Field Evaluation and Performance Analysis of Different Pre-wetting Ratios for Sustainable Salting

by

Jaspreet Kaur

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2018

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Jaspreet Kaur

Abstract

In countries like Canada road safety and mobility could be compromised to a great extent during winters due to deterioration of road surface conditions (RSC). Adverse winter weather conditions such as ice, frost, and drifting snow could generate hazardous roads and thus poor driving conditions. These adverse effects of winter weather can be significantly reduced through an affective winter road maintenance (WRM) program involving operations such as plowing and salting. WRM can help maintain an adequate level of service on roads by removing snow and ice from the road surface for improved friction between vehicle tires and road surface.

WRM activities are however costly and may also have negative environmental impacts due to the use of salt. Therefore, transportation agencies are continuously seeking for smart and efficient treatment techniques to reduce salt usage and operating costs while maintaining the required level of service. Pre-wetting is one of such techniques that have gained increasing popularity in the WRM sector; it involves spraying salts with liquid chemicals before their application on the road surface. It is proven to be economically and environmentally sustainable as it lowers the amount of materials required to attain the same level of service.

According to the current standards by the Ministry of Transportation Ontario (MTO), salt (NaCl) is pre-wetted at a ratio of 5% and sand is applied in a dry form for maintenance of highways in Ontario. However, the optimal pre-wet ratio of salt is still largely unknown. The objective of this research is to realize the full potential of pre-wetting and is guided by the question, whether or not more benefits can be realized if higher pre-wet ratios of salt are used while not compromising on the level of service. The aim of this study is, therefore, to compare the performance of salt at higher pre-wet ratios i.e. 10% and 20% to the standard pre-wet ratio of 5% by mass using similar granular rate (for example 130 kg/ 2-lane-km). Three measures, namely, friction, amount of material used and RSC were used to compare the performance of the three pre-wet ratios.

Field trials were conducted on three sections of Highway 6, which is a Class 2 provincial highway and requires bare pavement RSC within 16 hours after storm ends according to maintenance standards of MTO, located in Durham, Western Ontario in the winter season 2016-17. Three different types of analyses were performed, namely Comparative Analysis, Visual Analysis and Regression Analysis. Results from quantitative analysis shows that salt pre-wetted at higher ratios (10% and 20%) improved friction levels by approximately 11% and 15% respectively as compared to pre-wet (PW) 5% ratio whereas the difference between friction levels attained using 10% and 20% PW ratios is minimal i.e. 4%. In terms of material usage, the use of PW 10% ratio consumed 13% more salt and 22% less sand as compared to PW 5% ratio whereas salt pre-wetted at 20% ratio consumed 19% less salt & 35% less sand as compared to PW 5% ratio. In addition to this, the visual analysis outlines better RSC and less snow coverage on the section treated with PW 20% ratio as compared to the other two sections, hence exhibiting higher snow melting capability of salt pre-wetted at 20% ratio.

The regression analysis was performed to formulate the relation between measure of performance i.e. friction and other variables like air temperature, wind speed, relative humidity, etc. A categorical variable was included in the model to evaluate the impacts of the different PW ratios (5%, 10% and 20%) on snow melting performance of salt. Modeling results are similar to comparative analysis and concludes that PW 20% ratio generates higher friction levels as compared to other two ratios at any controlled condition.

It can be concluded from the analysis that salt pre-wetted at a ratio of 20% is more efficient as compared to other two pre-wet ratios (5% and 10%). PW 20% ratio of salt can generate higher friction levels as well as better RSC while consuming less material as compared to the standard 5% PW ratio. The consumption of less material using PW 20% ratio of salt eventually leads to less chlorides in the soil and groundwater and can result in environmental benefits.

Acknowledgements

Special thanks are owed to my supervisor Dr. Liping Fu who has always supported and encouraged me through the research process. I express my sincere gratitude for his invaluable guidance and for enriching my research skills throughout the project. It has been a great honor to work with him and to learn from his experience.

I would like to thank Dr. Taimur Usman from iTSS (Innovative Transport System Solutions) Lab, who has always been a tremendous help throughout my graduate career. He provided expert support throughout the research process and his continuous involvement in the project is highly appreciated.

This research was supported by Ontario Ministry of Transportation (MTO) through the Highway Infrastructure and Innovations Funding Program (HIIFP). I extend my appreciation to Winter Materials Working Group at MTO and in specific my sincere thanks to Max Perchanock, James Brouwer and Lorne Howlett for their input and for their cooperation on providing information.

I would also like to thank an intern, Christie Cho from iTSS Lab for her efforts in conducting a survey.

Special thanks beyond measure are due to my colleagues, Rajdip Nayek and Juan Fran for their support and kindness throughout my graduate career.

Lastly, I would like to appreciate my strength and perseverance that enabled me to finish this research.

Dedication

I would like to dedicate this thesis to my father, Gurcharan Singh Brar and my mother, Manjit Kaur Brar

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Winter road maintenance (WRM) is indispensable for Northern countries with severe snow storms like Canada, Finland, and Sweden in order to provide efficient and accessible transport networks. For example, most parts of Canada experience long winters every year with low temperatures and many snow storms (Salt Institute, 2016). Public safety, mobility, commerce & industry are impacted heavily due to snow and ice formation on roads; hence WRM demands a special attention. Adverse winter weather conditions make the roads unsafe for driving and create collision-prone conditions. (Pisano et al, 2004) Some past research has indicated that, for a given distance travelled, the risk for motorists to get involved in accidents during a winter season was twice as high when compared to a summer season (Nilsson and Obrenovic, 1998).

WRM is however also costly, both directly and indirectly. Many transportation authorities disburse heavily each year to provide adequate levels of road service. For instance, the Ministry of Transportation of Ontario (MTO) spent around $171 million on WRM in the fiscal year 2013-14 (Ontario Auditor General Office, Special Report, 2015). Road collisions exert a heavy toll on economy, which could cost around 2% of Gross National Product in high income countries (Pedan et al, 2004). Canada's commerce & industry is dependent on safe road transportation systems, which could lose between $300 and $700 million if the road network were completely shut down (Salt Institute, 2016).

WRM is employed to combat adverse winter weather conditions by making roads clear of snow and ice, thus promoting a safe and efficient transportation network. It also plays a crucial role in fulfilling the vision of transportation policy aiming at social, economical and environmental sustainability (Sustainability insight, 2009)

Despite having advantages, materials used for winter road maintenance cause negative environmental impacts. The use of abrasives (sand) could deteriorate the environment by constituting particulate matter (PM_{10}) and damaging air quality. It may also block catch basins and storm drains, increasing sedimentation and turbidity in lakes (Nixon, 2001; Perchanok et al, 1991; Hyman and Vary, 1999), which would require expensive post-application cleaning (Fonnesbech, 2001). Sand is also considered as hindrance to aesthetics as well (NCHRP, 2004).

Similarly, de-icing chemicals such as salt have negative effects on aquatic life, ground water, surface water and the ecosystem in proximity to salted roads. They promote corrosion on highway infrastructure and vehicles (Perchanok et al, 1991; Environment Canada, 2002). Salt could also affect air quality. Research conducted in NORDIC countries shows that residual salt can get suspended in air and constitute particulate matter (Perchanok et al, 1991). A detailed discussion on various environmental impacts of de-icers can be found in Blomqvist, 2001 and Ramakrishna & Viraraghavan, 2005.

Since millions of tonnes of salt and sand are used on the roads every year, while taking into account the negative impacts of the materials on the environment, efforts are being made to look for WRM best practices with the least impact on the environment. According to Environment and Climate Change Canada, 4,183,000 tonnes of salt was used across Canada in 2008. The amount of salt spread annually for WRM of provincial highways in Ontario from 2005 to 2009 is shown in Figure 1.1, depicting an annual average use of 600,000 tonnes of salt, considering 2005 – 2009 salt usage data.

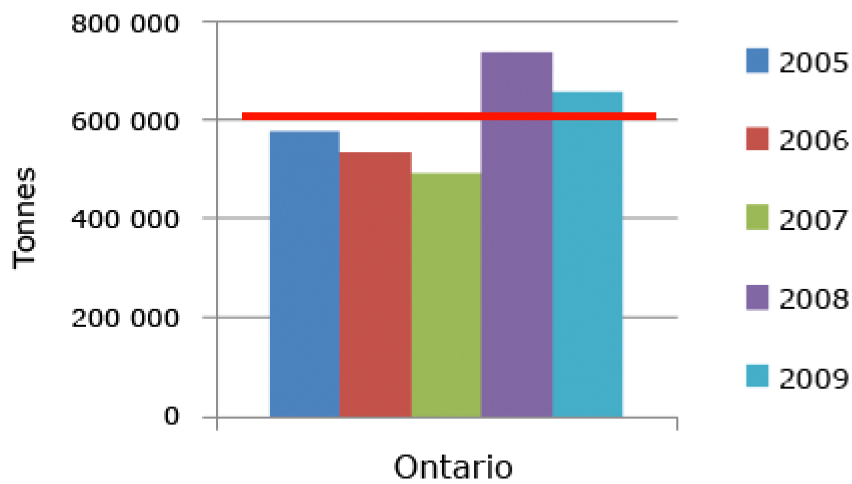


Figure 1.1[1]: The quantity of salt used for WRM of provincial highways in Ontario, 2005-2009 with an annual average of salt for five years (2005-2009)

It was until 1970 that abrasives and plowing formed the primary part of WRM and since then the use of de-icers has become quite extensive (Minsk, 1998). Salt (NaCl) is the pre-dominant de-icer used in Canada because of its lower cost and easy availability. The de-icers act by lowering the freezing point of water. They melt snow/ice at lower temperatures, i.e., below 0°C as well as break the bonds of snow/ice with road surfaces (O'Keefe and Shi, 2006). Each de-icer has a different effective working/melting temperature range, for instance, NaCl is effective up to -12°C (Minsk, 1998; O'Keefe and Shi, 2006). The abrasives, on the other hand, are used to enhance the friction between the vehicle tires and snowy roads (Nixon, 2001). Abrasives include slag, cinder and bottom ash from power plants but sand is the most commonly used abrasive (Wisconsin Transportation Bulletin No. 6). They are generally used when pavement temperatures are below an effective range of de-icers, on low-traffic highways and in drifting snow (Usman et al, 2017). Besides this, the practice to use sand on delicate

[1] Environment and Climate Change Canada

and slow moving locations such as curves, intersections and free-way ramps is strongly encouraged (Fortin and Dindorf, 2005). It is also used to combat slippery conditions.

It is well established practice to apply winter road maintenance materials in dry form. However, dry material can be blown off the road easily with the passage of few vehicles. Thereby losing effectivity easily and demanding frequent applications for prolonged effectivity.

The purpose of sand acting as a friction-enhancer is also not served when the passing of vehicles makes it drill into packed snow (Nixon, 2001; Usman et al, 2017). Research has shown that dry sand gets dispersed with the passage of 10-12 vehicles (Gray and Male, 1981) and friction levels get substantially reduced after the passage of 5-10 vehicles (Comfort and Dinovitzer, 1997). Hence, attempts have been made to achieve the long-lasting benefits by making the materials adhere to the surface. The techniques which are recommended so far for effective use of adhesives are: heated sand (heating the sand to 180 °C before it is applied to road), warm-wetted sand (mixing sand with water heated to 90 °C, before application) and pre-wet sand (pre-wetting sand with de-icing liquid) (Nixon, 2001).

Research was conducted in Ontario to compare the performance of dry sand and pre-wetted sand and has shown that adequate friction levels were sustained using pre-wet sand even after the passage of 400 vehicles whereas dry sand lost its effectivity after the passage of 50 vehicles (MTO, 1994). Similar studies conducted in Michigan demonstrate that pre-wetting of salt can save up to 26% of salt from being bounced and scattered as compared to dry salt (Wisconsin Transportation Bulletin No. 22). Pre-wetting is beneficial in not only making the materials better stick to the road surface but also speeding up the snow melting process.

In summary, due to increasing environmental concerns, transportation agencies are looking for efficient ways of material application that can reduce their quantities used while maintaining the required level of service for their highway networks. Pre-wetting is one of these techniques that has been widely applied as an outstanding strategy for snow and ice control (Williams, 2003; Sooklall et al, 2006; White et al, 2006). The effectiveness of the pre-wetting technique is however dependent of many factors related to the weather, the traffic and the pre-wetting ratio. Currently there are no guidelines and standards available pertaining to the pre-wetting practice. For example, MTO is still using a single pre-wetting ratio of 5% that was recommended on the basis of limited research conducted many years ago (MTO Best Practices Manual, 2003). Many questions still remain. For example, under what kind of conditions is pre-wetting most effective? What is the optimal pre-wetting ratio and what are the influencing factors?

1.2 Research Objective

As discussed previously, pre-wetting is a technique that can help improve the effectiveness of salting and sanding and thus reduce the amount of materials needed to maintain the desired level of service for a given highway. While the technique has been adopted widely in the winter road maintenance sector, a wide range of pre-wetting ratios have been used in the practice with few guidelines available on the optimal pre-wetting ratios that should be recommended for addressing particular road and weather conditions. This research was proposed to address this knowledge gap with the following specific objectives:

1) To compare the field performance of salt pre-wetted at a standard ratio of 5% to that at the higher pre-wet ratios, i.e., 10% and 20% using similar granular application rates (for example 130 kg/ 2-lane-km).

2) To develop statistical models that can be used to identify the factors that had significant effect on the snow melting performance of alternative treatments and to investigate the relative difference in performance of pre-wetted salt under three pre-wetting ratios (5%, 10% and 20%).

1.3 Organization of the Thesis

This thesis consists of five chapters. Chapter 1 was the introduction to the problem. The remaining thesis is organized as follows:

In Chapter 2, a literature review is presented in the areas of snow and ice control strategies (anti-icing, de-icing), pre-wetting including a survey done to determine pre-wetting best practices and WRM management in Ontario.

Chapter 3 highlights the study sites, data sources, data processing methods, and analyses approaches for this study.

Chapter 4 presents the evaluation and analyses of field trials.

Chapter 5 includes conclusions and future work.

Chapter 2

Literature Review

WRM plays an important role in addressing the problems caused by adverse weather conditions by making transportation networks more efficient in terms of safety and mobility. The strategies employed for snow and ice control operations include materials (chemicals and/ or abrasives) and mechanical means (e.g. plowing). Despite their usefulness, materials used for WRM are known to cause environmental concerns (Perchanok et al, 1991; Hyman and Vary, 1999; NCHRP, 2004). Therefore, it is important to introduce best WRM practices that could minimize the amount of material added to environment. Some of the strategies adopted to achieve this goal include pre-wetting, anti-icing, use of organic materials, etc. The focus of this project is to see the effectiveness of pre-wetting in achieving goals of environmentally as well as economically sustainable WRM. Pre-wetting lowers the overall cost by reducing the cost of operations and also lowers the utilization of materials, hence causing the least impact on environment. A literature review related to different WRM strategies and practices is presented in this chapter. To better understand the practice of pre wetting, a survey was conducted by contacting different jurisdictions. In the remaining chapter, different snow and ice control strategies are discussed followed by a detailed discussion on pre-wetting and WRM management in Ontario.

