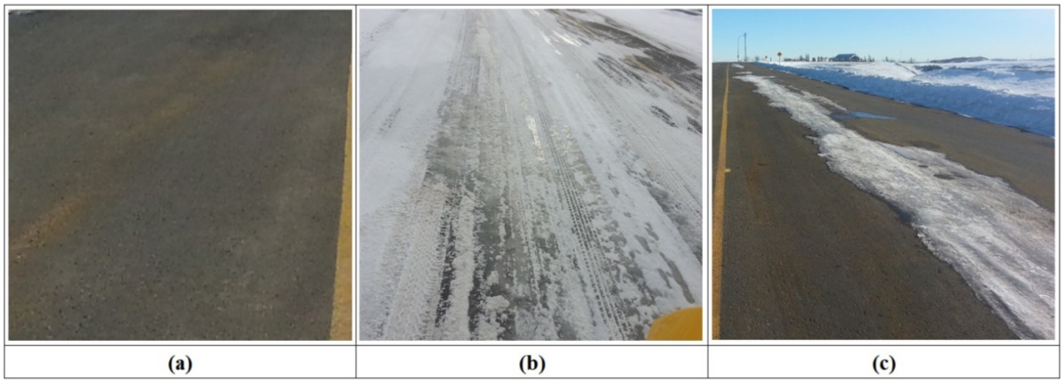
3.4.2. Test Variables

To simulate driving conditions within the city, the tests for this study were conducted at three speeds of 30, 50, and 60 km/h. The test truck was driven approximately 25 km to the test road before each test event. It is expected that this distance allowed for the tire pressure and temperature to reach equilibrium prior to testing. The RT3-Curve measuring wheels used new Bridgestone Insignia SE200 tires with an average tread depth of eight millimetres and an average inflation pressure of 187.5 kPa, both of which remained relatively constant during all test events. The friction measurements for this study were taken during five days in February and March 2013, covering a variety of ambient and road conditions. Major meteorological indices for each test day were extracted from the EWMC's closest weather station, approximately 400 m from the test road. Average ambient temperature during testing for each day is provided in Table 3-1. The ambient temperature for all five test days ranged from -3.5 to -17.5 °C. There was no precipitation during the test events, except for March 21, when it was snowing heavily.

Table 3-1. Road and Weather Conditions during Different Test Days.

Main Category	Road Surface Conditions	Test Event Date	Ave. Air Temp. during Testing (℃)	Weather Condition
Dry & Ice	- 100 m of ice at northern end followed by 200 m of bare dry on left lane - Dry with one large ice patch along right lane	Feb. 14 2013	-3.5	Mostly cloudy
		Feb. 21 2013	-5.0	Foggy and cloudy
Snow	- 3-10 cm of fresh snow on right lane (moderate snow) - 1-3 cm of fresh snow on left lane (light snow)	Mar. 14 2013	-17.5	Snowy
	- 1-3 cm of fresh snow (light snow)	Mar. 18 2013	-13.0	Snowy with ice crystals
	- 10-15 cm of fresh snow (heavy snow)	Mar. 21 2013	-8.0	Snowy

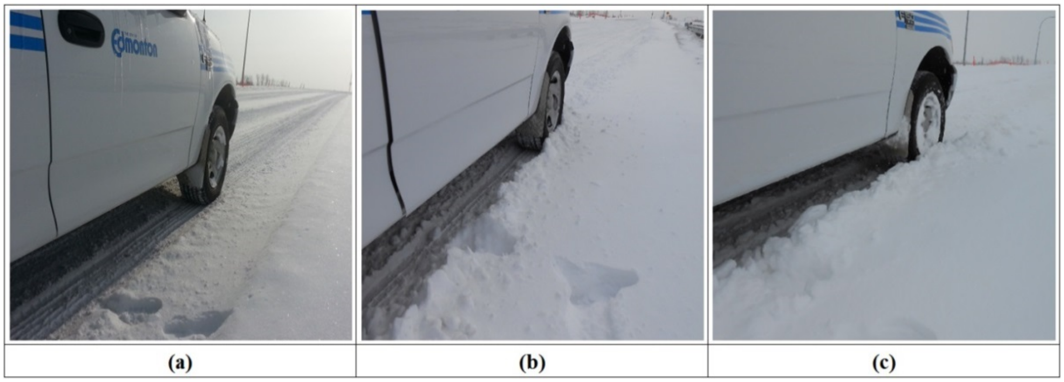
A picture of each condition encountered during the test events on February 14 and 21 is provided in Figure 3-4. During both days, 200 meters of the left lane was bare dry [Figure 3-4 (a)], followed by the first 100-m northern section of the left lane, which was completely covered with ice [Figure 3-4 (b)]. The right lane was dry but included one continuous ice patch along the lane [Figure 3-4 (c)]. When driving in the right lane, the truck’s wheels were on the two sides of the ice patch, while the RT3-Curve trailer generally rode directly on the ice patch; however, in some areas the ice patch was smaller than the RT3-Curve’s wheelbase, resulting in a variety of friction values recorded for this lane.



(a) (b) (c)

Figure 3-4. Road conditions on February 14 and 21; (a) Dry: 200-m of left lane; (b) ice: 100-m of left lane; and (c) dry with an ice patch: right lane.

Tests were also performed on three levels of snow accumulation during three different test events on March 14, 18, and 21. During the first snow test event (March 14), the left lane was covered with light snow (1-3 cm), as seen in Figure 3-5(a); whereas the right lane received a moderate amount of snow (3-10 cm), as evident in Figure 3-5(b). On March 18, both lanes were covered with light snow (1-3 cm), as seen in Figure 3-5(c). March 21 included tests on heavy snow (10-15 cm) in both lanes. According to Climate Canada (2013), the snowfall on March 14 was the first snow event after several weeks of no precipitation, therefore fresh snow on bare AC was tested that day. However, sporadic snowfalls were reported between this event and the following test day on March 18. Thus, the tests on March 18 were performed on the snow accumulated over the previous four days. No snow fell between March 18 and 21; snowfall started early on March 21, therefore tests on this day were performed on fresh, heavy snow.



(a) (b) (c)

Figure 3-5. (a) Light snow: left lane on March 14 and both lanes on March 18; (b) moderate snow: right lane on March 14, and (c) heavy snow: both lanes on March 21.

3.5. Test Results and Analysis

3.5.1. Speed Dependency

Literature regarding tire and dry road friction coefficients also indicates that in general, the friction coefficient is not affected by driving speeds ranging between 30 and 100km/h, however, friction will increase substantially at speeds of 160 km/h and above (Klamp 1977). Several friction measurement devices are proven to be reliable only in a limited speed range because of the sensitivity of their measurement mechanism to testing speed. However, for a friction measurement device to become widely-used in winter maintenance equipment fleet, it should be compatible to different testing circumstances, hence different testing speeds. Therefore, as part of the analysis, the reliability of RT3-Curve measurement data at different speeds is investigated.

As discussed previously, RT3-Curve measurements were taken on each lane at three different speeds of 30, 50, and 60 km/h, with runs repeated three times at each speed. Two test events on February 14 and 21 were conducted on the 200-m dry surface and 100 m of ice-covered surface in the left lane, and the 300 m of dry surface with a long ice patch in the right lane. During the three test events in March, the road section was covered with different amounts of snow (light, moderate, and heavy). Speed-dependency of the measurements for three of the four main road conditions of bare dry and ice (data from tests performed on

February 14 and 21) as well as snow (data from tests performed on March 14, 18, and 21) was investigated in Figure 3-6. Data from the measurements on the right lane on February 14 and 21 (dry with an ice patch) was not included in this analysis as the ice patches resulted in a wide variability in measurements, making it difficult to isolate the sole effect of speed.

No specific trend can be noted in friction for any of the three surface conditions in Figure 3-6 with respect to the driving speed. The low values of the coefficient of determination (R^2) for the linear regression fit to the three sets of data in the figure indicate that there is no correlation between the speed and the friction values measured by the RT3-Curve. The regression, for the ice condition, shows the highest R^2 of the three data series. However, it should be noted that the decreasing trend seen in the data is most likely due to the ice melt water produced with more passes of the test truck, which lubricates the surface and decreases the friction. The results of the speed analysis confirm similar findings in other studies that show that the RT3 friction coefficient is not speed-dependent (Engstrom *et al.* 2008; Tilley *et al.* 2008 and 2012).

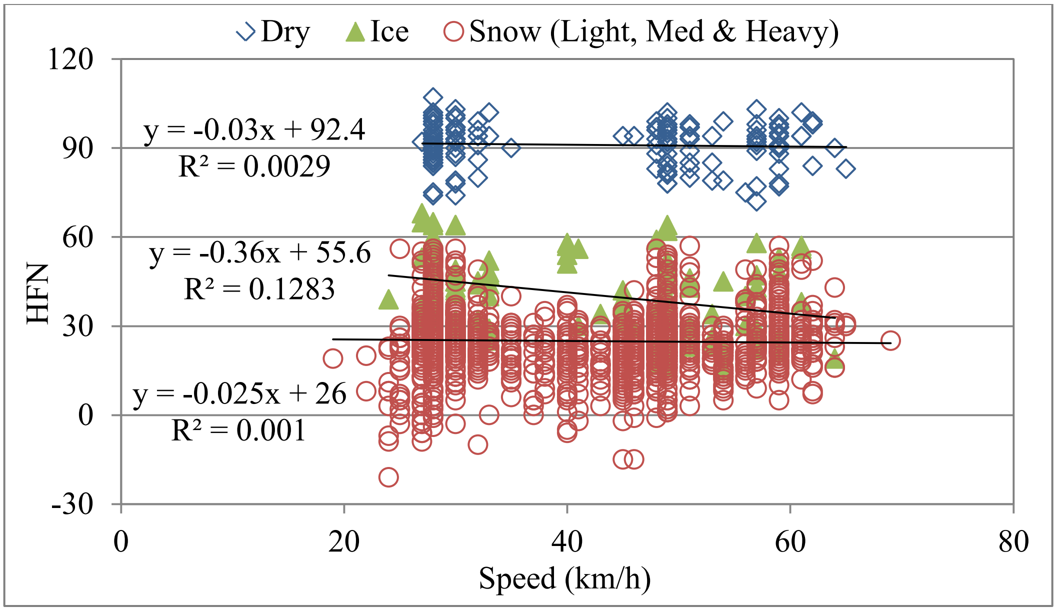


Figure 3-6. Analysis of speed-dependency of friction for three road conditions.

3.5.2. Tire Friction with Dry and Icy Surfaces

Following the speed analysis, the effect of different winter contaminants on the friction data was investigated. Figure 3-7 shows the number of data points, average, first and third quartiles, minimum, and maximum of all measurements taken at the three target speeds for the road conditions during February's tests. Figure 3-7 indicates that, as expected, the highest friction values were achieved for the bare dry condition, ranging from 72-107, with an average of 91. For the dry surface with the ice patch, friction ranged from 20-106, with an average of 63 (31 percent less than the bare dry condition). As mentioned previously, on the right lane, the RT3-Curve's measuring wheels rode over both dry and icy sections; resulting in a wide range of friction values for this lane.

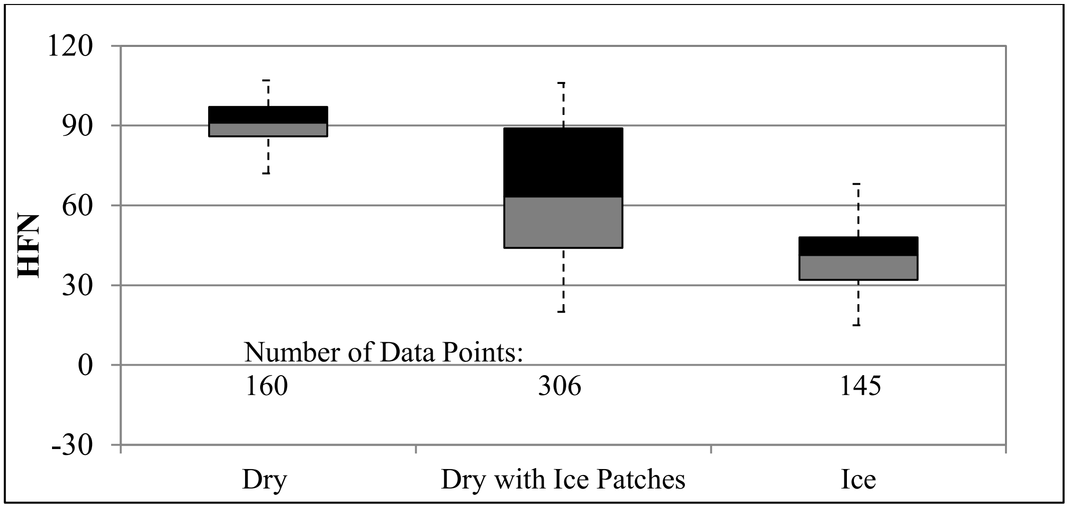


Figure 3-7. Lateral coefficient of friction for bare dry, dry with ice patches, and ice.

There are two reasons for the differing number of data points between the dry and dry with ice patch conditions: (1) the bare dry condition on the left lane was 100 m shorter than the dry surface with ice patches in the right lane, resulting in fewer data points; and (2) to facilitate data collection, data points were recorded at three-second intervals for the green zone (left lane), while data points for the yellow and red zones (conditions in the right lane) were collected at one-second intervals. The friction values collected on ice were low, ranging from 15-68, with an average of 40, which dropped by 55 and 35 percent compared to the bare dry and dry with the ice patch conditions, respectively. As discussed in the "Background" section of this paper, friction on ice decreases compared to a bare dry surface for two reasons: (1) adhesion between the AC layer's asperities and the rubber does not occur; and (2) the AC asperities are covered with ice, causing minimal deformation in the tire and, consequently, low hysteresis losses.

3.5.2.1. Further Discussion on Tire-Ice Friction

The average friction value of 41, seen previously in Figure 3-7, can be considered a relatively high value for ice. It should be noted that the ice tested in this study was not solid, polished ice as seen in Figure 3-4 (b) and instead, consisted of ice particles and crushed ice. This resulted in the formation of better adhesion bonds between the ice and the tire, as well as more deformation in both the tire and the ice (scratching the ice surface). Sensitivity of RT3 units to ice texture was also noted in the study conducted in Sweden on a frozen lake, as discussed in the “Introduction” section of this paper. The study’s results revealed that the HFN values can range from a minimum of 20 on a polished ice surface to a maximum of 90 on a plowed ice surface (Engstrom *et al.* 2008).

Next, the effect of the number of passes of the test truck on the ice was investigated for February 14 and 21 (Figure 3-8). A declining trend is evident in the average HFN values with respect to the number of truck passes over the ice. Although test data gathered on February 21 shows greater variability compared to that collected on February 14, the declining trend in the average friction with respect to truck passes is clear for both days. The observed trend implies that more tire passes over the icy surface resulted in the creation of a thin melt water film, especially since the ambient temperature varied between -5 to 0°C during the tests; this confirms the results of previous studies (Klein-Paste and Sinha 2010a; Klein-Paste and Sinha 2010b; Roberts 1981). This finding is especially critical for municipalities and highway agencies as it implies that icy conditions can be increasingly dangerous to drive on depending on the ambient temperature.

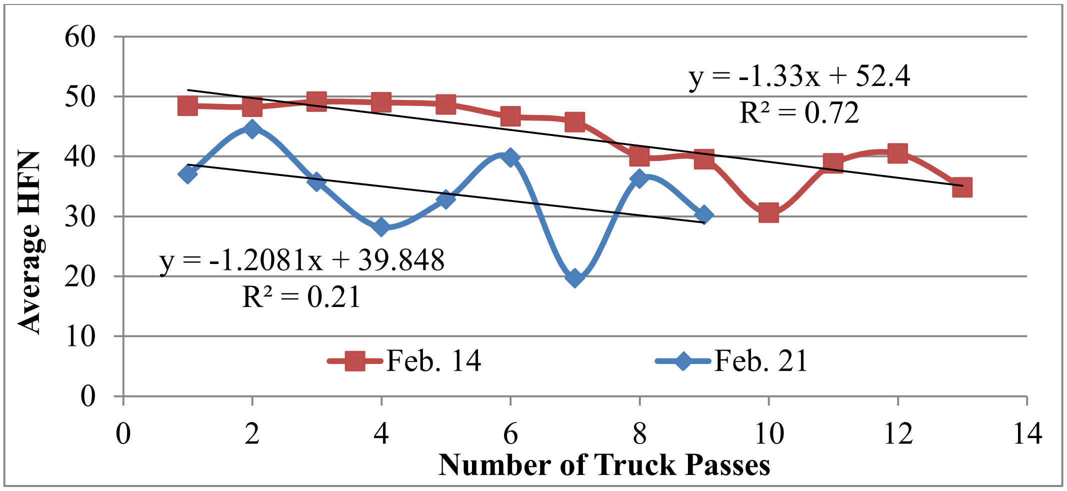


Figure 3-8. Effect of the number of truck passes on average HFN of each run over ice for the two test events on Feb. 14 and 21.

3.5.3. Tire-Snow Friction

Figure 3-9 shows the number of data points, average, first and third quartiles, minimum, and maximum of the measurements taken at the three target speeds for the three snow-covered conditions in March. Snow-covered conditions were categorized into three groups of light, moderate, and heavy based on snow accumulation. It should be noted that the difference seen in the number of data points for the three snow conditions is because the light snow includes data from three lanes (one on March 14 and two on March 18), whereas the moderate snow only includes data gathered on one lane (right lane on March 14). Also, because of unsafe driving conditions on March 21, fewer runs were performed over the heavy snow than were performed on the other two test days.

A decreasing trend in the HFN is noted from light to moderate to heavy snow, implying that as snow accumulated on the ground, driving conditions worsened. A similar trend has been observed in other tire-snow friction studies (Coutermarsh and Shoop 2009; Wallman *et al.* 1997). As seen in Figure 3-9, average HFN dropped 32 percent (from 41 to 28) from ice to light snow. Friction values for light snow ranged widely from -1 to 57. Moderate snow showed a 20-percent drop in friction compared to light snow. HFN for moderate snow ranged from 7 to 37, with an average of 23. The lowest friction was obtained for heavy snow, ranging from -21 to 36 with an average of 17. Average HFN dropped 26 percent from moderate to heavy snow (from 23 to 17). It should be noted that the reason for negative values in the measurements is due to the entire RT3-Curve trailer slipping to the right or left in moderate and heavy snow conditions, resulting in a negative angle between the measuring wheels and the longitudinal axis.