2.1 Snow and Ice Control Strategies

The approaches used for snow and ice control operations can be divided into two categories i.e. proactive and reactive approaches. The former is used to prevent the snow from bonding to the road surface whereas the latter is used to break the bond already formed between snow and the road surface. The following sections review relevant literature on anti-icing and de-icing:

2.1.1 Anti-icing

Anti-icing is a proactive approach that prevents ice or snow from bonding to the surface, with emphasis on prevention rather than reaction. It is the placement of brine also refered to as Direct Liquid Application (DLA), pre-wetted or dry salt on the road surface before precipitation begins (Brine Fact Sheet, APWA; Wisonsin Transportation Bulletin No. 6). For anti-icing, the brine solutions are proven to be more effective as compared to solid de-icers, their applications last for several days including residual effects (Wisconsin Transportation Bulletin No. 22). Research conducted in Michigan demonstrates that anti-icing can lead to a reduction in the amount of materials used as compared to traditional de-icing and thereby, lowers the cost of operations (Winter Sanding Guidelines, 2012). However, it requires accurate weather forecasting as resources could be wasted otherwise. The equipment required for anti-icing is different from de-icing equipment and is significantly costly.

Anti-icing is least effective at temperatures below -6 °C, heavy rain, freezing rain, heavy snowfall or windy conditions (Ketcham et al, 1996). The rainy conditions can make anti-icing ineffective, wash it away from roads. Similarly, anti-icing in form of DLA during windy conditions makes snow stick to the surface when otherwise is would be likely to get blown off the dry roads.

The notable disadvantage associated with anti-icing is the resulting slippery RSC on some occasions in the absence of precipitation. Therefore, special attention should be given to the type of de-icer used for anti-icing, the selected de-icer must not lose the ability to work efficiently at prevailing temperature and humidity levels. For example, it is not recommended to use $CaCl_2$ or $MgCl_2$ at temperatures above -2°C , since they absorb moisture and cause slippery conditions (Winter Sanding Guidelines, 2012).

2.1.2 De-icing

De-icing is a reactive strategy for WRM and is used to de-bond snow/ice already bonded to the road surface (Brine Fact Sheet, APWA). De-icing includes use of DLA, pre-wetted materials and dry materials. It also makes it easier to remove excess snow from roads by plowing. Brine solutions are effective for de-icing but it is more likely that they will get diluted and refreeze.

The effectiveness of de-icing action depends upon several factors such as pavement temperature, weather conditions etc. (Wisconsin Bulletin No. 6; Winter Sanding Guidelines, 2012) as explained below:

1) Concentration: The proportion of salt to water is critical to freezing point depression quality of brine. Too little salt or too much salt will make brine ineffective. At lower concentrations, brine may not be able to melt snow for the pavement temperature and the melted snow will be able to refreeze. Similarly, at higher concentrations, not all of the salt will dissolve in solution and will get added to environment. Hence, brine solutions are used at concentrations where they are most effective, see eutective curve explained later in this chapter.

2) Weather: The weather conditions also effect the quantity of salt used to clear snow. The heat from the sun causes the pavement temperature to rise above air temperature and also accelerates melting, hence less salt is required. On the other hand, when pavement temperatures fall below air temperature on clear nights they will need more salt.

3) Road Surface: The snow melts rapidly on asphalt as compared to concrete surfaces because asphalt absorbs heat for longer and doesn't radiate heat as easily.

4) Topography: The topographic conditions like high bank, vegetation, etc. screen the road surface from the sun and remain in the shade for longer. Pavement temperatures are lower in shaded areas and it is likely that ice will form, requiring a greater amount of salt.

5) Time of Application: Timing of material application is important for effective snow and ice control operations. It is useful to apply salt early, when the snow is loose and unpacked, it will melt some of the snow and turn the rest into slush. It makes plowing easier to clear the roads.

2.1.2.1 Types of De-icers

According to Environment and Climate Change Canada, NaCl is the most commonly used de-icer for pre-wetting and DLA, other chloride de-icers such as $CaCl_2$, $MgCl_2$, and KCl are also used for WRM but constitutes less than 1% of total chloride de-icers. Non-chloride de-icers such as beet juice, CMA, and KA are also popular but are used to a lesser extent, making less than 1% of the total amount of de-icers used (Environment and Climate Change Canada).

Some of the mostly used de-icers are discussed in the following sections:

1) Sodium Chloride (NaCl): NaCl is the most primarily used de-icer. It is readily available and inexpensive. Sodium Chloride has a eutectic temperature of -21°C at 23.3% concentration. It can effectively work till -12°C (Wisconsin Transportation Bulletin No. 6). The caustic effects caused by

NaCl on vehicles and infrastructure can be reduced by adding corrosion inhibitors (State of Nebraska, 2015). The practical working temperature of NaCl can be lowered further by blending it with other de-icers like $CaCl_2$, increasing performance of sodium chloride.

2) Calcium Chloride ($CaCl_2$): Calcium Chloride has a eutectic temperature of -51°C at 29.9% concentration with an effective working temperature of -31.6 °C. $CaCl_2$ is hygroscopic (absorbs moisture) and releases heat upon mixing with water. It is twice as fast as NaCl in melting snow. It is less caustic as compared to NaCl. However, it can result in slippery conditions because of its moisture attracting properties and is three times more expensive than NaCl (Michigan Department of Transportation).

3) Magnesium Chloride ($MgCl_2$): The eutectic temperature of $MgCl_2$ is -33°C at 21.6% concentration, can work effectively till -15°C. It causes less corrosive impacts as compared to $CaCl_2$. It is applied when pavement temperature is -1°C or below. But it attracts moisture and causes slippery conditions. It is five times more expensive than NaCl (Wisconsin Transportation Bulletin No. 6)

4) Calcium Magnesium Acetate (CMA): Calcium Magnesium Acetate has a eutectic temperature of -27.5°C at 32.5% concentration with an effective working temperature of -6°C. It acts slowly as compared to NaCl, hence more quantity is needed to obtain same de-icing capability. Its de-icing effect lasts for longer, requiring fewer subsequent applications as compared to NaCl, contrary to initial applications. It is biodegradable and has few adverse environmental impacts. The most important benefit of CMA is that it is non-corrosive. It is 20 times more expensive than NaCl (Michigan Department of Transportation).

5) Potassium Acetate (KA): The eutectic temperature of KA is -60°C at 49% concentration, and it can work effectively till -26°C. It is less harmful to the environment and eight times more expensive than NaCl.

To minimize the negative effects of chemical de-icers, which adversely impacts roadside vegetation, surface water, aquatic biota, ground water and infrastructure, de-icers are being synthesized from agricultural by-products such as Geomelt, Fusion and Ice ban. These products possess negligible environment impacts with higher snow melting capability. However, there is a high cost associated with them and they require special handling - due to the risk of fermentation (Fu et al, 2011).

2.2 Pre-wetting

Pre-wetting is a procedure of coating winter road maintenance materials (salt (i.e. NaCl) and sand) with de-icer solution also known as brine (solution of any salt, not necessarily NaCl, and water that has a freezing point lower than pure water) before or during the application to the road surface (Sooklall et al, 2006). Pre-wetting makes the winter road maintenance materials cling to the road surface by increasing their density and preventing them from getting bounced or scattered. Furthermore, in case of salts, it accelerates the melting action by providing an initial moisture boost and helps in restoring the bare pavement sooner. It also enables the salt particles to penetrate further into the snow or ice and thereby, increase its effectivity (Wisconsin Transportation Bulletin No. 22). Pre-wetting can melt snow or ice at lower temperatures if salt is pre-wetted with other de-icers such as $CaCl_2$, $MgCl_2$, etc.

Pre-wetting can be done by following three ways (Ketcham et al, 1996):

1) Injecting de-icing solution into the material stockpile.

2) Spraying de-icing solution on the material loaded into the spreader or being loaded into spreader.

3) On-board spray system i.e. spraying de-icing solution on material that is being spread.

The on-board spray system is the most common and effective method for pre-wetting in which liquid de-icer and material are kept separately from each other. The material gets more uniformly coated with de-icer using this method. In addition to this, only the required amount of material is pre-wetted and doesn't produce any unused or left-over pre-wetted material, which requires further attention. However, this method requires calibration and constant maintenance of the electric and hydraulic spray systems that are used in this method of pre-wetting (Winter Sanding Guidelines, 2012). On the contrary, the first method requires the pre-wetted stockpile to be covered and stored on an impermeable surface to prevent risks of dilution and runoff. Another disadvantage of the first method is that pre-wetted stockpile may not serve the purpose unless it is monitored regularly and cannot be carried through to the warm season without the liquid migrating from the pile (Ketcham et al, 1996).

The high corrosion effects on the spreader is the major drawback of the second method of pre-wetting. It also requires complete discharging of pre-wetted loaded material as unused pre-wetted material cannot be left in the truck. Also, both of the first two methods may not result in uniform pre-wetting or coating of the material with solution (Winter Sanding Guidelines, 2012).

As described earlier, de-icers depress the freezing point of water and melt the snow or ice. The de-icers used for pre-wetting are the solutions with lower eutectic temperatures such that they can cause melting of snow or ice at lower temperatures, where eutectic literally means easily meltable (Wisconsin Transportation Bulletin No. 22). For example, NaCl brine, $CaCl_2$ brine, etc. are de-icing solutions that can increase the effective melting temperature range of dry salt.

2.2.1 Eutectic Curve

Figure 2.1 shows the phase diagram of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) solutions explaining their freezing point as a function of concentration of solution (FHWA, U.S. Department of Transportation) A dip in the figure called a eutectic point, corresponds to the lowest freezing point. It can be seen from Figure 2 that the freezing point of brine decreases with an increase in concentration of solution until eutectic concentration is reached and after passing concentration at the eutectic point, the freezing point increases sharply with an increase in the solution's concentration.

The phase diagram demonstrates that the lowest freezing point of the $NaCl_2$ solution i.e. -21°C can be achieved at a concentration of 23.3% and for $CaCl_2$ brine, the freezing point can be lowered to -51°C at a concentration of 29.9%.

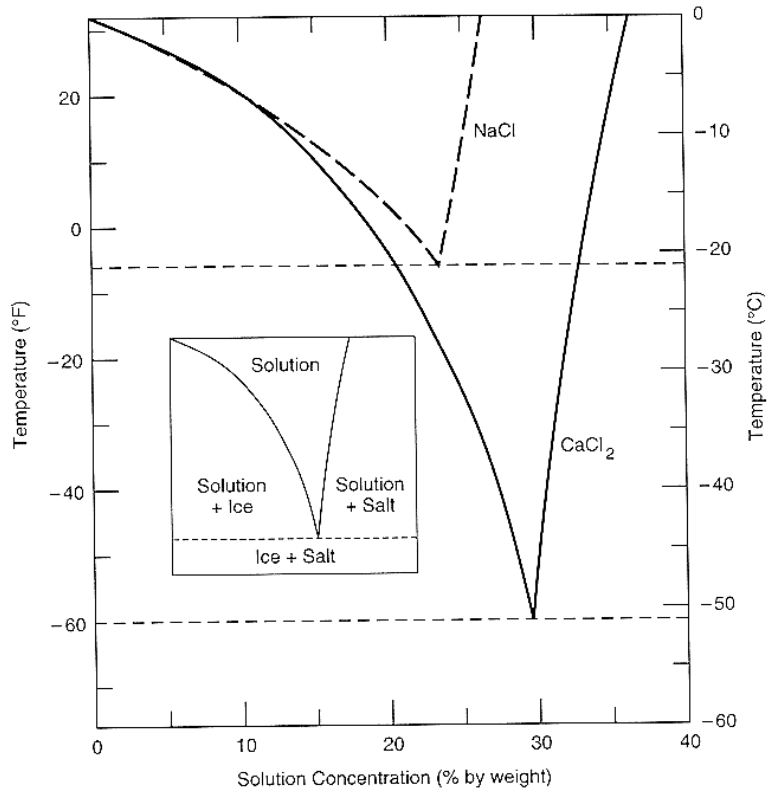


Figure 2.1[2]: Phase Diagram of NaCl and $CaCl_2$

It is important to note that the brine solution will only melt snow or ice if the pavement temperature is higher than the freezing point of the concentration of solution. Hence, brine possesses less melting capability at temperatures beyond the eutectic point as the concentration increases as compared to temperatures before the eutectic point when the concentration increases.

Brine solutions can get diluted by precipitation, melting of snow, etc. and lowering of concentrations will increase the freezing point of brines (Salt Institute, 2016; Wisconsin Transportation Bulletin No. 22). Refreezing will occur, if diluted brine solution is not capable of inducing melting at the pavement

---

[2] Federal Highway Administration, U.S. Department of Transportation

temperature. Therefore, constant monitoring of pavement temperature, melting of snow, and precipitation is needed if brine is used in form of DLA, which is explained later. Additional material applications or other treatments will be required to control refreezing (Wisconsin Transportation Bulletin No. 22). The different phases of brine solution, separated by the eutectic curve in Figure 2 are summarized below (Salt Institute, 2016):

1) Above the curve – Melting action;

2) Below the curve – Refreezing due to colder temperatures;

3) Left of the curve – Refreezing due to not enough salt;

4) Right of the above – Crystallization due to too much salt.