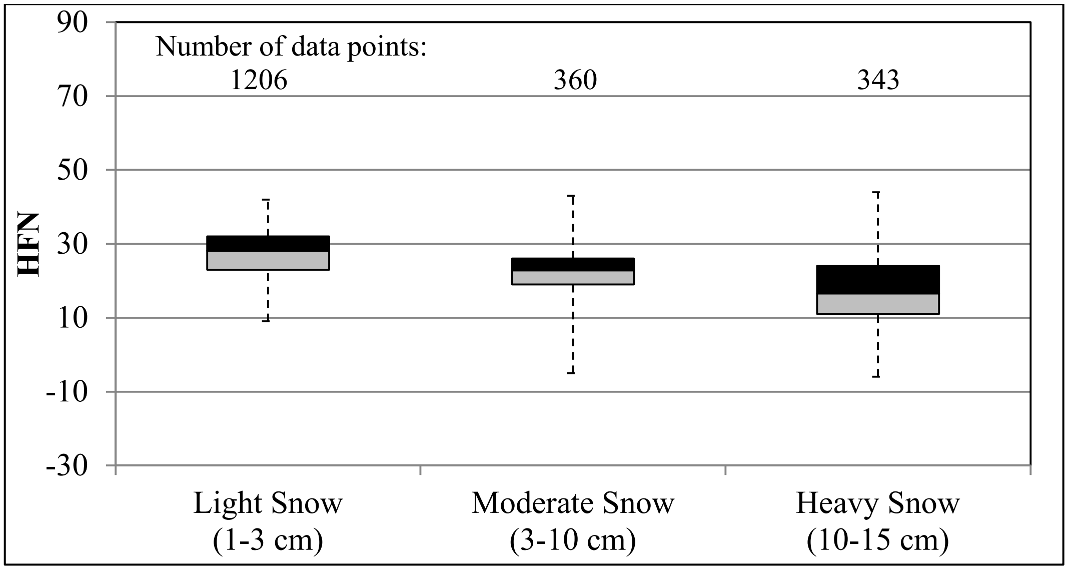
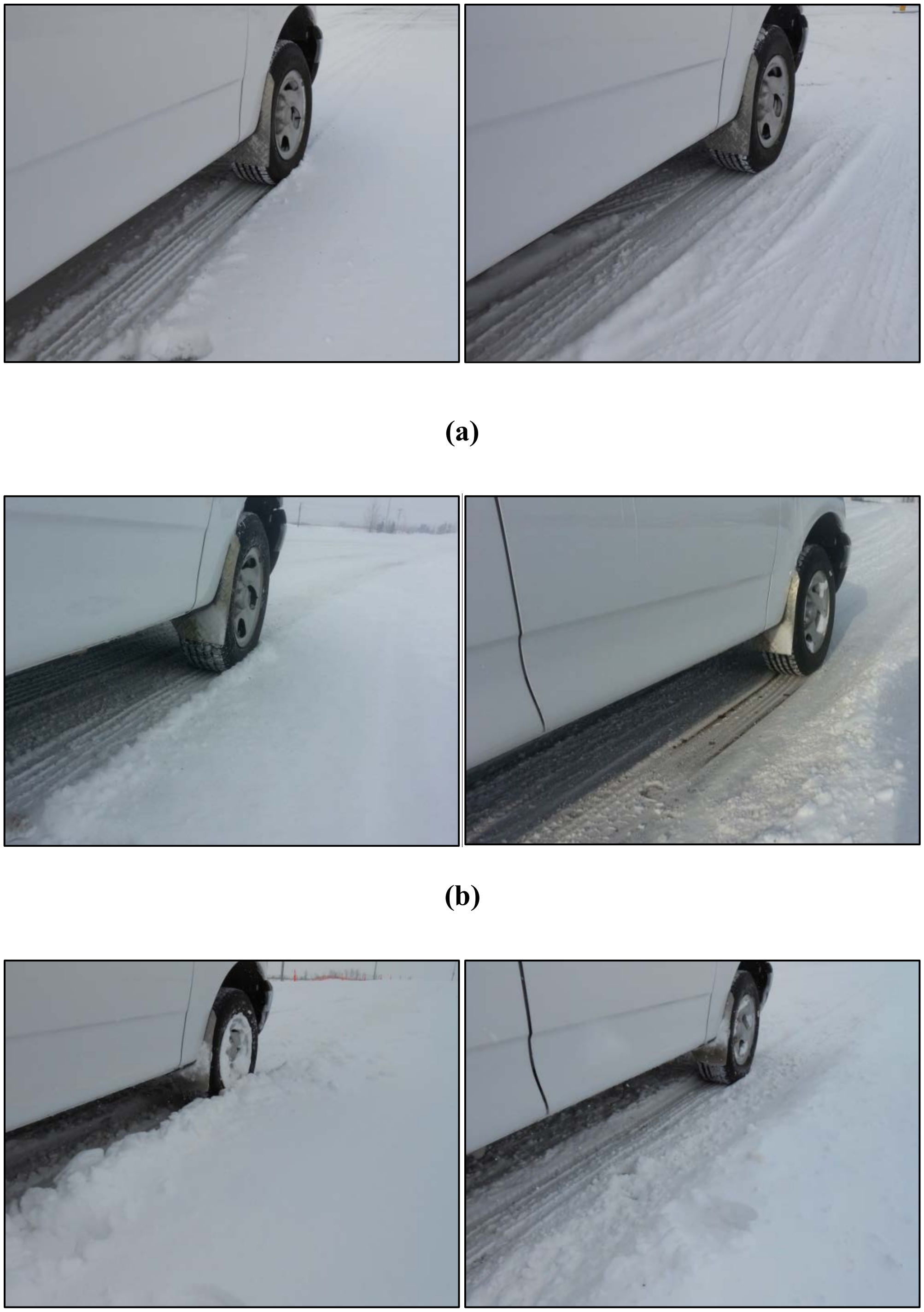


Figure 3-9. Lateral coefficient of friction for three snow groups of light, moderate, and heavy.

3.5.3.1. Further Discussion on Tire-Snow Friction

The effect of traffic on packing snow as well as the effect of frictional heat on melting snow and their consequent effects on tire-snow friction is a critical issue, when investigating tire friction on snow-contaminated surfaces. Municipalities typically follow predetermined policies that define when streets must be cleared of snow by following a snowstorm. During this time interval, vehicles travel over fresh snow; therefore, an analysis on the effect of traffic passing on snow can help investigate the status of roads safety in this particular period of time. In this section, the effect of passes of the test truck during each test day was investigated.



(a)

(b)

(c)

Figure 3-10. Pictures of the test road conditions during the runs at the beginning (Left) and runs at the end (Right) of each fresh snow condition: Mar. (a) 14, (b) 18, and (c) 21.

The pictures in Figure 3-10 (a, b, and c) show the effect of the test truck passes during the three snow test events on March 14, 18, and 21. Although the number of truck passes during the experiment is considerably less than typical hourly traffic for arterials, their effect is undeniable.

Average friction of the road for each run was compared to the number of passes in Figure 3-11 (a, b and c) for March 14, 18, and 21, respectively. Figure 3-11 (a) shows an evident declining trend in the tire-snow friction as the number of passes increases. It should be noted that during this test event, the left lane received light snowfall, while the right lane was covered with moderate snow. However, regardless of the snow accumulation, both lanes show a similar trend with respect to traffic at two different friction levels. The declining trend in friction can be the result of the vehicle passes packing the snow and frictional heat creating a film of water over the packed snow surface (Engstrom *et al.* 2009). The relatively strong declining correlation between friction and the number of vehicle passes implies that, if treatment is not timely, light or moderate snow on arterials would be packed into a less tractive surface as traffic increases.

Conversely, an increasing trend is seen in Figure 3-11 (b) for the light snow conditions prevalent during test on March 18. The correlation between the HFN values and the number of truck passes is relatively strong. The increasing trend can be explained by the fact that, unlike the conditions on March 14, the light snow accumulation on March 18 started to melt due to frictional heat, resulting in asphalt exposure with higher friction values. See the pictures in Figure 3-10 (a and b).

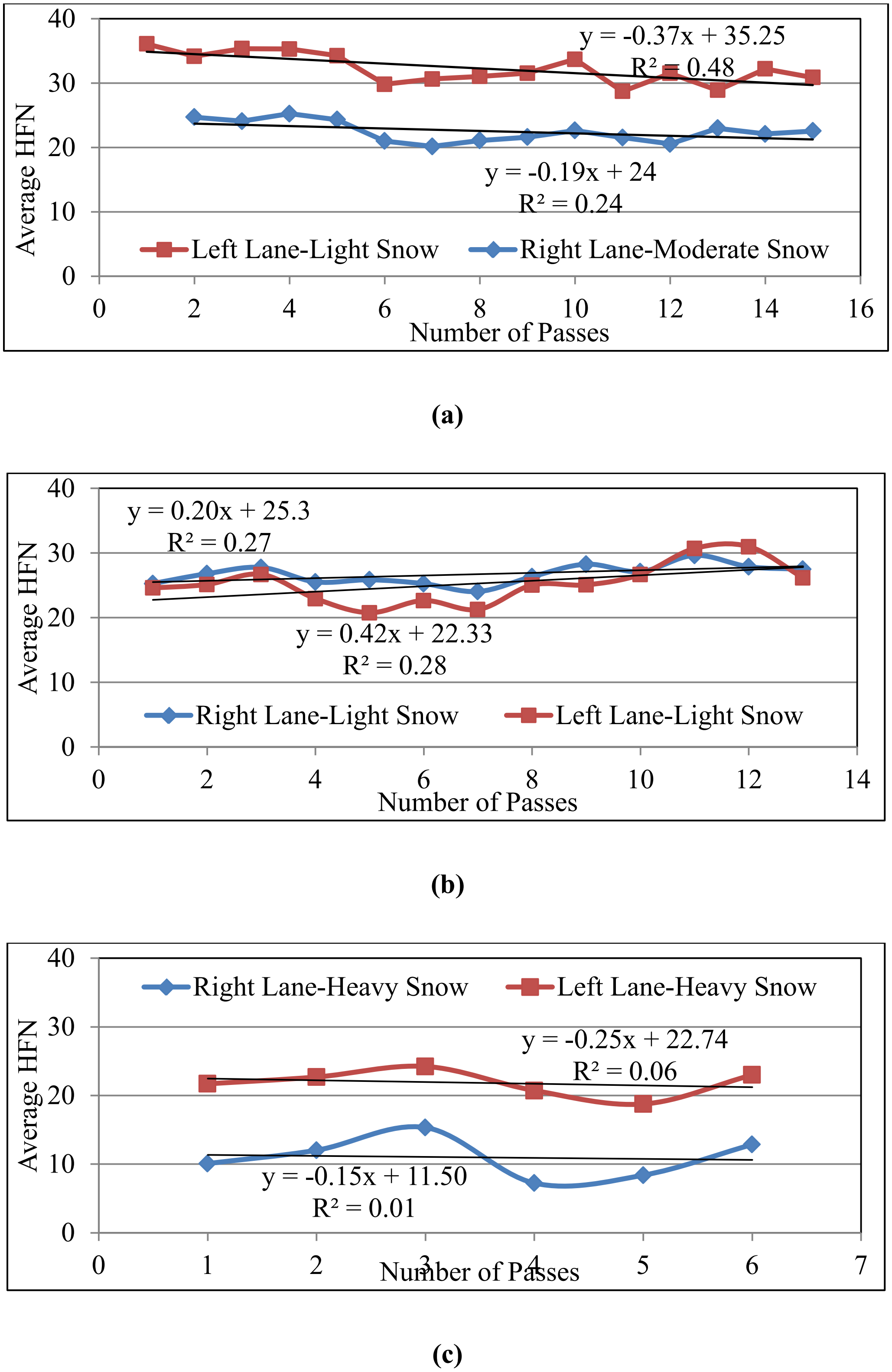


Figure 3-11. Effect of number of truck passes on average HFN of each run for three snowy test events on Mar. (a) 14; (b) 18, and (c) 21.

Figure 3-11 (c) presents the runs conducted on heavy snow on March 21. As seen in this figure, no considerable correlation exists between the HFN and the number of truck passes. The reason for this behaviour can be due to the driver's steering control, which was poor during the runs on the thick snow, causing the truck to pass over different paths during the runs. Therefore, as seen in Figure 3-10 (c), even after several runs, the snow was heavy and could be packed further. Yet, more investigation on such condition is required to capture the compaction effect of traffic passes.

3.6. Conclusions

The friction behaviour of tire with ice and snow was investigated in this study using the RT3-Curve, a side-force road friction measuring device, through five test events in February and March 2013. The experiments were performed on the University of Alberta's test road in Edmonton by driving the test truck at target speeds of 30, 50, and 60 km/h over various road conditions. A range of road conditions were covered over the five events, including bare dry, dry with an ice patch, ice, and three levels of snow accumulation. Analysis on the main winter conditions of bare dry surface, dry with ice patches, ice, and three levels of snow accumulation showed that:

- Friction measurements for dry, ice, and snow conditions did not reveal any speed-dependency. No considerable correlation was found between the vehicle speed and the friction coefficient in the studied range of target speeds (30, 50, and 60 km/h).

- Bare dry surfaces had the highest friction values with an average of 91. Ice patches on a dry surface caused a drop in friction, thus the variability of total friction values increased considerably, while the average decreased by 31 percent.

- Ice showed 55 percent less friction compared to bare dry conditions. The ice particles and crushed ice on the tested area resulted in higher friction values for the ice when compared to snow. Analysis of the effect of traffic on tire-ice friction at -3.5 and -5°C showed a decreasing trend in average HFN as truck passes increased. This behaviour implies that tire passes removed the ice chips from the surface and potentially created a water film on top of the ice, creating a more slippery surface with less friction after each pass.

- Light, moderate, and heavy snow reduced the dry surface friction significantly by 69, 75, and 81 percent, respectively. This revealed that even a light amount of snow (1-3 cm) can cause a drastic drop in the friction coefficient and result in dangerous driving conditions. A descending trend was observed in friction values from light to moderate to heavy snow, implying that friction drops as the snow accumulates.
- Analysis of the effect of traffic on tire-snow friction revealed that more traffic over snow thicker than 3 cm, at temperatures below -15°C, will compact the fresh snow into a slippery surface, revealing that roads covered with a moderate amount of snow need to be plowed as soon as possible. For less snow accumulation, even at low temperatures (<-10°C), passes of traffic will melt the snow through frictional heat, resulting in higher friction values.

4. Chapter 4: Using Lateral Coefficient of Friction to Evaluate Effectiveness of Plowing and Sanding Operations[2]

4.1. Introduction

During the winter, returning streets to safe driving conditions in a timely manner to facilitate mobility and avoid collisions is the main priority of municipalities in cold regions (O'keefe and Shi 2006). Winter road operations in Canadian cities can involve a variety of activities. Operations include proactive road treatment through the application of de-icer compounds prior to snowstorms to prevent ice/snow bonding to the pavement (C-SHRP 2000) and clearing or removing snow from the streets during and after a snowstorm according to a priority plan. Typically, street-salt (and/or chemical de-icers) and abrasives mixed with salt and pre-wetted with brine or chemical de-icers are applied to road surfaces to provide temporary traction.

Many of the winter road maintenance decisions, especially those involving the application of abrasives, are typically made based on empirical data and simple rules-of-thumb. Street-salt and sand are commonly applied generously, despite the environmental and aesthetic impacts of over-application. Further, the effectiveness of these operations in enhancing tire-road traction is not clear and has been criticised in recent studies (Nixon 2007; O'keefe and Shi 2006). Limited laboratory and field studies have focused on establishing the true effectiveness of plowing and the use of abrasives on improving tire-snow or tire-ice friction, as discussed below.

4.1.1. Background

One of the simplest methods for characterizing rubber tire-surface friction in the laboratory as well as in the field is the British Pendulum Tester (BPT). The BPT

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[2] A version of this paper was submitted to CSCE's Canadian Journal of Civil Engineering, Authors: Sahar Salimi, Somayeh Nassiri, Alireza Bayat

comprises a rubber-headed pendulum that contacts the test surface while swinging over a standard contact area when released from a certain falling height. The friction coefficient of the surface is established using the distance the pendulum travels after contact, based on the concept that higher surface friction impedes the pendulum's swing [ASTM E303-93 (2013)]. In 2010, a laboratory experiment tested sanded ice samples over a range of temperatures using the BPT. To avoid rolling, the sand particles were glued to the ice surface. Sanded ice did not show higher friction in the tested temperature range of -20 to 0°C (Klien-Paste and Sinha 2010a). In a microstructural laboratory experiment using the Etching and Replicating Method (ERT), the deformations of sanded and un-sanded ice under a rolling rubber tire were compared. When testing the un-sanded ice, slight deformations were observed including dislocated ice pieces that scratched the surface. More severe deformations were observed for sanded ice since the sand and ice particles deeply scratched the surface (Klien-Paste and Sinha 2010b). The Ministry of Transportation of Ontario (MTO) also performed a series of experiments to investigate the effectiveness of winter maintenance operations. These experiments included a laboratory study that used an all-season-tire pendulum in a controlled environmental chamber to investigate the influence of fine, medium, and coarse sand on ice and snow when applied at two different rates at temperatures of -18, -12, and -5°C. Application of fine, medium, and coarse sand on snow at a rate of 570 kg/two-lane km resulted in friction coefficients of 0.18, 0.16, and 0.20 at -18°C; and 0.22, 0.18 and 0.20 at -12°C, respectively. The same application rate on ice resulted in lower friction coefficients of 0.12, 0.11, and 0.10 at -5°C, and 0.16, 0.15, and 0.17 at -18°C for fine, medium, and coarse sand, respectively. All three types of sand were then applied at a higher rate of 1,140 kg/two-lane km under the same conditions. Comparison between the two application rates showed that at -18°C, coarse sand resulted in the highest friction coefficient for snow, while at -12°C, fine sand effected friction the most positively. It was also found that high sanding rate did not considerably affect the ice at -18°C; however, 17, 18, and 70 percent improvements were observed in the friction coefficient at -5°C for fine, medium, and coarse sand, respectively (Perchanok *et al.* 1997). The findings from the laboratory experiments discussed above implies that the effect of more aggressive winter road treatments on friction is not always positive and in fact can be very complex, since it depends on not only on the road surface condition but also the surface temperature, abrasive material type and rate of application.

In addition to laboratory tests, various friction measuring devices have been developed to evaluate the in-situ surface friction of pavement surfaces. These devices vary in configuration and measuring mechanisms. The most commonly used ones include an(two) extra wheel(s), either fully- or partially-locked to simulate a braking event with and without an anti-lock braking system (ABS), respectively. Another type of friction-measuring devices, known as the side-force measuring devices, include a(two) measuring wheel(s) angled from the direction of travel, simulating a turning or cornering event. Apart from wheel-based devices, electronic devices such as decelerometers have also been used to characterize surface friction according to the vehicle's speed, deceleration, and stopping distance during a braking event.

The Norwegian Public Roads Administration used such technologies from 1998 to 2000 to perform winter road testing. ROAR and OSCAR, two devices with adjustable, partially-locked measuring wheels, were used to evaluate two different methods of sanding: A dry abrasive mixture, including 15-30 kg of salt per cubic meter of sand, was compared to an abrasive mixture wetted with near-boiling water weighing 30 percent of the mixture's weight. Both mixtures were applied at an average rate of 200 g/m^2. The average friction coefficient of a typical winter road is approximately 0.20, which increased by 0.18-0.20 when using the wet abrasive mixture, and only by 0.06-0.09 with the dry abrasive mixture (Dahlen and Vaa 2007).

Additionally, the MTO experiments also included field friction measurements conducted using a decelerometer. A positive correlation was found between the friction coefficient and sanding application rates up to 400-500 kg/two-lane km on medium-density snow regardless of its temperature. The same trend was noted for hard-packed snow at temperatures higher than -20°C. Hard-packed snow at below -20°C, as well as ice at above -20°C, showed a steadily increasing trend over the range of application rates (up to 800 kg/two-lane km); therefore, no optimum rate was found for these conditions. Another critical factor the MTO found to affect the friction coefficient of sanded surfaces was traffic. The experiment indicated that sand on ice and snow less than -15°C became less effective as traffic passes increased; however, different trends were observed for ice and snow above -15°C. For packed snow, a negligible decreasing trend was found between friction and traffic. For ice, this trend was positive, as the sun had melted the ice and traffic had scratched and roughened the ice surface (Comfort and Dinovitzer 1997). The effect of traffic on sanded surfaces was also reported as critical by other studies. In Germany, a study was conducted on sanded snow-covered highways, revealing that sand is blown off the road after only 10-12 vehicles passes at highway speeds (Nixon 2007). A study in Sweden on a road with an Average Annual Daily Traffic (AADT) of 500 showed that just a few hours following sand application, all sand has scattered from the road and then no friction enhancement were observed (Nixon 2007).

The studies reviewed above indicate that variables such as traffic pass and ambient temperature, as well as rate and method of application of sand can substantially influence friction gain. Each unique experiment reviewed above was conducted at a certain temperature range and application rate. Additional studies will help validate these findings and expand their scope to cover a wider range of variables. For instance, the effect of plowing on friction gain for ice surfaces and different accumulations of snow must be included in the experiment. Further, the friction measuring devices used in past studies, including the BPT, decelerometers, and locked-wheel systems, fail to accurately represent critical driving conditions on winter roads due to their intrinsic mechanism of measurement (Hall *et al.* 2009; Al-Qadi *et al.* 2002).

4.1.2. Objectives & Scope

This study aims at investigating the effectiveness of common winter road operations. The objectives of the study are listed as follows:

- To evaluate the effectiveness of plowing on different winter road conditions;
- To investigate the effectiveness of application of abrasive mixtures at different rates for different winter road conditions;
- To assess the effect of elapsed time since the treatment, traffic, and vehicle speed on effectiveness of the sanding operations for different winter road conditions.