2.2.2 Pre-wetting Best Practices

As part of this study, a survey was conducted to obtain information on the state-of-the-practice with the pre-wetting applications. A simple questionnaire was prepared and sent to 75 different jurisdictions (cities, municipalities, provinces/states, countries) in North America and Europe (Appendix A). Response from 33 jurisdictions are summarized in Table 2.1

Table 2.1: Pre-wetting Best Practices across different jurisdictions

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications: Temperature Range	Pre-wet Specifications: Precipitation / Other	Pre-wet Specifications: Pre-wet Rate(L/tonne)	Pre-wet Specifications: Granular Rate	Comments
Government of Alberta Transportation	Salt and Sand	20-23% NaCl brine; 30-36% $CaCl_2$ brine; 26-32% $MgCl_2$ brine					
City of Barrie		100% salt brine		Light	47		Trials with Magic Minus Zero shows reduction in salt with some minor cost savings
				Normal	47		
				Heavy	63		
		70% salt brine and 30% Agrimelt 55		Light	10		
				Normal	20		
		70% salt brine and 30% Magic	Temperatures below -14°C	Heavy	20-30		

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
	Salt	Minus Zero (molasses and $MgCl_2$ mixture)					
City of Brampton	Salt	23.3% salt brine Denmar Freeze Fighter Sodium 23 Brine			60	52 kg/lane-km 80 kg/lane-km	Trucks have capacity to prewet any winter mainteneance material. Pre-wetting has reduced solid application rate (g/sq. m) by 20%
		Denmar Freeze Fighter HI-CAL 50	Colder temperatures			104 kg/lane-km 160 kg/lane-km 208 kg/lane-km	
City of Brantford	Salt	22% $MgCl_2$ (Pro Mag 22%)		Red Routes	43.5 - 47.5	200 kg/lane-km	
				Blue Routes		100 kg/ lane-km	
				Green Routes		100 kg/lane-km	
Government of British Columbia	Salt and Sand	NaCl Brine; $MgCl_2$				Depends upon Contractor	

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
		Brine; $CaCl_2$ Brine					
Connecticut DOT	Salt and Sand	30% $MgCl_2$ Brine				91kg Dry NaCl and 2.35 L brine /lane-km	
Highways England	Salt	NaCl Brine; $MgCl_2$ Brine; $CaCl_2$ Brine ; ABP(Agricultural By Product) Brine	Surface Temp at -5°C & above -7°C			27,28,29,34 g/m^2	Dry salt is also acceptable.
			Surface Temp at -7°C & above -10°C			38,40,42,48 g/m^2	
			Surface Temp at -10°C & above -12°C			46,49,56 g/m^2	
			Surface Temp at & below -7°C			56,61,76 g/m^2	
Liikennevirasto (Finnish Transportation Agency)	Salt and Sand	23% NaCl Brine; 32% $CaCl_2$ Brine					Other than pre-wetting, DLA is also effective

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
Halifax Regional Municipality		23% NaCl Brine				90 kg/lane-km 125 kg/lane-km 150 kg/lane-km	
Idaho DOT	Salt and Sand	23.3% NaCl brine			75-83		
		Boost (18.8% NaCl and 2.3% $CaCl_2$ by volume)			63-83		
		30% $MgCl_2$			50-75		
Kansas DOT	Salt and Sand-Salt Mix	NaCl brine; $MgCl_2$ brine; Agricultural by-product additives			33.5-42	28-113 kg/lane-km	
City of Kitchener	Salt and Sand	23.3% salt brine; Salt brine & Agrimelt 55 Blend at					Application rate changes with weather and road conditions but

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
		20-30% ratio					pre-wet by 20% is fixed
Maine DOT	Salt and Sand	30% salt brine; Magic Minus Zero; 70-60% salt brine & 30-40% MMZ	Warmer temperatures	Light snow	25,33.5,42	44-56 kg/lane-km	We also have about 7 pieces of equipment that use just straight salt brine and dispensed pre-wetting solution 250 L/tonne reduce the amount of granular rate
			Normal temperatures	Normal snow		70-85 kg/lane-km	
			Colder temperatures	Heavy snow		99-113 kg/lane-km	
Maryland State Highway Administration	Salt	23.3% salt brine	Average temperatures		25-50	141 kg/lane-km per inch of precipitation	Don't use sand unless it is absolutely necessary because of negative
		Mg treated Salt	Colder temperatures				

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications: Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	Comments
							environmental impacts
Massachusetts DOT	Salt	26-30% $MgCl_2$ Brine			33.5-42	68 kg/lane-km	Use very little abrasives
City of Mississauga	Salt	23% salt brine; Mg treated salt			40		Pre-Wetting reduce salt application rate by 10%
Missouri DOT	Salt	salt brine; Ice Ban	till -2.2°C	Flurry conditions		7 kg/lane-km	
			down to -12°C	Heavier precipitation		up to 56 kg/lane-km	
Montana DOT	Salt and Sand-Salt Mix	NaCl + corrosion inhibitor MgCl2 + corrosion inhibitor			33.5-62.5	56-225 kg/lane-km(pre-wet sand-salt mix) 21-56 kg/lane-km (pre-wet salt)	Use limited pre-wet salt, mostly pre-wet sand -salt mix
New York State DOT	Salt	$MgCl_2$ $CaCl_2$		Black ice	25-33.5	25 kg/lane-km	
				Freezing rain		32-101 kg/lane-km	
				Sleet		25-63 kg/lane-km	

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
				Light snow		28-45 kg/lane-km	
				Moderate or heavy snow		28-56 kg/lane-km	
North Dakota DOT	Salt and Sand	20% Geomelt (Beet 55) and 80% salt brine			33.5-42		
Town of Oakville		salt brine		Light	40	70 kg/lane-km	Use Pre-wet only at start of event, it is not beneficial if snow or slush is present
				Normal		105 kg/lane-km	
				Heavy		150 kg/lane-km	
Region of Peel		23.3% salt brine	Till -10°C	Light	20-27.5	32.5 or 50 kg/lane-km	
				Normal		65 kg/lane-km	
		30% $MgCl_2$ Brine	Below -10°C	Heavy		80-85 kg/lane-km	
Pennsylvania DOT		$CaCl_2$			25-50		
		$MgCl_2$			25-33.5		
	Salt and Sand	23.3% salt brine	0°C and warmer	Snow/freezing rain			Pre-wet reduces the
			-4 to 0° C	Snow/freezing rain			

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
Government of Prince Edward Island			-4 to 12°C	Snow			granular rates. They are conducting trials of brine enhanced with Magic Minus Zero
Transports Québec	Salt and Sand-Salt mix	$MgCl_2$ $CaCl_2$ NaCl KCl			30 (aboard trucks) 40 (stockpiling)		Pre-wetting is not common to entire organization. It is used where equipment are available and at locations where stockpile of pre-wet material is constituted

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
Government of Saskatchewan	Salt and Sand-Salt mix	5% calcium chloride flake	-6 to -35°C				For temperatures -6°C and warmer, Dry salt or Dry Salt-sand mix is used. While for temp down to -25°C, pre-wet sand-salt mix or pre-wet salt is used
Transport Scotland	Salt	23% salt brine				10-40 g/m^2	
Trafikverket (Swedish Transportation Administration)	Salt	23% salt brine		Light frost		8 g/m^2	While spreading sand, salt is added to prevent freezing
				Heavy frost		17 g/m^2	
				Thin ice < 2 mm		≥ 18 g/m^2	
				Thick ice > 2 mm		≥ 20 g/m^2	
				Ongoing icing		24 g/m^2	
				Wet roads		12 g/m^2	

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
				Very wet roads before snowfall		18 g/m^2	
				Snowfall		18 g/m^2	
City of Thunder Bay	Sand-Salt mix	$CaCl_2$		Frost/black ice	62	100 or 300 kg/lane-km	
				Light snow < 1 cm/hr		100 or 130 or 300 kg/lane-km	
				Heavy snow > 1 cm/hr		130 or 150 or 350 kg/lane-km	
				Freezing rain		150 or 350 kg/lane-km	
Washington DOT	Salt and Sand	salt brine; $MgCl_2$; $CaCl_2$	-9 to 0°C		63-146		
City of Waterloo	Salt and Sand	$MgCl_2$		Light	55.5	50 kg/lane-km	
				Medium		95 kg/lane-km	
				Heavy		141 kg/lane-km (regional roads) 112 kg/lane-km (city streets)	
Wyoming DOT	Salt and Sand	$MgCl_2$	-18 to -2°C		25-42	169 kg/lane-km	
		Salt brine; Geobrine	-11 to -2°C				

Jurisdiction	Pre-wetted Materials	De-icer Solution	Pre-wet Specifications				Comments
			Temperature Range	Precipitation / Other	Pre-wet Rate(L/tonne)	Granular Rate	
Regional Municipality of York	Salt	23.3% salt brine			60 ,80 ,100	70, 100, 130, 170, 200 kg/lane-km	Application rates for pre-wet salt are same as dry salt

As expected, the survey revealed that salt is the most commonly pre-wetted materials, followed by sand. Interestingly, some agencies also reported pre-wetting their salt-sand mixtures, but this was least common. The material application rate/granular rate is measured in kg/lane-km or gm/m^2. A total of 21 jurisdictions responded with their pre-wet rates (L/tonne), as summarized in Figure 2.2. In this figure, respondents are grouped by the maximum pre-wet rate used, regardless of weather conditions or type of de-icer solution. The maximum pre-wet ratio varied from 3.3% (27.5 L/tonne) to 18% (146 L/tonne) across different jurisdictions. Figure 2.2 shows that most of the jurisdictions are using a pre-wet ratio of 5% while higher pre-wet ratios are less common.

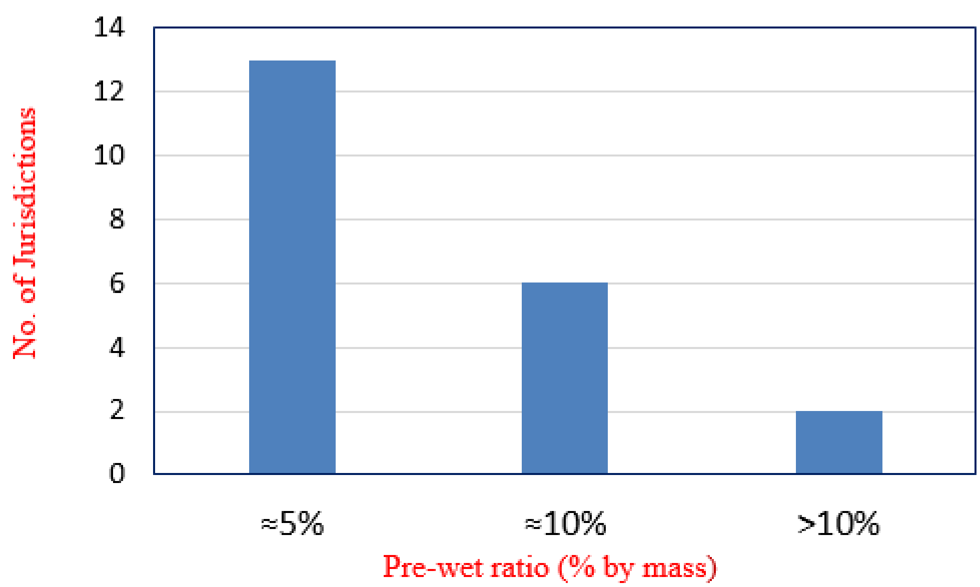


Figure 2.2: Pre-wet ratios across different jurisdictions

The survey also showed that sodium chloride is the most commonly used de-icer. However, a wide range of other de-icers are also used including additives like corrosion inhibitors and agricultural by products (Michigan Department of Transportation, 2002; Fu et al, 2011; Wisconsin Transportation

Bulletin No. 6) and are enumerated in Table 2.2. The use of acetate is not found in any of the jurisdictions, in spite of being one of the major de-icers used for Winter Road Maintenance.

Table 2.2: De-icer solutions employed across different jurisdictions

Major Component	De-icer Soultion
Sodium Chloride (NaCl)	Brine(20-23.3%), Denmar Freeze Fighter 23(NaCl)
Magnesium Chloride($MgCl_2$)	Brine(22-32%)
Calcium Chloride ($CaCl_2$)	Brine(30-36%), 5% $CaCl_2$ flakes
Agricultural by products(ABP)	Magic Minus Zero($MgCl_2$ and Molasses), Agrimelt55, Geobrine, Ice Ban
Others	KCl, Boost(NaCl and $CaCl_2$), Denmar Freeze Fighter 50 (NaCl, $CaCl_2$ and $MgCl_2$)

Additional comments from various jurisdictions are summarized below:

1) Most of the jurisdictions have stated that pre-wetting has reduced the material application rate which is in compliance with literature (Williams, 2003; White et al, 2006).
2) Due to negative environmental impacts, some of the jurisdictions like Massachusetts DOT avoid the use of abrasives unless necessary.
3) The jurisdiction of Oakville pre-wets only at the start of an event, they don’t find it beneficial if snow or slush is present. It might be due to risk of dilution (Sooklall et al, 2006).
4) According to Finnish Transportation Agency, DLA is as effective as pre-wetted salt.

2.3 Winter Road Maintenance (WRM) Management – Ontario

Under the Public Transportation and Highway Improvement Act, Ministry of Transportation of Ontario (MTO) is liable to maintain the Provincial Highways. MTO has divided the province of Ontario into five different regions, namely, Central (CR), Eastern (ER), Western (WR), North-West (NWR) and North-East (NER). These regions are further subdivided into different contract areas. MTO outsources the undertaking of Winter Highway Maintenance to the performance based – Area Maintenance Contractors (AMC). Other than Ontario, British Columbia and Quebec also follow a similar approach. This trend is also popular in other countries like Norway, Sweden, Finland as well as Alaska (USA) (Ontario Auditor General Office, Special Report, 2015).

MTO has categorized highways based upon Winter Average Daily Traffic (WADT) into five classes that have different limits for WADT in Northern and Southern Ontario (Table 2.3). Each class is governed by a set of maintenance standards specified in terms of bare pavement recovery time, circuit time for salting and sanding, and plowing (maximum distance that can be covered per plow). There are some general guidelines applicable for maintenance of all highways irrespective of their class such as deployment time and spreading speed (Table 2.3).

WRM fleet consist of plows, salt and sand spreaders, and combination units (that can plow and spread). It can be deduced from the maintenance standards that level of service depends upon the class of highway such that higher classes, with high traffic volume, are served with higher standards.

The materials used for WRM, comply to MTO’s material specifications in aspects of chemical composition and gradation (METRIC OPSS.PROV 2502, MTO 2017; METRIC OPSS.PROV 1004, MTO 2012). The guidelines established for salt are such that at least 96% sodium chloride by mass, 100% passing 9.5 mm sieve and at most 65% passing 2.36 mm sieve for coarse crushed salt while 100%

passing 4.75 mm sieve and at least 35% passing 1.18 mm sieve for fine crushed salt. The gradation requirement for winter sand is 100% passing 9.5 mm sieve and at least 20% passing 1.18 mm sieve.

Table 2.3[3]: Maintenance Standards for Highways in Ontario

<table>
<tr><th>Highway Class</th><th>WADT</th><th>Bare Pavement Recovery Time</th><th>Circuit Time for Salting***</th><th>Circuit Time for Sanding***</th><th>Plowing (max single lane km/plow)</th></tr>
<tr><td>Class I</td><td>>10,000</td><td>8 Hrs</td><td>1.3 Hrs</td><td>N/A</td><td>55 km</td></tr>
<tr><td>Class II</td><td>10,000-2,000S
10,000-1,500N</td><td>16 Hrs</td><td>1.8 Hrs</td><td>N/A</td><td>75 km</td></tr>
<tr><td>Class III</td><td>2,000-1,000S
1,500-8,00N</td><td>24 Hrs</td><td>2.9 Hrs</td><td>N/A</td><td>120 km</td></tr>
<tr><td>Class IV</td><td>1000-500S
800-400N</td><td>24 Hrs*</td><td>4.9 Hrs</td><td>N/A</td><td>206 km</td></tr>
<tr><td>Class V</td><td><500S
<400N</td><td>24 Hrs**</td><td>N/A</td><td>8 Hrs</td><td>336 km</td></tr>
<tr><td colspan="6">S and N, represent traffic volume in Southern and Northern Ontario respectively</td></tr>
<tr><td colspan="6">* for class IV highways, centre bare condition (the centre 2.5 m) needs to be bare within 24 Hrs of storm's end</td></tr>
<tr><td colspan="6">** for class V highways, snow packed conditions (smooth and hard snow covered surface) with excess snow needs to be plowed off within 24 Hrs of storm's end</td></tr>
<tr><td rowspan="3">DEPLOYMENT</td><td colspan="5">Salting begins before 0.5 cm accumulation of snow, N/A on Class V Highways</td></tr>
<tr><td colspan="5">Plowing is done before or upon 2 cm of snow or slush accumulation</td></tr>
<tr><td colspan="5">Sanding is done as soon as Slippery Conditions are detected</td></tr>
<tr><td colspan="6">Spreading speeds are specified as 32-48 Km/hr and for plowing up to 70 km/hr</td></tr>
<tr><td colspan="6">*** Circuit Time is maximum time within which plowing, salting or sanding should be done on entire circuit, doesn't include time to return to yard.</td></tr>
</table>

[3](MTO Quality Standards Manual, 2003; MTO Best Practices Manual, 2003; Ontario Auditor General Office, Special Report, 2015)

2.4 Summary

WRM operations are performed to clear snow or ice from roads and bring the deteriorated RSC to normal driving conditions, includes two approaches - anti-icing and de-icing. Pre-wetting salt before their application is a technique to improve their adhesion to pavement thus reduce the quantities of materials used and loss to environment. The survey conducted to determine pre-wetting practices adopted by various jurisdictions shows that NaCl is the commonly used de-icer for pre-wetting and materials are mostly pre-wetted at a ratio of 5%.

Chapter 3

Methodology

The primary objective of this research is to investigate the effectiveness of pre-wetting in achieving sustainable winter road maintenance. To achieve this goal, field trials were conducted at various locations across Ontario, Canada. Different pre-wetting ratios were compared for salt whereas impacts of pre-wetting explored in case of sand. This chapter details (1) the analysis and modeling approach (2) the data sources to be used in this study, and (3) the data processing including image classification scheme and integration procedure to generate the data set for the subsequent modeling.

3.1 Analysis and Modeling Approach

Analysis of the relative performance between the different treatments is conducted by considering three measures of performance - levels of friction, amount of material used and RSC. The following three analysis methods are applied to evaluate the performance differences:

1) Comparative Analysis: It is a technique which draws comparison between the population means of two groups by assuming that the tests were conducted under completely random settings or there were no systematic differences in environmental factors between the test sections. In this research, two measures of effectiveness will be considered, namely, level of friction (or coefficient of friction) and amount of material used.

2) Visual Analysis: This analysis is designed to compare the differences in performance as measured by the visual appearance – snow coverage of test routes using the images collected from the tests. The snow coverage measure addresses the issues of the friction measurement which includes essentially point measures with limited lateral representation of the road surface conditions.

3) Regression Analysis: Regression analysis is an approach that can be used to capture and understand the effects of multiple factors on the performance differences such as wind speed, air temperature, and traffic, etc. Another objective of regression modeling was to quantify the relative difference in performance under different treatments.

3.2 Study Site and Data Sources

The field trials were conducted for the winter season, 2016-17 to demonstrate the benefits of pre-wetting for salt. In order to evaluate the relative effectiveness of different treatments, data on both performance measures and environmental factors were collected from different sources. This section describes the selected study sites, various data sources and the pre-processing steps taken before starting the subsequent analysis and modeling.

3.2.1 Study Site

Winter field trials were conducted at Durham and the relative performance of salt with different pre-wet ratios, i.e., PW 5%, PW 10% and PW 20%, were compared by selecting three sections on Highway 6 (Figure 3.1).

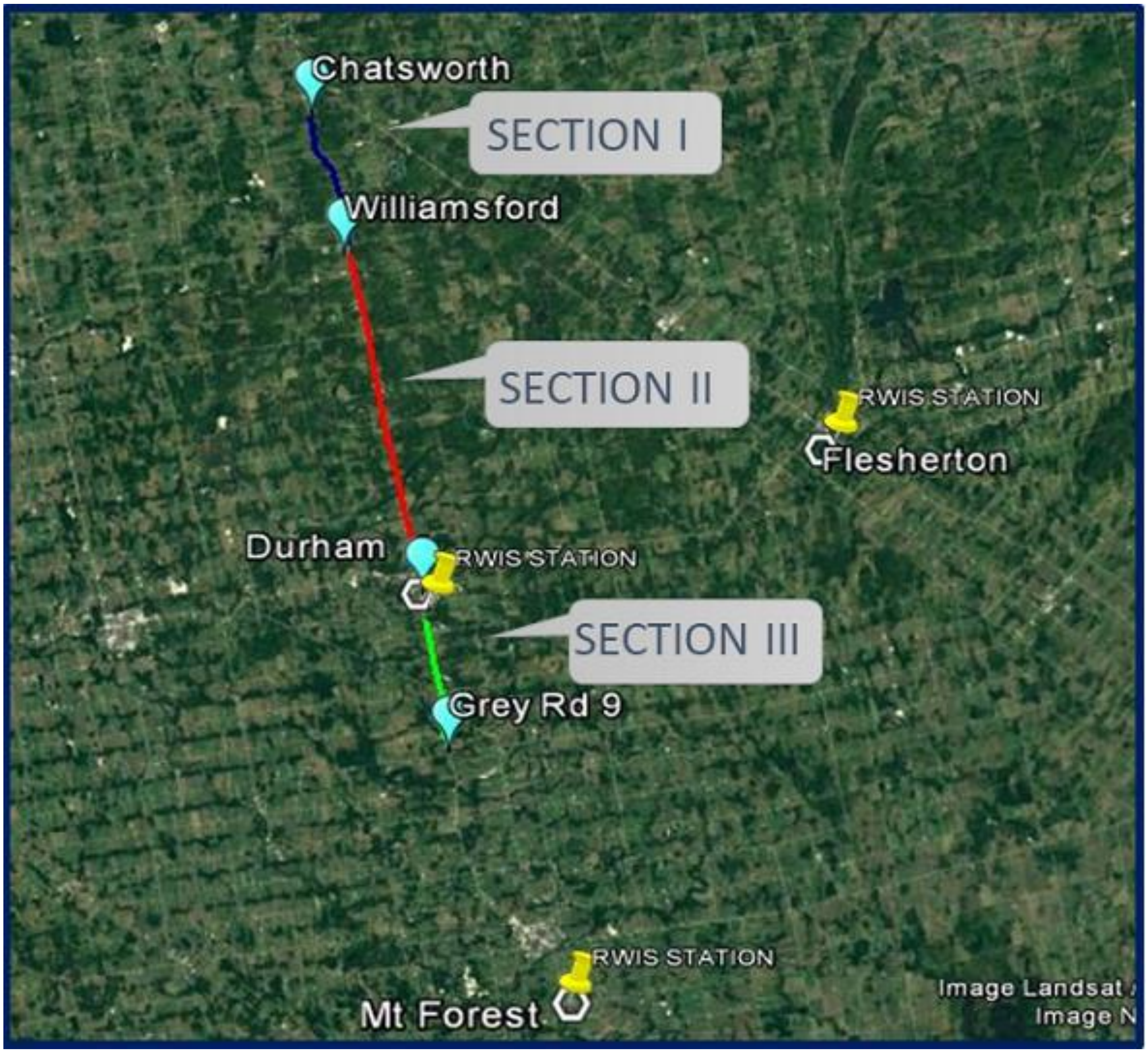


Figure 3.1: Study site

3.2.2 Data Sources

In order to compare the relative performance of different treatments, six types of data sources were sought including weather data, traffic data, material data, friction data, image data and winter operations data. This section provides a detailed description of these data sources whereas samples of the data sources are provided in Appendix C. Special attention was given to compiling data collected during individual snow storm events. A snow storm event was defined with the following constraints:

1) Event beginning is the time when accumulation begins with the start of falling snow or freezing rain; when drifting snow begins to accumulate on the driving surface of the road; and/or when frost creates a slippery condition. Bare pavement is considered lost as an event begins.
2) Event ending is the time when snow or freezing rain stops falling and accumulating, when drifting ceases to cause accumulation on the road surface, or when frost is no longer creating a slippery condition
3) Bare pavement regain time is the time when 95% of the driving surface (edge line to edge line) is free of snow, slush and/or ice.

A snow-storm event was defined from the beginning of accumulation of snow or slippery conditions to the time when RSC were restored to some pre-defined conditions and is depicted clearly in Figure 3.2. Maintenance operations sometimes continue after an event ends to achieve bare pavement conditions; as a result, an event includes the time taken for this effort.

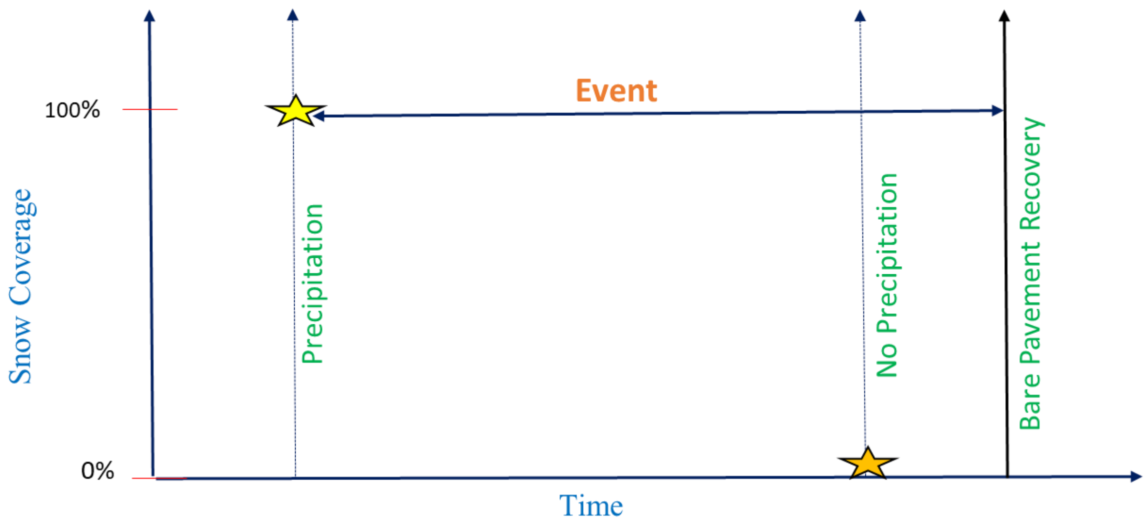


Figure 3.2: Definition of Snow-storm event

3.2.2.1 Weather Data

Weather data such as air temperature, wind speed, relative humidity, gust speed, etc., was obtained from Road Weather Information System (RWIS) stations near the study site. RWIS stations record data every 20 minutes and the RWIS sites used in this research are – Durham, Mt Forest and Flesherton (Figure 3.2). If data was derived from more than one RWIS station for a given study site, the RWIS station closer to the test routes was considered a primary source while others as a secondary source. The data from the secondary source was used for filling in missing data from the primary one. However, if data was available from all the RWIS sites and differed insignificantly for a given variable, a station-wise average was used for that variable.

3.2.2.2 Traffic Data

Traffic volume data was collected from loop detectors. This data was provided by MTO in hourly format for both Northbound (NB) and Southbound (SB) directions. Traffic count data was collected by installing two loop detectors on Section – I and one loop detector was installed on Section – II of the study site. The data was screened for any outlier due to malfunctioning of the loop detectors. Traffic data required some pre-processing and was first totaled for NB and SB directions at every given interval. The following steps were taken to process traffic data:

1) An average of traffic count data from multiple stations was used for the test section when data was available from more than one station.
2) Traffic data for the test sections that were not equipped with any traffic station was acquired by using hourly traffic volume from the nearby section multiplied by the ratio of their AADT (Annual Average Daily Traffic).
3) A 24*7 matrix was computed for each station, corresponding to traffic data for each day of week with every hour of day using the traffic data information provided by MTO. The matrix was then used to generate continuous hourly traffic data set for each station by filling in the missing information for the time period when the field trials were conducted.

3.2.2.3 Material/ AVL Data

Material data was gathered from the AVL (Automatic Vehicle Location) system, which includes the GPS location, time stamp and material application rate of all operating maintenance vehicles. Data was recorded in a high resolution, i.e., at intervals of every few seconds, when a maintenance vehicle was traversing the scheduled routes. The information about the type of material being used was not available directly, but was inferred from the recorded data on the “material application rate” and “material dry” fields. The “material dry” field has values 0, 1 or 5, with 5 used for sand and others for salt. Furthermore, material application rate of more than 200 kg/ 2-lane-km would imply the use of sand as salt is never applied at such a high rate. The type of vehicle used for WRM is shown in Figure 3.3.

Figure 3.3: Vehicle used for spreading winter road maintenance materials

3.2.2.4 Friction Data

Friction data is collected by a Mobile Data Collector Unit (MDCU) using a Teconer which uses a spectroscopic sensor to detect the state of the road surface and then estimate the friction levels. It provides information about the coefficient of friction ranging from 0 to 1 (higher values imply better RSC and vice-versa), water layer thickness in millimeters, pavement temperature (°C) and surface conditions. The surface conditions are classified into six categories (dry, moist, wet, slushy, ice, snow/frost). Figure 3.4a shows the Teconer fixed to the front end of an MDCU.

It is connected to a cell phone/tablet that displays information using Mobile Road Condition interface (Figure 3.4b). The interface also shows a GPS location and time stamp. The information is collected at intervals of 1 to 2 seconds when the MDCU is traversing the test routes. Due to the huge number of observations in Teconer data, data is averaged for each test run, which is explained later in the thesis.

Figure 3.4: Teconer system installed on the MDCU

3.2.2.5 Image Data

The images of road surface are captured by the camera of the cell phone/tablet that is connected to the Teconer and are displayed on the Mobile Road Condition interface with the GPS location and the time stamp.

3.2.2.6 WO Records/ BP Reports

Winter Operations (WO) records contain almost the same information as the material data from the AVL system such as location, time, amount of materials used, and maintenance vehicle number but have less details. The Bare Pavement (BP) reports record start of event time, the time bare pavement was lost, event ending time and bare pavement regain time. It also provides information on the type of the event such as snow, freezing or both.

3.3 Data Processing

The focus of this section is on methodology employed for processing the data needed for different types of analyses. After the data was acquired from different sources, the first step was to extract the data corresponding to the test routes based on the location and time stamps that are available for almost all data sources.

The MDCU, in any operation, continuously collects the data while traversing the test sections repeatedly back and forth. A test section in any direction is covered in 10 to 15 minutes on average and is named as test run in this analysis. It should be noted that a single operation is comprised of multiple test runs and named as operational run. Data obtained from the MDCU was aggregated at two different levels. For comparative analysis, data was averaged at the level of operations whereas for regression analysis data was averaged at the test run level. A run could include many observations or readings, depending on the sensor sampling frequency of the system. The number of test runs also varies depending on the event severity and duration.

The raw data from the MDCU was first partitioned into blocks by sections and then checked for any outliers caused by sensor failures and operation errors. The next step was to perform comparative analysis by summarizing the friction data for each operational run by test section (Figure 3.5). The individual average run-wise friction values for each section were further summarized by each event for subsequent analysis.