4.1.3. Methodology

The Real-Time Traction Tool (RT3)-Curve (a side-force device) was used to evaluate the effectiveness of winter operations by measuring the lateral coefficient of friction. The RT3-Curve is specially designed to simulate light passenger and truck cornering and turning maneuvers and has proved to be reliable and very sensitive to changes in road surface conditions (WisDOT 2007; Tilley *et al.* 2007; Engstrom *et al.* 2008; Salimi *et al.* 2013). Typical abrasive mixtures used by the City of Edmonton, were applied using the City's sand spreader, and snowplow truck. Three common sanding rates of 100, 250, and 420 kg/one-lane km practiced by the City were used in the experiment. The tests were performed on the University of Alberta's Integrated Road Research Facility (IRRF)'s test road in Edmonton, Alberta, Canada, which was closed to traffic during the testing period, allowing for controlled test conditions. The tested road conditions included bare dry, dry with ice patches, ice-, and snow-covered surfaces.

To evaluate the efficiency of plowing, the mentioned road conditions were first tested in their existing conditions; they were then plowed to remove as much winter contamination as possible and the plowed surface's friction was then measured.

Further, to investigate the effectiveness of different sanding rates, three common rates of 100, 250, and 420 kg/one-lane km were applied to each plowed condition and road friction was measured after each sanding level. It should be noted that on snowy conditions, one round of medium sanding was also applied before plowing.

A statistical analysis was also conducted to establish the effect of elapsed time since the road treatment, traffic and vehicles speed on the surface friction.

4.2. Description of the Equipment

The Halliday RT3-Curve (Figure 4-1) is a towed-behind trailer with two measuring wheels and a third wheel used to steer when the measuring wheels are not operating. To replicate turning, the RT3-Curve measuring wheels are maintained at a fixed slip angle of approximately 1.5 degrees outward from the longitudinal axis of the vehicle (Figure 4-1), which changes according to surface friction. RT3-Curve measures the lateral friction force (F_Y) applied to the measuring wheels using a load cell installed in the Grip Evaluation and Management (GEM) hub (Figure 4-1).

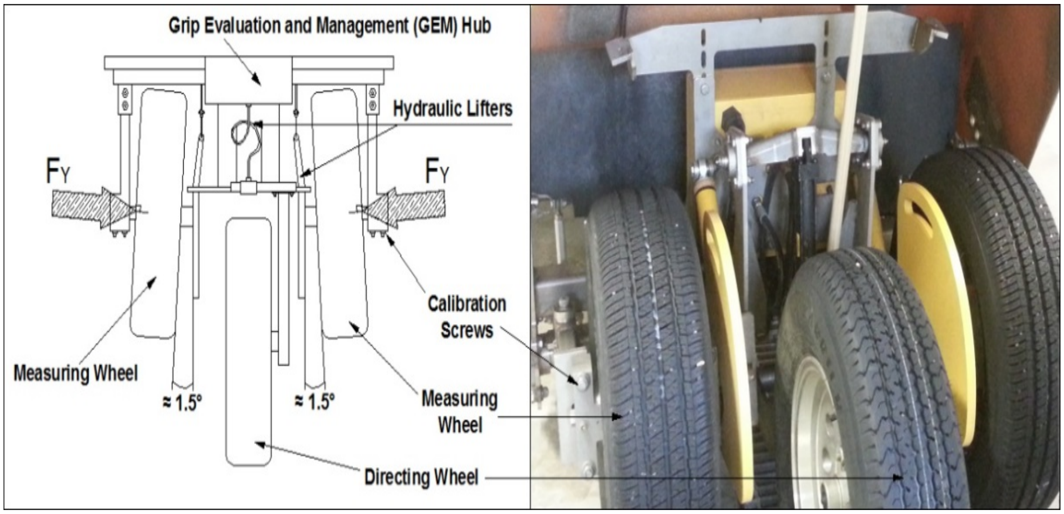


Figure 4-1. Schematic plan view of the RT3-Curve and a picture of the RT3-Curve trailer.

The F_Y applied on each wheel is measured at 100 Hz and is normalized by the vertical forces (F_Z) applied on the measuring wheels through the hydraulic system; to produce a lateral friction coefficient, L_C, according to Equation 4-1.

$$\boldsymbol{L_C = \frac{F_Y}{F_Z}} \qquad \textbf{Equation 4-1}$$

For RT3 machines, the average L_C from both wheels is called the Halliday Friction Number (HFN) ranging from 0 to 114 (Al-Qadi *et al.* 2002; Engstrom *et al.* 2012; D. Halliday (personal communication, 2013)).

The equipment is operated by a control panel installed inside the vehicle's cabin which displays HFN values in real-time. The control panel is connected to a smartphone via Bluetooth to transmit HFN data to an online database, as well as using its Global Positioning System (GPS) to locate each data point in online maps. The HFN values are displayed and reported in three different colors of green (safe driving conditions), yellow (require caution), and red (dangerous) for easy interpretation. The default thresholds for the three colors are, HFN > 70 for green, 50 < HFN < 70 for yellow, and HFN < 50 for red.

For the tests in this study, the RT3-Curve's measuring wheels were Bridgestone Insignia SE200. The tires were new with an average tread depth of 8 mm, a mean inflation pressure of 187.5 kPa, and a standard deviation of 6.9 kPa.

4.3. Description of the Test Road

As mentioned previously, all the tests were conducted on the University of Alberta's IRRF's test road in Edmonton, Alberta. The test road is a future access road to Edmonton Waste Management Center (EWMC) located in northwest Edmonton and was closed to traffic during the period for this study, allowing for controlled test conditions. The test road is nearly 500 m long and includes two driving lanes and hot-mix asphalt (HMA) wearing surface. Using traffic cones, the 300-m middle portion of the test road was marked as the testing section for this study, leaving 100-m at both ends for the driver to reach the desired test speeds (see Figure 4-2).

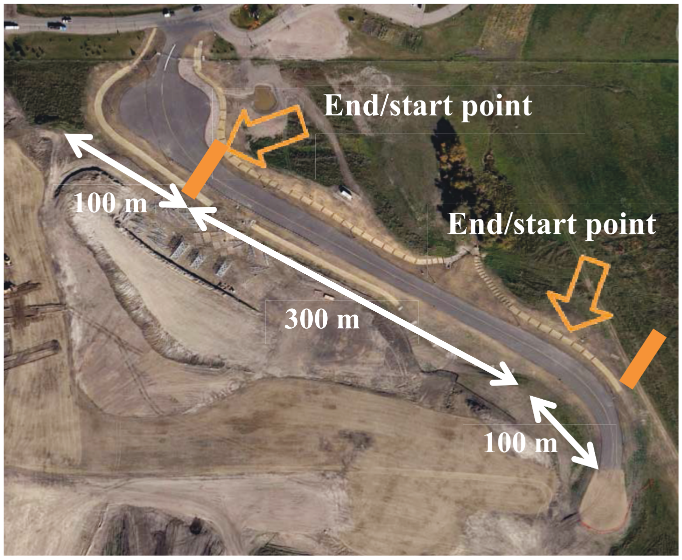


Figure 4-2. The test road image from Google Maps and the test section identification

4.4. Description of the Experiment

Test runs for this study were performed on three days (February 21 and March 4 and 21), as shown in Table 4-1. Major climatic indices during testing, including air temperature, relative humidity, wind speed, and dew point, were retrieved from EWMC's onsite weather station. All runs were repeated at three target speeds of 30, 50, and 60 km/h and three runs were conducted at each target speed.

During the test events on February 21 and March 21, friction measurements were taken initially on the existing road conditions and after plowing. Tests were then conducted after the application of abrasives at low, medium, and high rates of 100, 250, and 420 kg/one-lane km, respectively. The abrasive mixture included four percent salt on February 21 and 50 percent salt on March 21, representative of the City's stockpiles on those days. Friction measurements were performed immediately after sanding without delay. On March 4 no road treatment was conducted and only measurements were conducted to investigate the remaining effects of the treatment applied on February 21.

Table 4-1. Road and ambient conditions during testing.

Road Surface Condition	Test Date	Operation Type	Avg. Ambient Temp. (℃)	Avg. Relative Humidity (%)	Avg. Dew Point (°C)	Weather Condition
Left lane: bare dry with an ice sheet (~100-m) at the northern end. Right lane: dry with ice patches.	Feb. 21 2013	Plowing & Sanding	-5.0	88	-6.5	Foggy & Cloudy
Dry with residual sand	Mar. 4 2013	None	-3.5	79	-4.5	Mostly Cloudy
10-15 cm of fresh snow	Mar. 21 2013	Plowing & Sanding	-8.0	100	-7.5	Snowy

4.5. Evaluation of Road Winter Maintenance Operations' Effectiveness

4.5.1. Bare Dry Surface and Dry Surface with Ice Patches

As described above, on February 21, the entire right lane was visually characterized as dry with ice patches, while the southern 200 m of the left lane was bare dry (the first 100 m was covered with ice which will be discussed in a separate section). Plowing and sanding operations were performed on both lanes, as explained previously. Figure 4-3 (a) and (b) show the conditions on the right lane before and after plowing; and Figure 4-3 (c) and (d) present the bare dry section of the left lane before and after plowing. It should be noted that although the left lane was bare dry before plowing, plowing cleaned and removed all external particles and debris from the road surface. The freshly sanded dry surface (both lanes) and the residual sand on dry surface conditions prevalent on March 4 are shown in Figure 4-3 (e) and (f), respectively.

Figure 4-4 (a) presents a statistical summary (average, first and third quartiles, minimum and maximum) of all friction data collected on dry surface with ice patches in the right lane on February 21. According to Figure 4-4 (a), after plowing, the average HFN improved from 76 to 84, since plowing cleared most of the ice patches, as evident in Figure 4-3 (b). Low sanding of the plowed surface resulted in a slight increase of four percent in tire-road friction. Medium and high sanding, however, reduced tire-road friction by 17 and 14 percent, respectively. The reason for irregular trends in the data is that sanding improved the friction on the remaining ice patches, while it reduced the friction on the dry sections.

A similar analysis was performed on the data collected from the bare dry section in the left lane. Average friction for this lane increased from 91 to 97, since plowing cleaned the surface from external particles. Figure 4-4 (b) shows that low, medium, and high sanding decreased friction values drastically by 11, 31, and 37 percent, respectively. Medium and high sanding reduced the surface friction to the point that the average HFN fell into yellow zone. These results confirm the findings of a past study on a bicycle trail, which revealed that sanded bare dry surfaces show significantly less friction compared to un-sanded dry surfaces (Wallman *et al.* 1997). This phenomenon can be because the HMA surface micro-texture cannot engage with tires while sand particles roll underneath the tires and is especially critical for drivers and bikers during the spring season before the residual sand is collected from the city streets.