The unit material usage on each test section over each event was calculated by dividing the total material used over the event by the total 2-lane kilometers of the section. All weather related data such as air temperature and wind speed were averaged by event. It should be noted that all data from the Teconer sensor such as pavement temperature and water layer thickness was processed in the same way as the weather data.

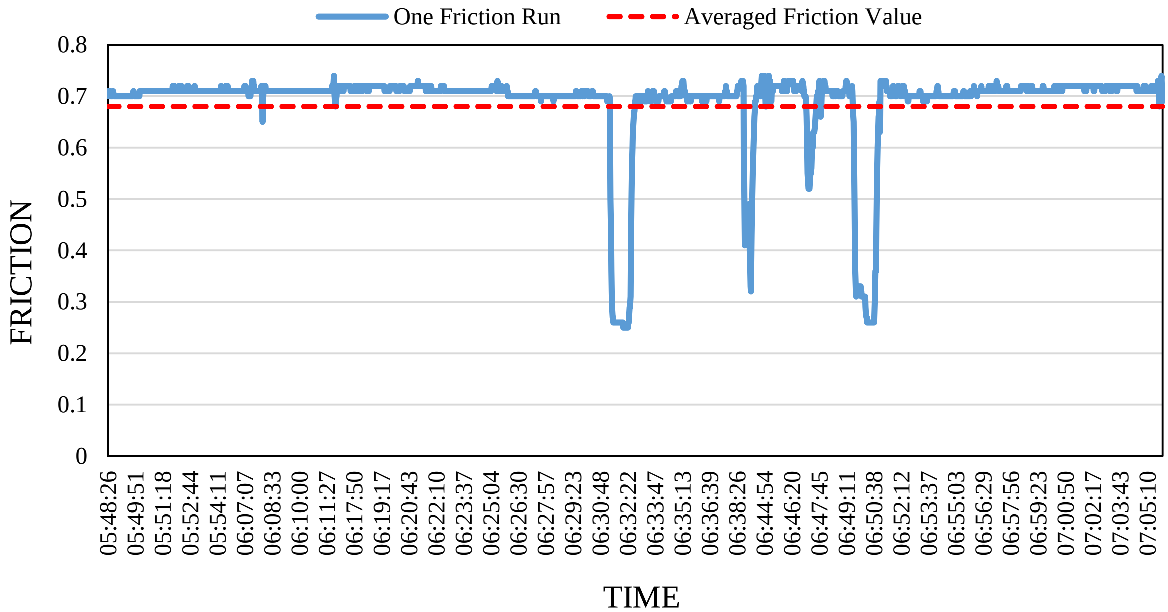


Figure 3.5: Example of friction run from PW 20% section on December 23rd, 2016

WO records/BP reports were used as an additional source of information to supplement material data and information related to the duration of event as well the type of event. The schematic of data processing for comparative analysis is shown in Figure 3.6.

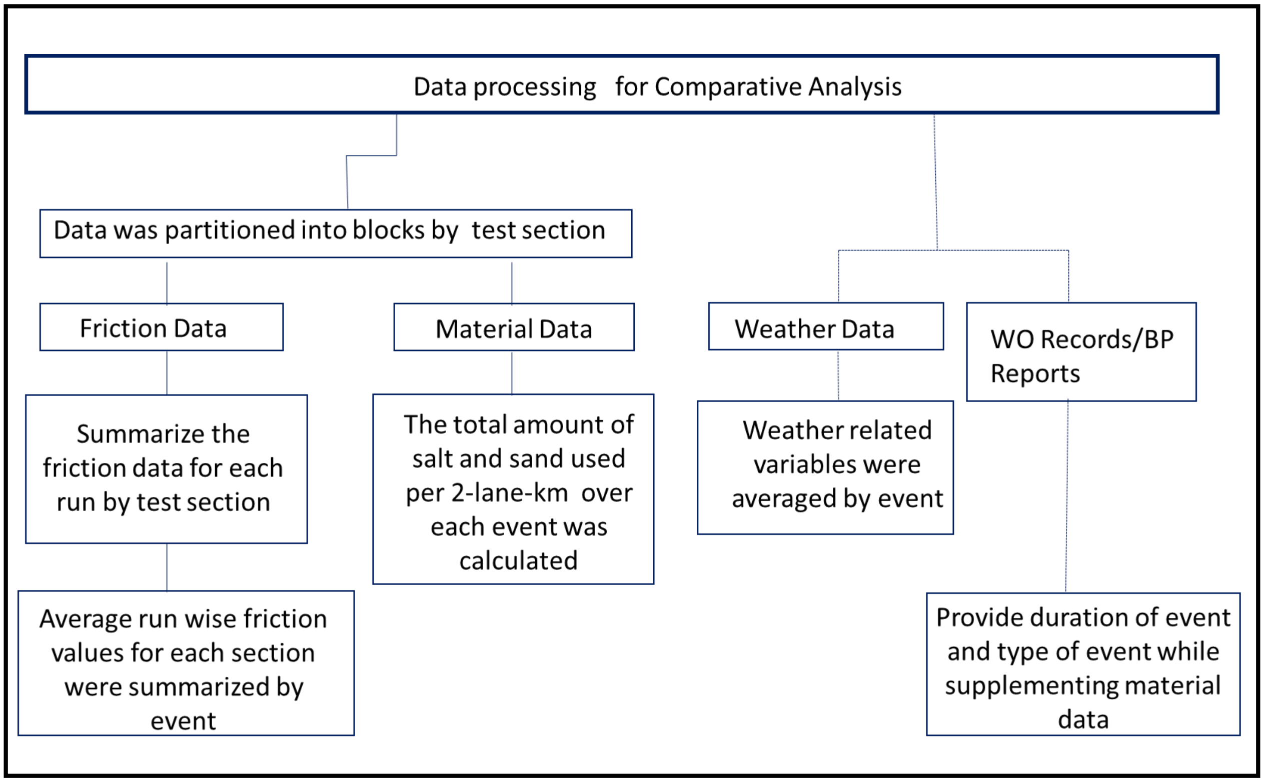


Figure 3.6: Schematic of data processing for comparative analysis

In order to examine the road conditions for visual analysis, the images recorded from each test run were manually classified into six categories with each being assigned a number value – Snow Index Number, as defined in Table 3.1.

Table 3.1: Classification of Road Surface Condition from Images

Road Surface Condition Description	Road Surface Condition Example	Snow Index Number Assigned
1) Fully Bare Pavement: The road surface is clear between edge lines with visible central lane markings. However, shoulders might be covered with snow but the driving surface is clear of snow.		0
2) Bare Lane: The road surface is generally clear of snow but some part of road i.e. edges or middle are partially covered with snow.		1

3) Two Track Bare: Both wheel tracks are clear of snow with accumulation of snow at middle of lane and at centre of road.		2
4) One Track Bare: Only one-wheel track is clear of snow but rest of surface is covered with snow.		3

5) Central Bare: The road surface is generally covered with snow with bare pavement at the centre of road. The picture manifests central bare condition in both lanes.		4
6) Fully Snow Covered: The road surface is fully covered with snow and lane markings are not visible.		5

The Snow Index Number varies from 0 to 5 with 0 standing for fully bare road conditions and 5 for fully snow covered surface. The other four categories – Bare Lane, Two Track, One Track and Centre Bare are assigned with snow index numbers 1, 2, 3 and 4, respectively (Table 3.1).

All images were manually labeled with a snow index number based on snow coverage in both primary and opposite directions. The data was then summarized by averaging snow index numbers for each section by each event.

In order to form an integrated dataset for regression analysis, the various variables were merged together using the date and time as the common reference. Average friction values were computed for each test run by section and other variables such as the pavement temperature recorded by Teconer, weather data and elapsed time (time difference between material application and friction measurement) were synthesized from the various data sources based on the time stamp of the friction measurements. Additional steps were required for traffic data and the amount of salt used. It was assumed that traffic volume is uniformly distributed for each hour. The hourly traffic counts were assigned in a prorated manner based on the minutes elapsed in the friction reading. For example, if the friction value was observed at 11:30 a.m. and traffic volume data for 11:00 a.m. is 200 then traffic assigned would be 100 vehicles. The amount of salt used at time t of any friction value was calculated by adding the material used between this time and the time the previous friction reading was taken.

Chapter 4

Analyses of Field Trials

This study was aimed to determine whether a higher pre-wet ratio for salt can result in similar or better performance while consuming less material as compared to the standard pre-wet ratio. To fulfill this objective, field trials were conducted to compare the performance of higher pre-wet ratios of salt, i.e., 10% and 20%, to the conventional pre-wet ratio of 5% by mass using similar granular rate in Durham, Western Ontario for the winter season 2016-17. This chapter highlights the study site, the analyses conducted and the results based on the field trials.

The de-icer solution used for the pre-wetting of salt was Promelt Mag 22, which is 22% $MgCl_2$ with a specific density of 1.210 g/ml (Table 4.1). Occasionally, sand was also used in addition to salt to improve the surface traction; however, only dry sand was used in order to control the test with a focus on the performance of pre-wetted salt. An on-board spray system was used to pre-wet salt.

Table 4.1: Pre-wetting practices employed for field trials

Pre-wetting Method	Pre-wetted Material*	De-icer Solution	Specifications of Promelt Mag 22		
			Component	Concentration	Specific Density
On-board Spray System	Salt	Promelt Mag 22	MgCl2	22%	1.210 g/ml
*Sand was used in dry form					

The current MTO standards for pre-wetting salt is 5% by mass with a granular rate of 130 kg/ 2-lane-km. The pre-wet ratio by mass indicates the amount of de-icer solution to be used for pre-wetting a certain amount of material (salt or sand). For instance, a pre-wet ratio of 5% implies that the amount of de-icer solution is to be 5% of the total amount of salt, i.e., 5 kg of de-icer solution should be added as pre-wet to 100 kg of salt or 50 kg of de-icer solution to 1000 kg of salt. However, equipment used for pre-wetting the salt was calibrated in L/tonne and hence the specific density of de-icer solution is important to know. The specific density of Promelt Mag 22 is 1.210 gm/ml and therefore, 0.826 litres of Promelt Mag 22 supplements one kg of its use as de-icer solution. The pre-wet ratio of 5% results in an addition of 4.13 litres (5*0.826) Promelt Mag 22 per 100 kg of salt or 41.3 litres of Promelt Mag 22 per tonne of salt. Table 4 shows calibrated pre-wet rates in L/tonne for given pre-wet ratios by mass.

Table 4.2: Calibration of PW ratios by mass in L/tonne

PW Ratio (%) by mass	PW Rate (L/tonne)
5%	41.3
10%	82.6
20%	165.2

The types of approaches used to compare the effectiveness of different treatments includes comparative analysis, visual analysis and regression analysis, as discussed previously. In addition, a questionnaire was prepared for field staff to learn their opinion regarding the performance of different pre-wet ratios of salt and the survey results are provided in Appendix D along with the questionnaire.

4.1 Study Site

In order to evaluate the relative performance of salt with different pre-wet ratios, three highway sections of Highway 6 near Durham, Western Ontario were selected (Figure 4.1); they are labeled section I, II and III. Section I extends from Chatsworth to Williamsford with a length of 9.5 km, Section II starts from Williamsford and ends at Durham with a length of 21.6 km, whereas Section III starts from Durham and ends at Grey Rd 9 with a length of 9.33 km. Highway 6 is a maintenance service Class 2 provincial highway. For this class, the immediate maintenance objective is to establish bare pavement conditions within 16 hours after the storm ends.

The selected sections are two-lane, two-way highways for most of their defined lengths with some including passing lanes at some stretches in two directions. Section I does not include any passing lanes whereas Section II and Section III include a 1.9 km passing lane in NB and 2.2 km passing lanes in both NB and SB, respectively. The sections vary in terms of traffic volume such that annual average daily traffic (AADT) is 4700, 3650 and 5500 for Section I, Section II and Section III, respectively. The test sections were treated with salts with different pre-wet ratios: Section I with 5%, Section II with 10% and Section III with 20% pre-wet salt. All of the details are summarized in Table 4.3.

Table 4.3: Description of test sections

Test Route	Start Point	End Point	Pre-wet Ratio	AADT	Length (km)	Length of Passing Lanes(km)	
						NB	SB
Section I	Chatsworth	Williamsford	5%	4700	9.5	-	-
Section II	Williamsford	Durham	10%	3650	21.6	1.9	-
Section III	Durham	Grey Rd 9	20%	5500	9.33	2.2	2.2

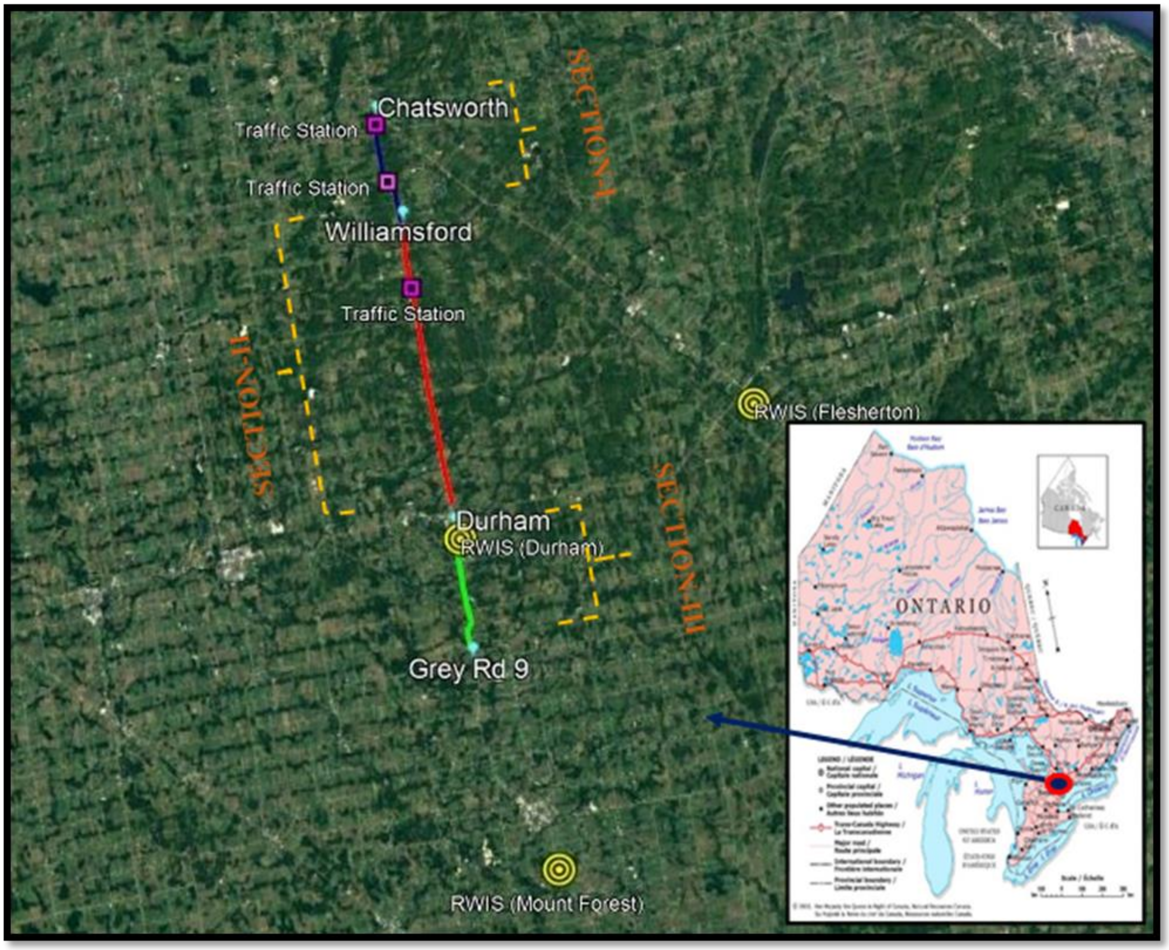


Figure 4.1: Study site of field trials

Figure 4.1 also shows locations of RWIS and traffic stations, used to acquire weather and traffic count data. Two loop detectors were installed on Section I and one on Section II. The weather data was collected from three RWIS stations at Durham, Flesherton and Mount Forest. However, the former was used as a primary source of weather data and the latter two as a secondary source, as explained previously.

A total of 29 snow events were recorded from Dec 15, 2016 to March 18, 2017 in the winter season 2016-17. However, only 25 events are used for analysis as friction data was not available for the other events. A short summary of 25 events with their original IDs is provided in Table 4.4 and shown in Figure 4.2. Besides this, detailed descriptions for each of 25 events in terms of levels of friction achieved and material application rate (material used is sand if material application rate is more than 200, else salt is used) along with the relative performance of different pre-wet ratios of salt for each of the event is given in Appendix B.

It should be noted that the length of the test sections forming the part of passing lanes is removed from analysis as they are treated differently as compared to the normal driving lanes. That is, the 1.9 km length of Section II and 2.2 km length of Section III is excluded from further analyses.

Table 4.4: Summary of events

Event	Event type	AVG TEMP(°C)	MAX TEMP(°C)	MIN TEMP(°C)	AVG WIND SPEED(Km/hr)	MAX WIND SPEED(Km/hr)	MIN WIND SPEED(Km/hr)	AVERAGE RELATIVE HUMIDITY	AVERAGE GUST(Km/hr)
2	Snow	-9.6	-3.2	-15.8	14.0	32.0	0.0	84.1	19.0
3	Snow	-4.6	-2.9	-6.8	25.4	45.0	14.3	71.7	34.9
4	Snow/Freezing Rain	-1.9	-0.4	-3.3	13.5	18.3	10.3	87.5	18.7
5	Freezing Rain	-3.3	-2.9	-3.9	16.8	19.3	16.0	88.5	23.8
6	Snow/Freezing Rain	-0.3	0.3	-1.0	15.9	21.7	11.0	90.4	21.9
8	Snow	-4.8	-4.2	-5.1	16.8	23.3	11.0	84.0	22.6
9	Snow	-2.9	-0.1	-6.0	18.3	31.0	7.3	87.5	25.0
10	Snow	-9.9	4.8	-16.8	20.8	51.3	1.7	-	28.6
11	Freezing Rain	-0.5	0.0	-0.9	11.2	15.7	4.7	99.0	16.3
12	Snow	-1.4	-1.0	-2.0	12.2	15.7	6.0	96.9	16.7
13	Snow	-7.6	-7.1	-8.3	16.6	22.0	9.3	73.9	23.0
15	Snow/Freezing Rain	0.1	0.6	-1.0	5.3	16.3	1.0	52.7	7.5
16	Snow	-3.0	-0.6	-4.5	20.7	31.3	10.3	87.2	28.5
17	Snow	-9.2	-7.7	-10.7	7.5	17.0	0.7	83.7	11.2
19	Snow	-7.2	-1.4	-10.7	17.7	34.3	3.7	80.6	24.4
20	Snow	-2.9	3.7	-8.3	18.5	35.0	0.0	-	25.9
21	Not Available	-7.2	-1.4	-10.1	16.1	24.7	5.7	81.5	22.6
22	Not Available	-3.7	-0.2	-7.0	17.6	34.0	1.0	86.3	25.2
23	Snow	-5.8	0.9	-12.3	13.5	24.7	2.3	89.7	18.8
24	Snow/Freezing Rain	-6.8	7.2	-11.5	19.3	29.7	8.0	89.0	26.9
25	Snow	-11.4	-8.0	-14.7	12.4	27.0	2.3	76.8	18.0
26	Snow	-12.9	-10.5	-16.1	13.7	32.0	0.0	78.4	19.6
27	Not Available	-11.2	-10.4	-11.9	16.3	19.7	12.7	76.5	22.0
28	Not Available	-9.3	-6.5	-11.2	23.0	31.7	16.0	58.4	33.1
29	Not Available	-1.2	-0.6	-2.2	14.8	20.3	10.0	82.4	20.5

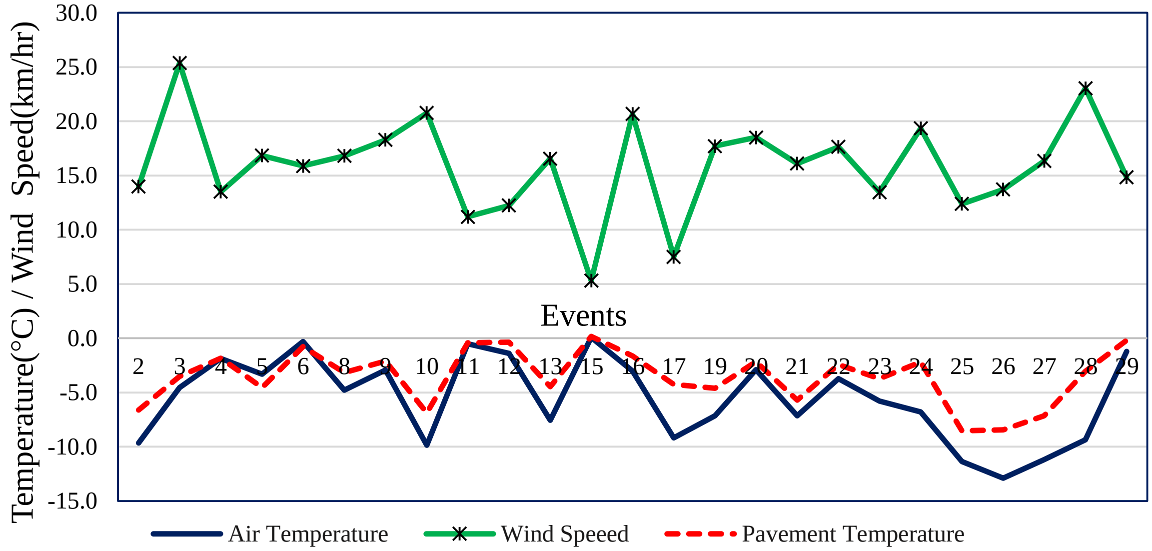


Figure 4.2: Air Temperature, Pavement Temperature and Wind Speed associated with the events

The selected sites have the same orientation and similar weather conditions, as shown in Figure 4.3, demonstrating similar average pavement temperature across the test routes treated with different PW ratios (5%, 10% and 20%) for salt for each of the recorded events.

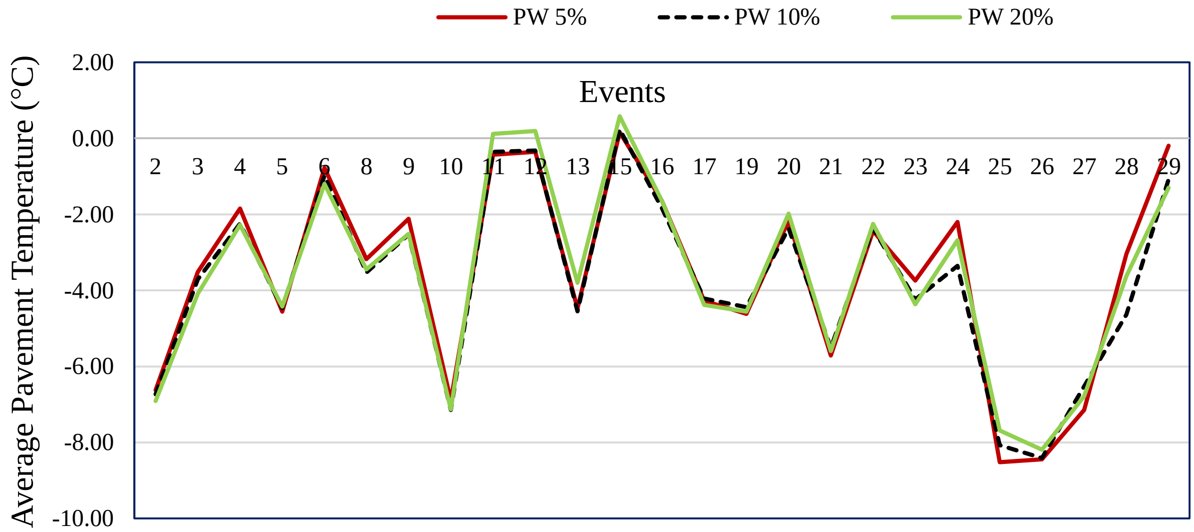


Figure 4.3: Section-wise average pavement temperature

4.2 Comparative Analysis – Friction

This section presents a comparison of the performance of salt at the three pre-wetting ratios with friction as a performance measure such that the coefficients of friction observed from the three test sections were compared at two levels of aggregation, namely, run-wise averages (frictions are averaged by each test run) and event-wise averages (average of all run-wise averages over an event).

A detailed comparison using the run-wise averages were first conducted using a t-test to determine if significant differences in the levels of friction between the sections of different pre-wetting ratios existed over an event (Table 9). A paired t-test using the event-wise averages was performed to determine significant difference between overall average friction values attained for different pre-wet ratios of salt (Appendix E). The idea behind using a paired t-test is to reduce the effect of any variability present among test sections due to differences in site-specific factors. In other words, it makes the experiment more sensitive to detect differences between the treatments. The outcomes for Comparative Analysis using friction as a performance measure are described below in this section.

As compared to salt pre-wetted at a ratio of 5%, PW 10% and PW 20% salt shows an improvement of 11% and 15% respectively in friction on the average, as shown in Table 4.5 and the paired t-test infers that the improvement is statistically significant (Appendix E). However, PW 20% shows a minimal and statistically insignificant improvement of 4% in average friction as compared to PW 10% (Table 4.5 and Appendix E).

Table 4.5 shows that the sections treated with PW 10% and PW 20% salt were found to be significantly different in six events when compared to the PW 5% section and all of these events showed that the higher pre-wet ratios offer more improvement. In addition to this, the sections treated with PW 10% and PW 20% salt performed better in 17 and 18 events respectively as compared to the section treated with conventional 5% pre-wet salt. However, the comparison of sections treated with higher pre-wet ratios implies that PW 10% and PW 20% salt were significantly different from each other only in one event, favouring PW 10% salt and the section treated with 20% pre-wet ratio was found better in 16 events whereas in other nine events the section treated with PW 10% salt performed better.

Figure 4.2 shows the event-wise averages friction levels of the three sections over the individual events. Overall, the average friction levels of the sections treated with pre-wetted salt at PW ratios of 10% and 20% were similar but higher than those of the section with normal treatment (salt with PW 5%).

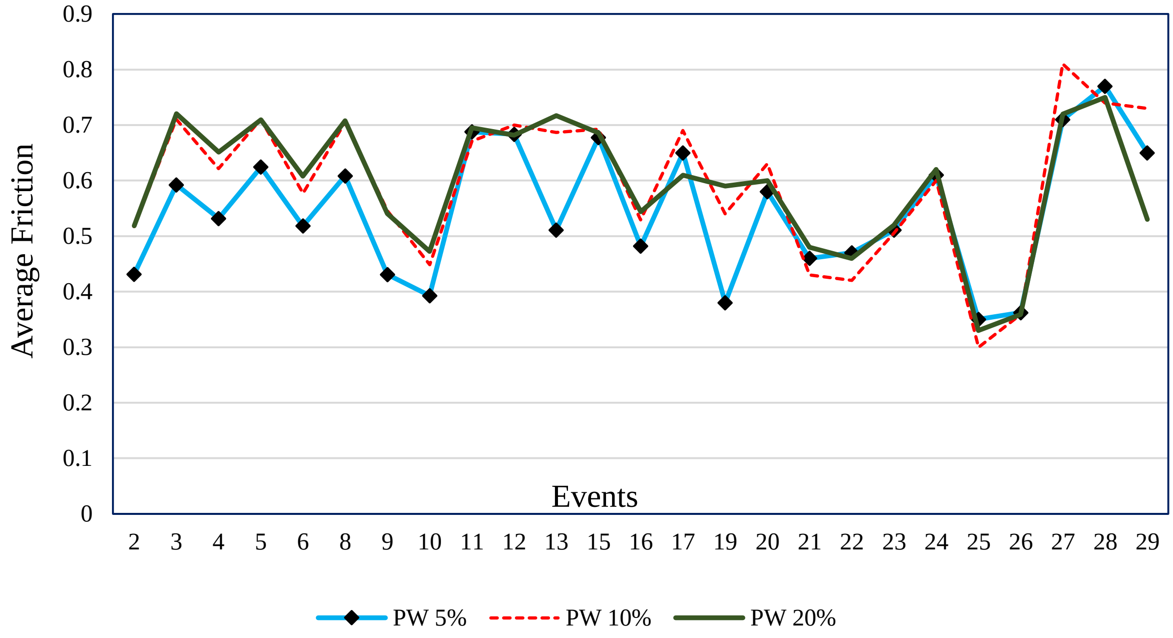


Figure 4.4: Section-wise average friction levels over individual events

Table 4.5: Comparative Analysis - Friction

Event Description			5% PW Section			10% PW Section			20% PW Section			Comparative Analysis - 10% PW wrt 5% PW			Comparative Analysis- 20% PW wrt 5% PW			Comparative Analysis- 20% PW wrt 10% PW		
Event #	Start Date	End Date	Average Friction	Standard Deviation	No of Runs	Average Friction	Standard Deviation	No of Runs	Average Friction	Standard Deviation	No of Runs	Test Sections Differ Significantly	Test section performing well	% improvement wrt 5% PW	Test Sections Differ Significantly	Test section performing well	% improvement wrt 5% PW	Test Sections Differ Significantly	Test section performing well	% improvement wrt 10% PW
2	2016-12-15 12:00	2016-12-19 19:30	0.43	0.095	26	0.52	0.154	26	0.52	0.142	24	YES	10%	19.88	YES	20%	20.26	NO	20%	0.32
3	2016-12-20 11:00	2016-12-21 9:00	0.59	0.034	8	0.71	0.018	8	0.72	0.046	8	YES	10%	19.92	YES	20%	21.63	NO	20%	1.43
4	2016-12-21 22:00	2016-12-22 10:00	0.53	0.062	5	0.62	0.128	5	0.65	0.104	5	NO	10%	16.88	NO	20%	22.54	NO	20%	4.85
5	2016-12-23 5:00	2016-12-23 8:00	0.62	-	1	0.71	-	1	0.71	-	1	-	10%	13.80	-	20%	13.62	-	10%	-0.16
6	2016-12-23 21:00	2016-12-24 9:30	0.52	0.105	5	0.58	0.170	5	0.61	0.149	5	NO	10%	11.38	NO	20%	17.34	NO	20%	5.35
8	2016-12-27 18:00	2016-12-28 10:00	0.61	0.035	5	0.71	0.023	5	0.71	0.055	4	YES	10%	15.95	YES	20%	16.32	NO	20%	0.32
9	2016-12-28 18:00	2017-01-01 11:00	0.43	0.125	30	0.55	0.142	30	0.54	0.143	27	YES	10%	26.64	YES	20%	25.49	NO	10%	-0.91
10	2017-01-04 2:30	2017-01-11 4:00	0.39	0.110	49	0.45	0.144	51	0.47	0.169	44	YES	10%	14.26	YES	20%	20.22	NO	20%	5.22
11	2017-01-12 6:00	2017-01-12 9:00	0.69	-	1	0.67	-	1	0.69	-	1	-	5%	-2.38	-	20%	1.03	-	20%	3.49
12	2017-01-12 12:30	2017-01-12 15:00	0.68	-	1	0.70	-	1	0.68	0.006	2	-	10%	2.45	-	5%	-0.17	-	10%	-2.56
13	2017-01-13 6:00	2017-01-13 16:00	0.51	0.136	3	0.69	0.035	3	0.72	0.050	2	NO	10%	34.39	NO	20%	40.26	NO	20%	4.36
15	2017-01-25 19:30	2017-01-26 12:00	0.68	0.021	6	0.69	0.009	6	0.69	0.007	6	NO	10%	2.22	NO	20%	1.21	NO	10%	-0.99