Figure 4-3. Dry road conditions during Feb. 21 tests: (a) dry surface with ice patches along the right lane, (b) plowed right lane, (c) bare dry surface on 200-m of left lane, (d) plowed left lane, and (e) sanded dry surface; (f) Residual sand on dry surface, Mar. 4.

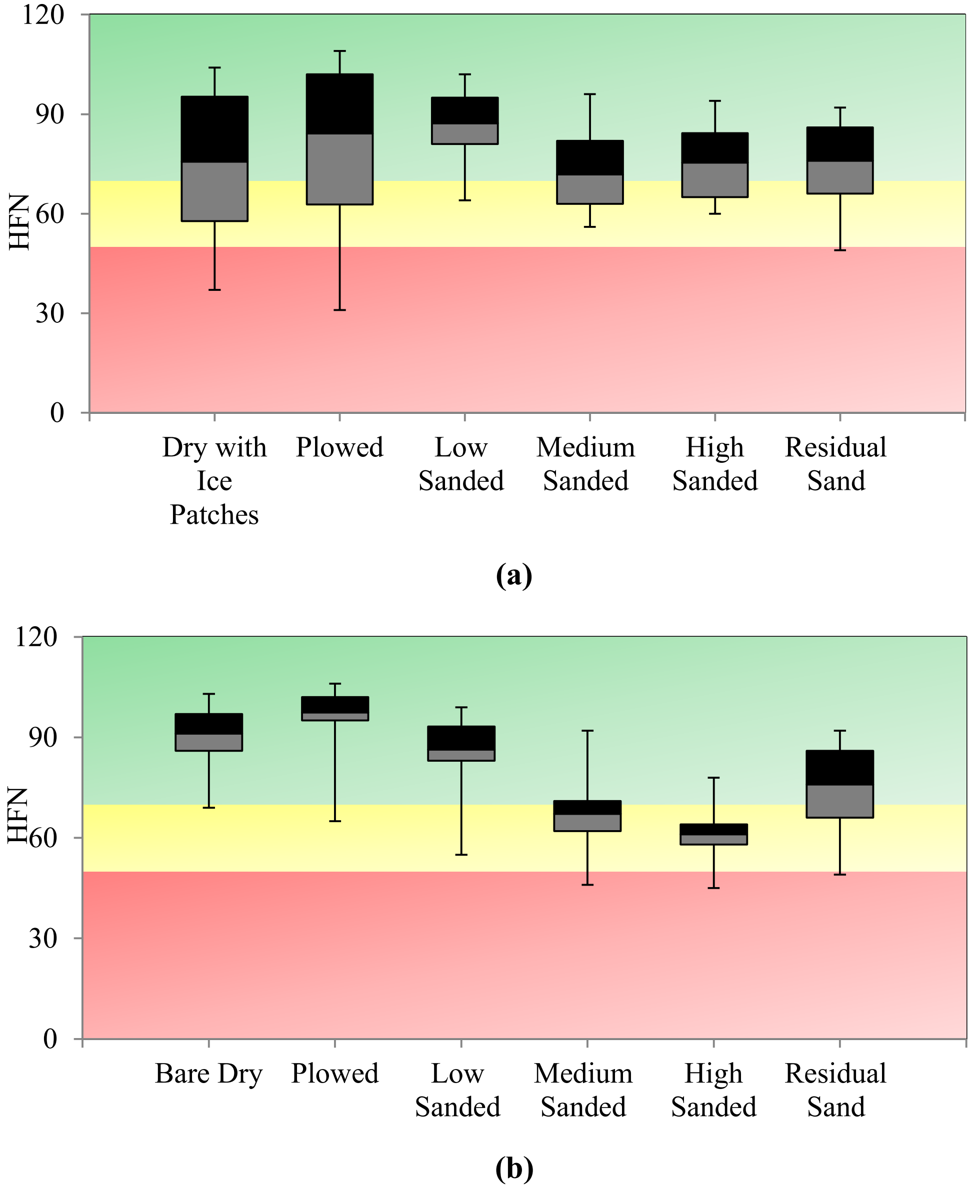


Figure 4-4. Effect of plowing and sanding on tire-road friction for (a) dry surface with ice patches (right lane); and (b) bare dry surface (left lane).

Sand from the operations on February 21 remained on the road when tests were conducted on March 4. Figure 4-4 (a) and (b) also include the data collected on the right and left lanes, respectively, on March 4. The improvement in tire-road friction on March 4 is especially evident in the left lane, where the surface was completely bare dry. Friction improved by 25 percent for this lane as the sand was scattered by the wind and melting snow during the previous two weeks.

4.5.2. Ice-Covered Surface

As indicated previously in Table 4-1, one third of the left lane was covered with ice on February 21. After initial friction measurements on the ice, this section was plowed and sanded as discussed in the "Description of the Experiment" section of this paper. Figure 4-5 shows the effect of plowing and sanding on the ice during this test event.


(a) **(b)** **(c)**

Figure 4-5. Icy road conditions during Feb. 21 tests: (a) Existing ice, (b) plowed ice, and (c) sanded ice after high sanding.

Figure 4-6 shows the statistical summary of all measurements taken on the ice-covered area of the left lane on February 21. An average HFN of 36 was obtained for this section. The tested ice was rough with crushed ice particles, resulting in higher friction than the polished ice due to scratching from the particles and an overall rougher macro-texture. According to Figure 4-6, plowing changed the range of tire-ice friction from 15-64 to 19-65, with a two-percent drop in the average HFN. This drop can be due to plowing procedures, which removed ice particles while polishing the ice into a smooth, slippery surface with the snowplow's blade. According to Figure 4-6, low sanding did not provide sufficient traction between the tires and ice and did not enhance friction values. However, medium and high sanding enhanced the average HFN by 23 and 43 percent, respectively. According to Figure 4-6, plowing did not change the ice friction (range of tire-ice friction changed from 15-64 to 19-65). Low sanding did not improve the friction between the tires and ice either. However, medium and high sanding enhanced the average HFN by 23 and 43 percent, respectively.

High sanding resulted in the highest friction values, with an average HFN of 50. Research has shown that sand, when situated between the tire and ice, can scratch the ice surface and create a rough micro-texture, which increases adhesion with the tire (Klien-Paste and Sinha 2010a). Note that after all the applied treatments, the average HFN remained in the red zone, implying that the surface condition did not satisfy safe driving conditions.

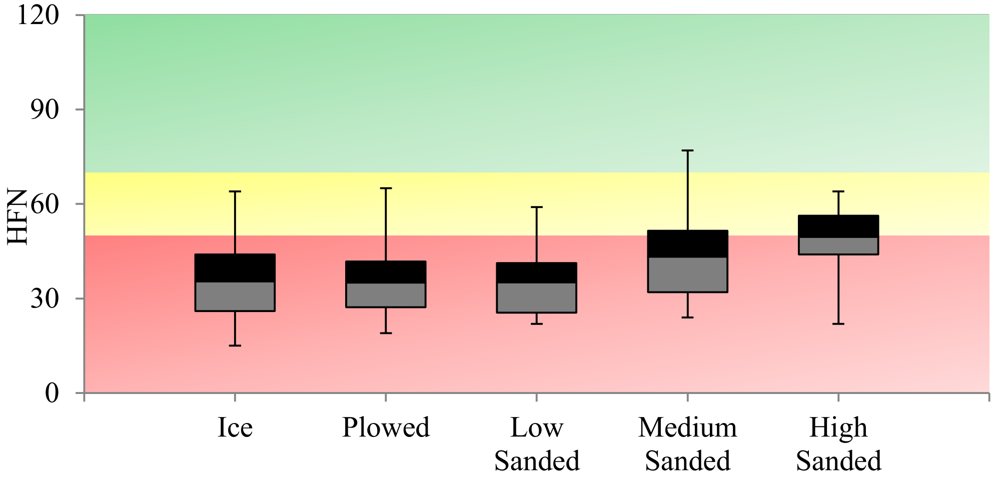
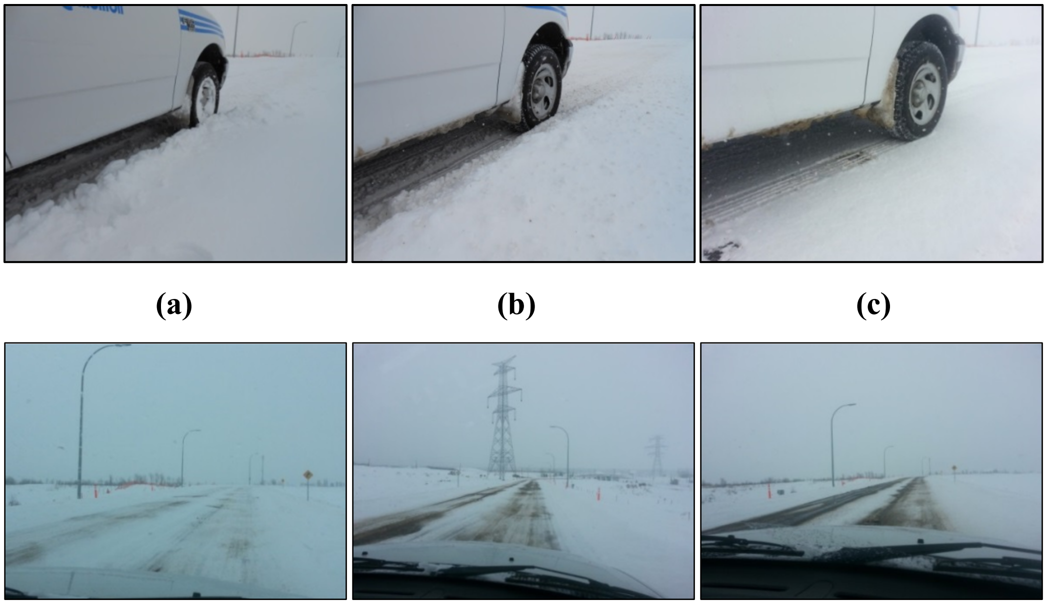


Figure 4-6. Effect of plowing and sanding on tire-ice friction.