Event Description			5% PW Section			10% PW Section			20% PW Section			Comparative Analysis - 10% PW wrt 5% PW			Comparative Analysis- 20% PW wrt 5% PW			Comparative Analysis- 20% PW wrt 10% PW		
Event #	Start Date	End Date	Average Friction	Standard Deviation	No of Runs	Average Friction	Standard Deviation	No of Runs	Average Friction	Standard Deviation	No of Runs	Test Sections Differ Significantly	Test section performing well	% improvement wrt 5% PW	Test Sections Differ Significantly	Test section performing well	% improvement wrt 5% PW	Test Sections Differ Significantly	Test section performing well	% improvement wrt 10% PW
16	2017-01-26 17:00	2017-01-28 22:00	0.48	0.146	17	0.53	0.151	17	0.54	0.167	15	NO	10%	9.87	NO	20%	12.83	NO	20%	2.70
17	2017-01-29 11:00	2017-01-29 23:30	0.65	0.030	4	0.69	0.018	4	0.61	0.088	4	NO	10%	6.15	NO	5%	-6.15	NO	10%	-11.59
19	2017-01-31 11:00	2017-02-04 14:30	0.38	0.106	25	0.54	0.122	28	0.59	0.150	25	YES	10%	42.11	YES	20%	55.26	NO	20%	9.26
20	2017-02-07 18:00	2017-02-08 17:00	0.58	0.114	6	0.63	0.100	6	0.60	0.137	6	NO	10%	8.62	NO	20%	3.45	NO	10%	-4.76
21	2017-02-09 15:30	2017-02-11 9:00	0.46	0.116	13	0.43	0.092	13	0.48	0.149	13	NO	5%	-6.52	NO	20%	4.35	NO	20%	11.63
22	2017-02-12 8:00	2017-02-13 18:00	0.47	0.159	9	0.42	0.129	10	0.46	0.169	10	NO	5%	-10.64	NO	5%	-2.13	NO	20%	9.52
23	2017-02-14 20:00	2017-02-16 8:00	0.51	0.190	4	0.51	0.136	4	0.52	0.191	4	NO	5%	-1.00	NO	20%	1.96	NO	20%	1.96
24	2017-03-01 15:30	2017-03-02 11:00	0.61	0.089	5	0.60	0.173	5	0.62	0.170	5	NO	5%	-1.64	NO	20%	1.64	NO	20%	3.33
25	2017-03-03 3:30	2017-03-04 12:00	0.35	0.084	4	0.30	0.045	7	0.33	0.063	7	NO	5%	-14.29	NO	5%	-5.71	NO	20%	10.00
26	2017-03-10 16:30	2017-03-12 12:00	0.36	0.079	14	0.36	0.099	14	0.36	0.098	12	NO	5%	-0.88	NO	5%	-0.95	NO	10%	-0.07
27	2017-03-13 18:00	2017-03-13 22:00	0.71	0.000 6	2	0.81	-	1	0.72	-	1	-	10%	14.08	-	20%	1.41	-	10%	-11.11
28	2017-03-14 12:30	2017-03-15 21:00	0.77	0.034	4	0.74	0.067	4	0.75	0.070	11	NO	5%	-3.90	NO	5%	-2.60	NO	20%	1.35
29	2017-03-18 2:00	2017-03-18 12:00	0.65	0.114	3	0.73	0.053	4	0.53	0.132	4	NO	10%	12.31	NO	5%	-18.46	YES	10%	-27.40

Table 4.6: Significant vs Non-Significant Events

						5% PW Section			10% PW Section			20% PW Section		
	Test Sections	Average Temperature (°C)	Average Wind Speed (km/hr)	Average Relative Humidity (%)	Average Wind Gust (km/hr)	Salt (tonnes/2-lane-km)	Sand (tonnes/2-lane-Km)	Water Thickness (mm)	Salt (tonnes/2-lane-km)	Sand (tonnes/2-lane-Km)	Water Thickness (mm)	Salt (tonnes/2-lane-km)	Sand (tonnes/2-lane-Km)	Water Thickness (mm)
Sections differ Significantly	10% PW wrt 5%	-7	18	82	25	2	7	0.08	3	5	0.10	2	4	0.11
	20% PW wrt 5%	-7	18	82	25	2	7	0.08	3	5	0.10	2	4	0.11
Sections don't differ Significantly	10% PW wrt 5%	-6	15	80	22	1	2	0.14	1	2	0.14	1	2	0.16
	20% PW wrt 5%	-6	15	80	22	1	2	0.14	1	2	0.14	1	2	0.16

Table 4.6 summarizes the average conditions for the events when the test sections treated with higher pre-wet ratios (10% and 20%) differed significantly from that of the PW 5% section or otherwise. However, the average conditions are not provided for the comparison of higher pre-wet ratios as there is only one event for which PW 10% and PW 20% ratios of salt differs significantly. It can be seen from Table 10 that, on the average, when the test sections differed significantly, more material was used comparatively and the events were relatively more severe in nature, e.g., lower in temperature and higher in wind speed. From this it can be concluded that for relatively warmer events, no statistical difference exists between the different treatment types. One reason for this can be the presence of enough moisture in the snow to complement low pre-wet ratios (Table 4.6).

4.3 Comparative Analysis – Material Usage

This section highlights the comparison of different treatments with material usage as a measure of performance such that the amount of salt and sand used is calculated for each of the events for different treatments. Data on material applications were available for 17 events (out of 25 events observed), as summarized in Table 4.7.

Figure 4.5 compares the total material usage in tonnes per 2-lane-km for sections with different pre-wetting ratios. It can be observed that the test section treated with salt at a PW ratio of 10% used 13% more salt and 22% less sand when compared to the test section treated with salt at a 5% PW ratio. Similarly, the test section with salt at a PW ratio of 20% used 19% less salt and 35% less sand compared to the section with 5% pre-wetted salt. Comparing the sections treated with 10% and 20% pre-wet salt, the sections treated with 20% pre-wet salt used 28% less salt and 16% less sand.

Table 4.7: Comparison of material used

Event	PW 5% (tonnes/ 2-lane km)		PW 10% (tonnes/ 2-lane km)		PW 20% (tonnes/ 2-lane km)	
	salt	sand	salt	sand	salt	sand
2	3.23	5.00	3.10	6.42	2.36	4.52
4	0.57	0.00	0.56	0.00	0.42	0.00
5	0.11	0.00	0.09	0.00	0.11	0.00
6	0.39	0.00	0.40	0.00	0.43	0.00
8	0.67	0.00	0.55	0.00	0.44	0.00
9	2.02	4.51	3.85	1.53	1.41	0.60
10	3.54	15.95	4.87	13.19	2.57	8.96
11	0.09	0.00	0.18	0.00	0.11	0.00
12	0.11	0.00	0.12	0.00	0.13	0.00
13	0.31	0.00	0.47	0.00	0.06	0.00
15	0.62	0.00	0.78	0.00	0.51	0.00
16	1.43	4.90	1.55	4.23	1.54	2.17
19	2.25	9.45	1.46	3.48	1.48	2.04
21	0.68	1.89	0.84	0.90	0.80	4.34
22	0.70	3.37	0.21	2.13	1.03	4.14
24	0.58	0.71	0.66	1.39	0.62	0.84
26	0.99	2.86	1.03	4.74	0.91	4.23
Total	18.30	48.63	20.74	38.01	14.91	31.83

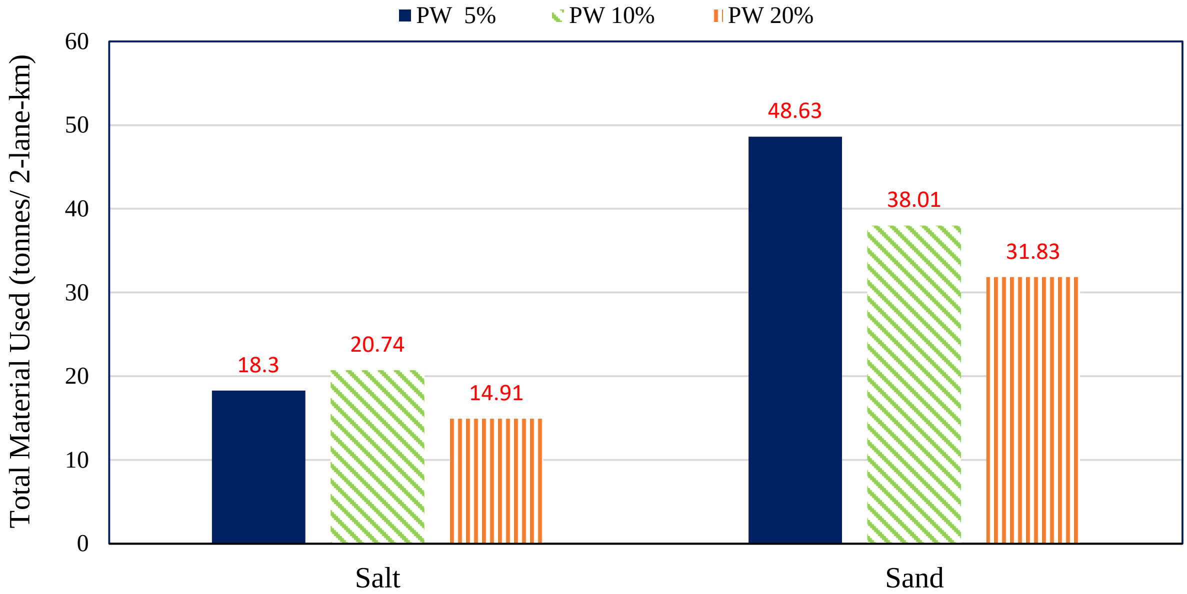


Figure 4.5: Comparison of total sand and sand used per 2-lane-km with salt of different pre-wetting ratios

4.4 Visual Analysis

This section compares the performance of different pre-wet ratios of salt by analyzing the road conditions treated with different pre-wetting ratios. A total of 23,000 images were recorded of which 16,034 images belong to three test sections (PW 5%, PW 10%, PW 20%). Some of the images were discarded due to poor quality; consequently, a total of 14,499 images were used in this analysis.

Following the process explained in section 3.3.2, the comparison of RSC on the sections treated with pre-wetted salt at three different ratios across the events is shown in Figure 4.6.

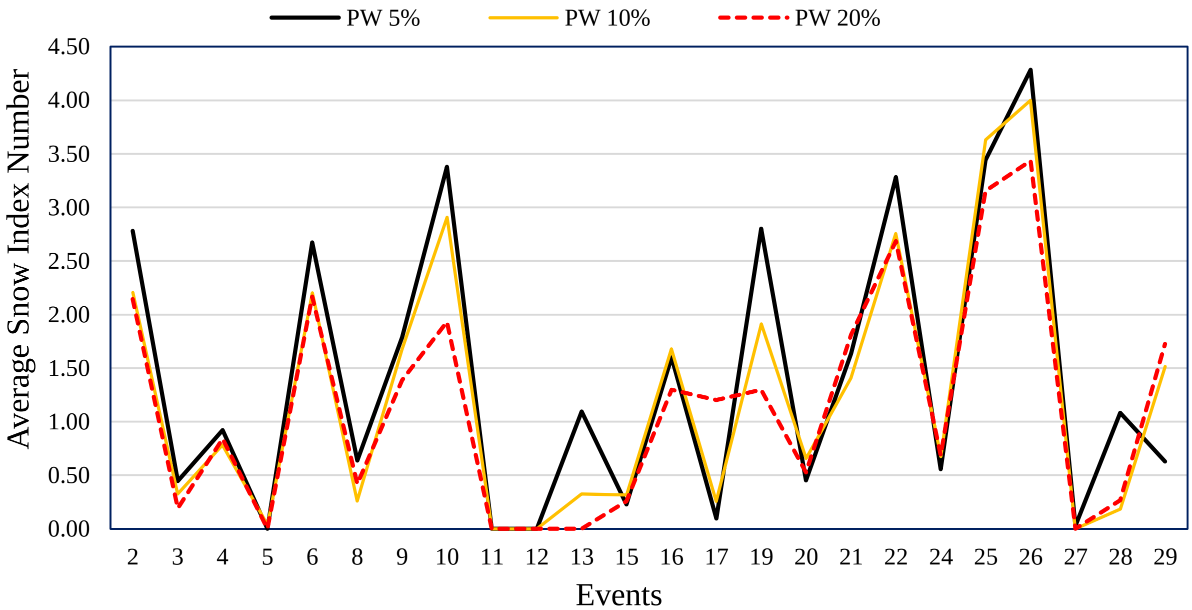


Figure 4.6: Section-wise average of snow index number over individual events

Figure 4.6 shows that the section treated with 20% pre-wet salt was associated with a lower snow index number in all events except one as compared to the sections treated with 10% and 5% pre-wet salt. On the other hand, the section treated with 10% pre-wet salt performed similarly to the one with 5% pre-wet salt that is related to a high snow index number across all the events except one. Therefore, it can be concluded that the treatment with salt at 20% pre-wet ratio had performed better in terms of snow melting result and friction level as compared to other two treatments.