4.5.3. Snow-Covered Surface

On March 21, a heavy snowstorm covered the test road with 10-15 cm of snow in both lanes. Immediately after the initial friction measurements on the fresh snow [Figure 4-7 (a)], both lanes were sanded at the medium rate [Figure 4-7 (b)]. Friction measurements were taken following the sanding, and the road was then plowed [Figure 4-7 (c)] and sanded at three rates of low [Figure 4-7 (d)], medium [Figure 4-7 (e)], and high [Figure 4-7 (f)]. Friction measurements were taken after each road treatment.



(a) **(b)** **(c)**

(d) **(e)** **(f)**

Figure 4-7. Snowy road conditions during Mar. 21 tests: (a) Heavy snow (10-15 cm), (b) medium sanded snow, (c) plowed snow, (d) low sanded, (e) medium sanded, and (f) high sanded plowed surface.

A statistical summary of the measurements taken on March 21 is presented in Figure 4-8. Medium sanding on the fresh snow did not have a significant effect on friction, perhaps because the sand was buried in the snow and did not contact the tires. Following sanding, the road was plowed, removing a considerable amount of snow and improving the tire-snow friction from 17 to 39.

It should be noted that low sanding the plowed snow slightly reduced the average HFN from 39 to 32: a trend contradictory to general belief that sand improves tire-snow friction. When the tires roll on the plowed snow, frictional heating can produce a film of melt water on top of the snow (Ella *et al.* 2013). Low sanding did not provide sufficient sand particles to enhance friction with the slippery, lubricated surface. The lubricated sand particles could have turned into small balls of ice under the tires, making the surface even more slippery.

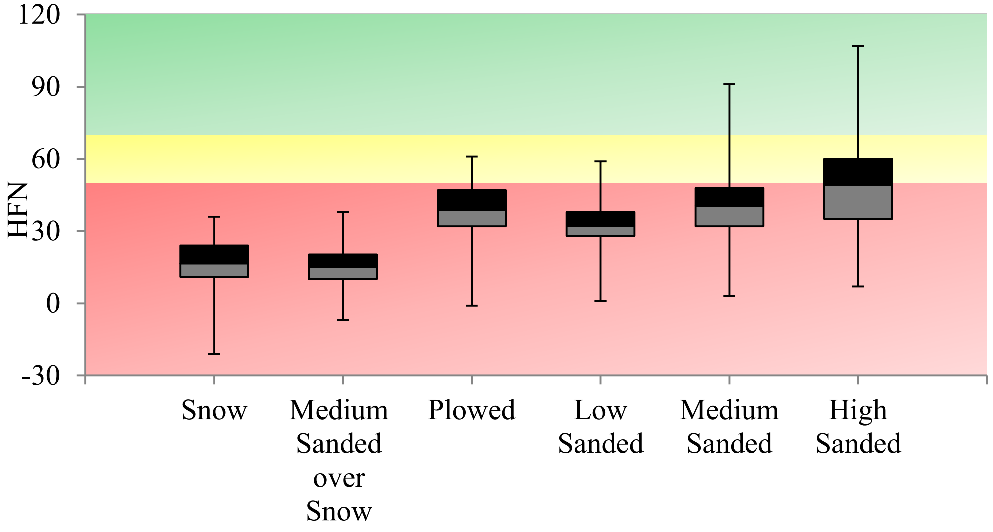


Figure 4-8. Effect of plowing and sanding on tire-snow friction.

According to Figure 4-8, medium sanding increased the friction range considerably from 1-59 after low sanding to 3-91, with an average of 40. High sanding improved both the average friction from 40 to 49 and the range from 3-91 to 7-107 when compared to medium sanding. Although medium and high sanding did considerably improve the snow and tire friction, the average HFN remained below 50, which falls in the dangerous driving condition area.

4.6. Effect of Speed, Traffic, and Time

The studies previously reviewed in the "Background" sections showed that traffic passes can scatter sand from the road surface, reducing the effect of sand on friction improvement (Comfort and Dinovitzer 1997; Nixon 2007). The amount of scattered sand may depend on vehicle speed. Additionally, abrasive mixtures typically contain salt, which can gradually melt the ice and snow; thus, time can also affect the HFN. Discussions in previous section revealed the effect of plowing and sanding on friction; however, the underlying effect of the number of passes, time, and speed of the test vehicle as well as the significance of the sanding rate are not evident. Since the effects of time, vehicle speed, and number of traffic passes on friction are interconnected, they cannot be treated as independent variables. As a result, a new variable (*STT*) was defined, which is a combination of all the three variables as follows:

STT = vehicle Speed $(\frac{km}{h})$ × *number of Traffic passes since each sanding operation* × *Time elapsed since each sanding operation until the start of its corresponding runs (minutes).*

A multiple linear regression analysis was performed on the collected friction data for all road surface conditions discussed previously. The dependant variables included in the analysis include *STT* and sanding rate. Table 4-2 shows the range of the HFN, variables used to establish *STT*, final *STT* and sanding rate for the runs performed on each surface condition. The time and number of passes assigned to the runs were zeroed after each sanding rate. Significant variables are identified as those showing p-values equal or less than 0.05, implying that these variables are correlated to friction at a 95-percent or higher confidence level. Table 4-3 summarizes the results of the regression analysis for the runs performed over each surface condition.

When applying the regression analysis to all sanding rates, the influence of *STT* on HFN for each sanding rate can be masked. Therefore, Pearson Correlations between *STT* and the HFN values within each sanding rate were also calculated. This simple statistical correlation identifies the linear relationship between two data series, while the corresponding p-value can show how significantly the two data sets are correlated.

Table 4-2. Range, average (Avg.) and standard deviation (SD) of collected data for all variables on tested road conditions.

Variable	**Bare Dry (Left Lane) [17 data points]**			**Dry with Ice Patches (Right Lane) [17 data points]**			**Ice-covered Surface [17 data points]**			**Snow-covered Surface [54 data points]**		
	Range	**Avg.**	**SD**	**Range**	**Avg.**	**SD**	**Range**	**Avg.**	**SD**	**Range**	**Avg.**	**SD**
Average HFN for each run	58-91	72	11	63-96	81	9.9	30-53	42	8	27-69	42	10
Speed (km/h)	28-60	45	12	28-59	45	13	28-60	45	12	28-59	45	12
Time elapsed between end of each sanding to start of corresponding run (min)	0.9-13	7	4	0.6-16	8	5	0.4-12	6	4	0.1-17	9	5
Number of passes after each sanding application	1-5 (low sanding) 1-6 (medium and high sanding)	-	-	1-6 (low and medium sanding) 1-5 (high sanding)	-	-	1-6	-	-	1-9 (for each rate)	-	-
STT (km.min/h)	28-359	176	112	19-5755	1879	1753	10-4205	1421	1366	4-9196	3126	2928
Sanding Rate (kg/one-lane km)	100, 250, 420	-	-	100, 250, 420	-	-	100, 250, 420	-	-	100, 250, 420	-	-

Table 4-3. Regression analysis summary on friction data for tested road conditions.

Road Condition	Predictors						R^2 (%)
	STT			Sanding Rate			
	Coefficient	P-value	VIF	Coefficient	P-value	VIF	
Bare Dry (Left lane)	0.003	0.002	1	-0.078	0	1	88
Dry with Ice Patches (Right Lane)	0.004	0	1	-0.027	0.03	1	70
Ice	-0.003	0.004	1	0.046	0	1	75
Snow	0.0007	0.006	1	0.063	0	1	69

4.6.1. Bare Dry Surface and Dry Surface with Ice Patches

A multiple linear regression analysis was conducted on the average HFN of each run collected on both lanes on February 21. For the bare dry surface six runs were conducted after each sanding rate (two at each target speed) with the exception of low sanding, where one of the runs at 30 km/h was not zeroed properly by the operator and thereby was eliminated from the analysis. For the dry surface with ice patches one of the runs after high sanding at 50 km/h was eliminated due to a similar reason, resulting in a total of 17 runs.

According to Table 4-3, both *STT* and sanding rate, are significant to friction measurements taken on both lanes (all p-values <0.05); additionally, the coefficient of determination (R-squared) values are high for both lanes, implying strong correlations between the two variables and HFN in each lane. The Variance Inflation Factor (VIF) is equal to one for both lanes, implying that the two variables are independent. Positive coefficients obtained for *STT* confirm that when sand is scattered from a dry surface, friction increases; whereas the negative coefficients for the sanding rate imply that friction decreases when more sand is applied.

Pearson correlations between *STT* and the HFN values within each sanding rate for the bare dry surface were 0.34, 0.99, and 0.93 for low, medium, and high sanding, with p-values of 0.575, 0.000, and 0.007, respectively. For the dry surface with ice patches, the correlations were 0.75, 0.94, and 0.9 with p-values of 0.087, 0.005, and 0.037 for low, medium, and high sanding, respectively. According to these results and as expected, the coefficients for all three rates in both lanes are positive, implying that at higher *STT* values sand was scattered which enhanced the friction. Also, for both lanes, the effect of *STT* on HFN for low sanding was not significant (p-values >0.05).

4.6.2. Ice-Covered Surface

Table 4-2 presents the range of HFN, *STT* and sanding rate for a total of 17 runs over the ice-covered surface. Six runs were conducted after medium and high sanding (two at each speed), and five runs after low sanding. As seen in Table 4-3, linear regression analysis resulted in a high R-squared value, p-values less than 0.05 for both *STT* and sanding rate and a VIF of one, which confirms the independency of the two predictors. The sign of the coefficient for *STT* is investigated further in the following section.

Pearson correlations of -0.67, 0.89, and -0.87 with p-values of 0.22, 0.02, and 0.02 were achieved for low, medium, and high sanding, respectively. These results indicate that the influence of *STT* on HFN for low sanding is negligible, as indicated by the high p-value. For medium sanding, on the other hand, *STT* has a significant positive relationship with HFN; while this coefficient is negative for high sanding. Explaining the underlying phenomenon resulting in each of the observed behaviours is a complex task and can better be best achieved through microscopic scans of the ice surface.

4.6.3. Snow-Covered Surface

A summary of the range of the variables is presented in Table 4-2 for a total of 54 runs over snow (nine runs at each lane, three runs at each speed), and the results of the analysis are summarized in Table 4-3. Both *STT* and sanding rate are significant to the friction measurements taken on the two lanes, as both p-values are less than 0.05. Additionally, the R-squared value is high (69 percent), indicating a strong relationship, and VIF is one for both variables, implying that they are independent. The positive coefficient obtained for sanding rate reveals that higher amounts of sand result in a positive effect, enhancing the friction values. The positive coefficient for *STT* is investigated further in this section.

Pearson correlations between average HFN for each run under each sanding rate and *STT* were calculated as -0.51, 0.59, and 0.54 with p-values of 0.029, 0.009, and 0.021 for low, medium, and high sanding, respectively. The declining correlation between HFN and *STT* for low sanding shows that sand is blown off from the wheel paths due traffic pass and speed before salt become effective in melting the snow, resulting in a trend between HFN and *STT*. Yet, snow was melting after medium and high sanding before sand is spread away from the surface, thus positive coefficients were achieved for Pearson correlations. It should be noted that the ambient temperature during testing was -8°C, which can increase to melting temperatures considering the frictional heat produced between the tire and road, especially at higher speeds. As a result, driving over sanded snow at higher speeds increased the surface friction. It should be noted that this study included a limited number of passes after each operation, where the effect of traffic in scattering the sand was eliminated by the relatively immediate increases in friction from the salt and the melted snow. Consequently, increased traffic is required to investigate the duration in which the sand remains in the wheel paths and whether friction will drop after a certain number of vehicle passes.

4.7. Conclusions

This study used the Real-Time Traction Tool (RT3)-Curve to measure the lateral tire-surface friction under different winter road conditions. It was found that low (100 kg/one-lane km), medium (250 kg/one-lane km), and high (420 kg/one-lane km) sanding the bare dry surface reduced friction by 11, 31, and 37 percent. Residual sand on the dry surface resulted in higher friction values than those on the highly sanded, bare dry surface, since sand scattered from the road by wind and melt water.

Average friction for the ice-covered surface was 36, which can be considered relatively high and resulted from the fact that the surface was not smooth or polished, and contained ice particles and snow. Plowing removed the snow and a portion of those ice particles, resulting in a two-percent drop in friction. A low amount of sanding did not provide sufficient friction; whereas, medium, and high sanding improved friction by 23 and 43 percent, respectively.

Sanding heavy snow did not have any effect on friction since sand particles became buried; however, when a considerable amount of snow was plowed, friction improved by 129 percent. Low sanding reduced the average friction from 39 to 32. Medium and high sanding increased the tire-snow friction by 25 and 53 percent, respectively, when compared to low sanding.

A multiple linear regression analysis on all conditions revealed that traffic passes, particularly at higher speeds, scatter the applied sand from bare dry, dry with ice patches, and icy surfaces. Even though salt mixture is expected to melt the ice over time, high speed traffic removes sand from the surface before it becomes effective. However, the 50-percent sand-salt mixture applied over snowy surfaces showed immediate influence on melting the snow. Additionally, frictional heat caused by increased traffic passes, especially the ones at higher speeds, caused the snow to melt faster. Considering the limited number of runs performed in the experiment, the effect of sand scatter from the road and the total time that sand remains effective could not be investigated.

5. Chapter 5: Summary and Conclusions

5.1. Summary

Winter road maintenance operations consume an essential part of the budget, time and other resources of transportation agencies and municipalities in cold regions. Large amounts of sand-salt mixtures are also consumed each winter, raising environmental concerns and imposing discomfort upon road users. Despite the significance of these operations, all the decisions related to these operations are made either empirically or based on general and pre-determined policies. These concerns have been the motive for many research studies to evaluate the severity of different road conditions and their corresponding proper treatment.

Surface friction is the one measureable parameter that well represents the driving condition. The potential application of friction measurements for road winter maintenance purposes has led to the development of various friction measurement devices.

Many research studies have investigated the tire-road friction and the effectiveness of different maintenance operations via laboratory/field friction measurement experiments; however, due to the complexity of the tire-road friction in wintery road conditions and several influential variables, as well as different friction measurement mechanisms, the findings from different studies are only comparable to a certain extent. Therefore, there is the need for a comprehensive experimental study with reliable equipment and controlled test parameters to evaluate the road conditions, identify influential parameters, and investigate the effectiveness of winter operations on each condition.

To address the above-mentioned objectives, in the current study – sponsored by the City of Edmonton – a series of friction measurement experiments were performed on University of Alberta's Integrated Road Research Facility (IRRF)'s test road under different wintery conditions. The Real Time Traction Tool (RT3)-Curve friction measurement device, developed by Halliday Technologies, was used in the experiments to measure the road surface friction under different winter conditions. The asphalt test road was closed to traffic during the experiments, providing a controlled test environment. The device was found to be reliable and functioned well in severe winter conditions.

Different road conditions including bare dry, ice, dry with ice patches, and snow (light, moderate and heavy) were tested in six test events in winter 2012-2013. Additionally, a snowplow and sand spreader truck, provided by the City of Edmonton, was used to evaluate the effectiveness of plowing and application of three levels of low (100 kg/lane-km), medium (250 kg/lane-km), and high (420 kg/lane-km) sand-salt mixture on each road condition. As part of the analysis, traffic pass, time lapse after application, and speed were found to affect the road surface friction via multi-linear regressions. The regression analysis was conducted using a new parameter (*STT*), combining the three variables, because the extent of their effects cannot be investigated independently.

5.2. Conclusions

During the six events using the RT3-Curve, main winter road conditions including bare dry, dry with ice patches, ice, light snow (1-3 cm), moderate snow (3-10 cm), and heavy snow (10-15 cm) were tested at target speeds of 30, 50, and 60 km/h. Analysis of the collected friction data revealed that:

- No considerable correlation was found between speed and friction over dry, ice and snow conditions, implying that the RT3-Curve’s friction measurements are not speed-dependent in the tested speed range.
- The RT3-Curve was able to very well capture the changes in road condition. Ice patches could be identified along the test road, and different snow accumulations were clearly distinctive based on the changes in friction values.

- A bare dry surface resulted in the greatest friction value (an average of 91), while random ice patches along the dry surface reduced the average friction by 31 percent.

- Average friction for ice was 55 percent less than bare dry condition. However, due to its rough surface texture, the tested ice showed greater friction than snow.

- Traffic pass over ice at melting temperatures (> -5°C) reduced the friction values because the crushed ice particles were removed from the surface; and also the thin melt-water layer on top of ice – created as a result of the heat generation from each vehicle pass – created a more slippery surface.

- Light, moderate, and heavy snow reduced the dry surface friction significantly by 69, 75, and 81 percent, respectively. This showed that dangerous driving conditions can occur even due to a light snow cover on the surface. Further, the descending trend in friction versus snow depth implied that friction declines as snow accumulates on the road.

- Analysis of the effect of traffic on friction revealed that traffic pass over light snow generates enough heat to melt the snow, resulting in higher friction. However, traffic passes over moderate and heavy snow (at temperatures below -15°C) compact the snow into a more slippery surface, thus friction decreases as more vehicles pass over snow thicker than 3cm.

During two test events, a snowplow and sand spreader truck were used to perform common winter maintenance operations as practiced by the City of Edmonton. These operations included plowing and three levels of low (100 kg/one-lane km), medium (250 kg/one-lane km), and high (420 kg/one-lane km) sand application on different road conditions. Moreover, on another test event, residual sand remained on the dry surface was tested. Analysis of the collected friction data before and after each operation on different road conditions showed that:

- Low, medium, and high sanding the bare dry surface reduced friction by 11, 31, and 37 percent, implying that sand particles on the dry surface roll under the tires and create a slippery surface.

- Residual sand on the dry surface showed higher friction values compared to the highly sanded dry surface. This behaviour is because sand particles were blown off the road by wind and melt water during the previous two weeks.

- Plowing the rough-textured ice, removed the crushed ice particles and created a smoother ice with lower friction. Although low sanding did not have a considerable effect on friction, medium and high sanding were able to improve the ice friction by 23 and 43 percent, respectively.

- Sanding the fresh heavy snow did not influence the friction, since sand particles were buried in the snow. Whereas, plowing removed a great amount of snow, resulting in 129 percent improvement in friction. Medium and high sanding the plowed snow improved friction by 25 and 53 percent, respectively, compared to low sanding.

A multi-linear regression analysis was performed on the collected friction data to investigate the effect of time lapse after each application, traffic pass, and speed for each road condition and sanding rate. Since the effect of the three variables cannot be studied independently, a new parameter (*STT*) was introduced as the combination of time, traffic, and speed. The regression analysis performed on friction, *X*, and sanding rate revealed that:

- Traffic passes on sanded dry and icy surfaces scattered the sand particles from the road, and this effect was intensified at higher speeds.

- Although, it was expected that the salt portion of the abrasive mixture would melt the ice at >-5°C, the high-speed traffic passes removed the mixture from the road before the salt became effective.

- The application of a 50-50 sand-salt mixture (ratio by weight) on snow was found to have immediate influence on melting the snow. Further, the generated heat through traffic passes helped melt the snow, resulting in higher friction values. Also, high-speed passes over snow produced greater heat, and melted the snow faster.

5.3. Future Research

The current study's approach was to evaluate each winter road condition itself, as well as the effect of common maintenance practices on that. It also identified that time lapse after each operation, traffic pass, and speed are potential affecting parameters. The RT3-Curve was found to operate properly and be suitable for wide use in the winter maintenance equipment fleet.

To achieve the ultimate goal of optimizing winter maintenance operations, further experiments are required using the RT3-Curve.

First, since the number of runs performed in this experiment was limited, the total time that the sand remained effective on snow and the required traffic to scatter sand particles from the sanded snowy road could not be investigated. Therefore, future experiments should include more traffic passes and extended test periods.

Moreover, the effect of other influential parameters on surface friction, including temperature, ice textures, snow moisture, and snow density, should be evaluated in controlled tests.

Application of different sand-salt mixtures is also recommended to be evaluated in different conditions and ambient temperatures. It is also suggested that another series of experiments be conducted to investigate the effect of other sanding rates, and method of application accompanied by a cost effectiveness analysis to identify the optimum sanding rate and mixture.

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