Figure 4.7 shows three sample images of the prevailing road condition on the test sections treated with salt of three different pre-wet ratios on December 20th, 2016. The sections with higher pre-wet ratios showed better road surface conditions and less accumulation of snow than the sections treated with salt at a pre-wet ratio of 5%.

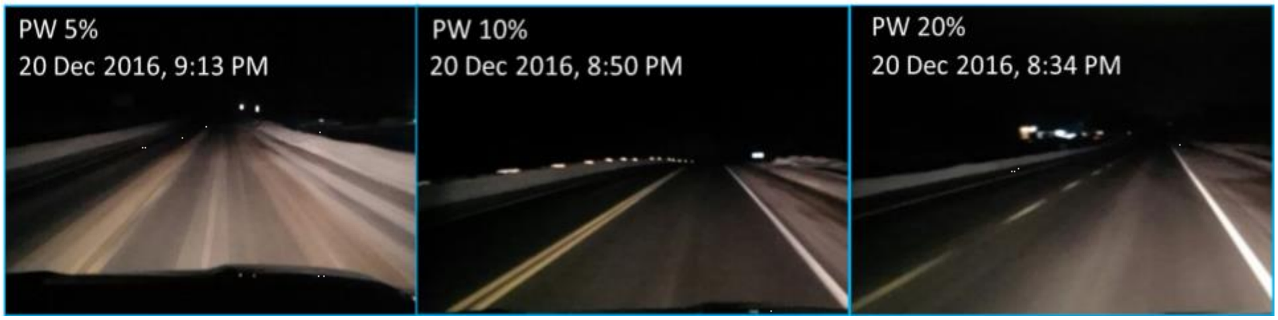


Figure 4.7: RSC on the sections treated with salt of different PW ratios

The findings from the visual analysis can be verified using information collected by Teconer under the field - road state number. Teconer assigns road state number from one to six based on the prevailing road conditions such that the higher the road state number, the worse the road surface condition and vice-versa (Table 4.8). A comparison of RSC on three sections using this information is shown in Figure 4.8.

Table 4.8: Identification of RSC by Teconer using road state number

Road Surface Condition	Road State Number
Dry	1
Moist	2
Wet	3
Slush, ice or snow with water	4
Ice	5
Snow or frost	6

The conclusions drawn from Figure 4.8 uphold the findings of the visual analysis that sections treated with PW 20% salt maintains a low state number, i.e., better RSC across the events with the exception of a few events as compared to the other two pre-wet ratios of salt. The section treated with pre-wet 10% salt is performing in between PW 5% and PW 20% salt. The section treated with pre-wet 5% salt is associated with higher state number, i.e., poorer RSC across the events other than few events.

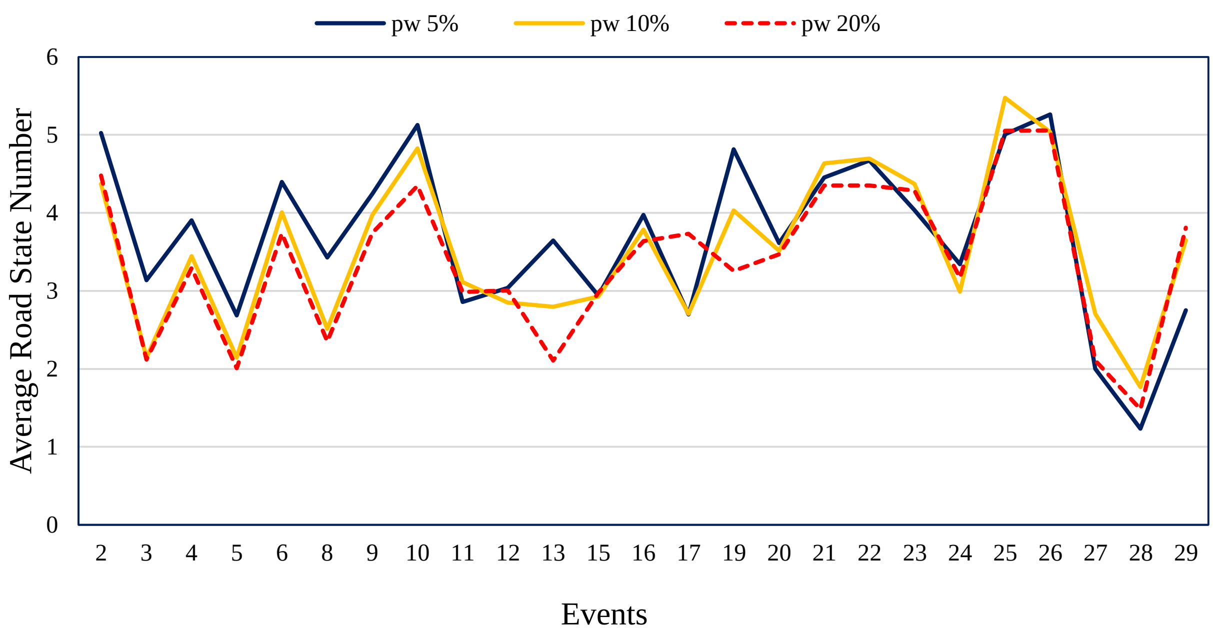


Figure 4.8: Section-wise average of road state number over individual events

Therefore, it can be concluded that pre-wet 20% salt possess higher snow melting capacity and results in earlier bare pavement restoration, less material consumption and better friction levels.

4.5 Regression Analysis

This section presents a more rigorous analysis, i.e., regression modeling to diagnose the potential factors that had contributed to the effectiveness of pre-wetting. The comparative analysis conducted in Section 4.2 has clearly shown the performance advantage of applying a higher pre-wetting ratio; however, it was unclear which factors contributed to the performance differences. A linear regression was therefore conducted to identify the possible contributing factors related to weather and traffic conditions.

Mathematically, general linear regression model can be written as:

$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k + \varepsilon$

where y is a dependent variable, which is average friction level in this study;

$x_1, x_2, \ldots, x_k$ = independent variables such as temperature and traffic volume, and may represent higher order terms, i.e. $x_2 = x_1^2$ or x_1x_3, ;

$\beta_0, \beta_1, \beta_2, \ldots, \beta_k$ = coefficients to be estimated through model calibration

$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k$ is expected value of y

ε = Random Error

where ε is assumed to be normally distributed with a mean equal to 0 and a constant and unknown variance. In addition to this, errors are also assumed to be independent of each other.

4.5.1 Model Building

The model was calibrated using the software package, Stata version 13. For this modeling assignment, integrated data corresponding to 25 events were pooled together for the three test sections, forming a total of 2485 observations. In order to represent a categorical variable, i.e., the type of treatment (PW 5%, PW 10% and PW 20%), two binary indicator variables were introduced: $PW_{10\%}$ (1 for 10% and 0 for other ratios) and $PW_{20\%}$ (1 for 20% and 0 for other ratios).

A technique referred to as coding was employed which transforms a set of quantitative independent variables to a new set of variables (Mendelhall and Sincich, 2012). The process could lead to more accurate estimates due to the following two primary reasons:

1) Multicollinearity: The problem of multicollinearity exists when two or more independent variables used in the model are correlated (linearly related). Multicollinearity can lead to unreliable parameter estimates. It can be avoided using the coding of independent variables.

2) Normalization: The range of the values of the coded variables become approximately the same, which can reduce the rounding errors during the matrix inversion for coefficient estimation.

Suppose x is an uncoded quantitative independent variable and u is the corresponding coded variable, the coding process involves the following (Equation 4.1):

$$u_i = \frac{x_i - \bar{x}}{\frac{R}{2}} \qquad \textbf{(4.1)}$$

where $\bar{x}$ is the average of the uncoded independent variable

R is range of uncoded independent variables

The range of coded variables can be compared to uncoded ones in Table 4.9. Moreover, the coefficient of correlation was not found to be more than 39% between any two variables during model building using the coded data.

Table 4.9: The range of coded and uncoded independent quantitative variables

Quantitative Independent Variable	Uncoded		Coded	
	Min	Max	Min	Max
Air Temperature (°C)	-16.67	6.83	-0.90	1.23
Traffic Volume	0	452.52	-0.33	1.67
Wind Speed (km/hr)	0	50	-0.70	1.30
Salt used (tonnes/ 2-lane-km)	0	1.26	-0.04	2.06

Elapsed Time (min)	0	1246	0	2.00
Relative Humidity (%)	0	100	-1.66	0.34
Pavement temperature (°C)	-14.47	5.08	-1.05	1.01

Using the step wise linear regression approach, the following model (Equation 4.2) was calibrated and the results are shown in Table 4.10. The variables included in the model are statistically significant at 95% confidence level. Note that the resulting adjusted R^2 value of 0.21 is relatively low, suggesting that the explanatory power of the model is limited. Despite this, the modelling result is still meaningful for the purpose of identifying the factors that had a significant effect on the snow-melting performance of alternative treatments, especially, the relative difference in performance under different pre-wetting ratios. The model also appears to make practical sense in terms of physical interpretations, as discussed in the following section. In addition to this, a variety of other models have been attempted with results being provided in Section 4.6. However, the model shown in Equation 4.2 was found to be superior over the other models with similar explanation power but simpler model structure (i.e., with fewer model parameters).

$$\text{Friction} = 0.5001 + 0.146\ AT + 0.148\ S + 0.054\ TV - 0.195\ RH + 0.024\ PW_{\mathbf{10\%}} + 0.035\ PW_{\mathbf{20\%}} \qquad \mathbf{(4.2)}$$

where,

AT = Air Temperature (°C)

S = Amount of Salt used (tonnes/ 2-lane-km)

TV = Traffic Volume

RH = Relative Humidity (%)

$PW_{10\%}$ = Indicator for the use of PW 10% salt, 1 for 10% ratio and 0 for other ratios

$PW_{20\%}$ = Indicator for the use of PW 20% salt, 1 for 20% ratio and 0 for other ratios

Table 4.10: Modeling Results

Friction	Coeff.	Std. Err.	t	P>t	95% Confidence interval	
Air Temperature	0.146	0.007	19.71	<0.001	0.132	0.161
Salt	0.148	0.032	4.57	<0.001	0.085	0.212
Traffic Volume	0.054	0.008	6.14	<0.001	0.036	0.071
Relative Humdity	-0.195	0.012	-15.87	<0.001	-0.219	-0.171
PW 10%	0.024	0.007	3.39	0.001	0.010	0.039
PW 20%	0.035	0.007	4.81	<0.001	0.021	0.050
Constant	0.500	0.005	100.1	<0.001	0.490	0.509

4.5.2 Model Interpretation

Model results are intuitive and are further elaborated as follows:

1) Air Temperature: The positive coefficient of air temperature shows that an increase in air temperature is associated with an increase in friction. Increase in temperatures can expedite the snow melting process and thus helps to recover bare pavement quickly.

2) Salt Usage: The positive coefficient of salt application rate suggests that an increase in friction levels is associated with an increase in amount of salt applied. The higher the quantity of salt used during an event, the better the overall friction level due to more snow melting action.

3) Traffic Volume: Higher traffic volume is associated with higher friction levels which could be attributed to one or more of the following reasons:

a) Heat from vehicle exhaust accelerate the melting action

b) The kneading action by tires helps to breaks the bond between snow and road

c) The vehicles crush snow and de-icers together, thereby increase the surface area of de-icers in contact with snow and boost the melting action

4) Relative Humidity: The negative coefficient of Relative Humidity indicates that friction levels decrease with an increase in the relative humidity. Higher levels of relative humidity coupled with low temperatures can result in reduced friction values due to possible frosting.

5) PW Indicator: The PW indicator associated with a pre-wet ratio is an indication of the average improvement in friction level that had resulted from the alternative ratio as compared to the base scenario of 5%, holding all other factors constant. The positive coefficients associate with $PW_{10\%}$ and $PW_{20\%}$ suggest that both ratios had resulted in an improvement in friction level as compared to the base case (5%), with a corresponding increase of 0.025 and 0.036, respectively.

4.5.3 Model Adequacy

In order to assess the adequacy of the developed model, the diagnostic measures (Figure 4.9 – 4.15) are analyzed:

1) Confidence Intervals: The confidence intervals of the estimated coefficients do not include zero, implying the significant contribution of included dependent variables to the model.

2) Normal Probability Plot of Residuals: The plot of observed residuals (difference between observed and predicted friction values) versus expected normal values of residuals follows a straight line pattern with

some diversions at the tails. It implies that data follows a normal distribution and satisfies the normality assumption of errors (Figure 4.9).

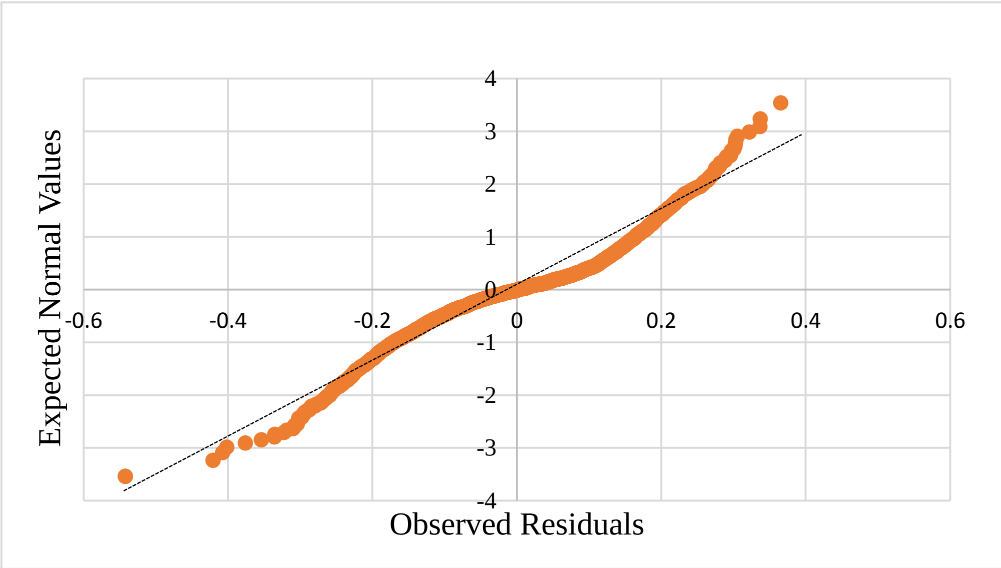


Figure 4.9: Normal Probability Plot of Residuals

3) Residual Plots: The residuals are plotted versus the dependent variable (i.e. friction) and individual independent variables (Air Temperature, Salt, Traffic Volume and Relative Humidity) as shown in Figures 4.10 – 4.14. The spread of residuals does not show complete randomness in their distribution around the mean values and follows some pattern. Therefore, an assumption of constant variance is not being satisfied by the residuals. In addition to this, the model failed to pass Breusch-Pagan / Cook-Weisberg test, designed to check homoscedasticity in the residuals.

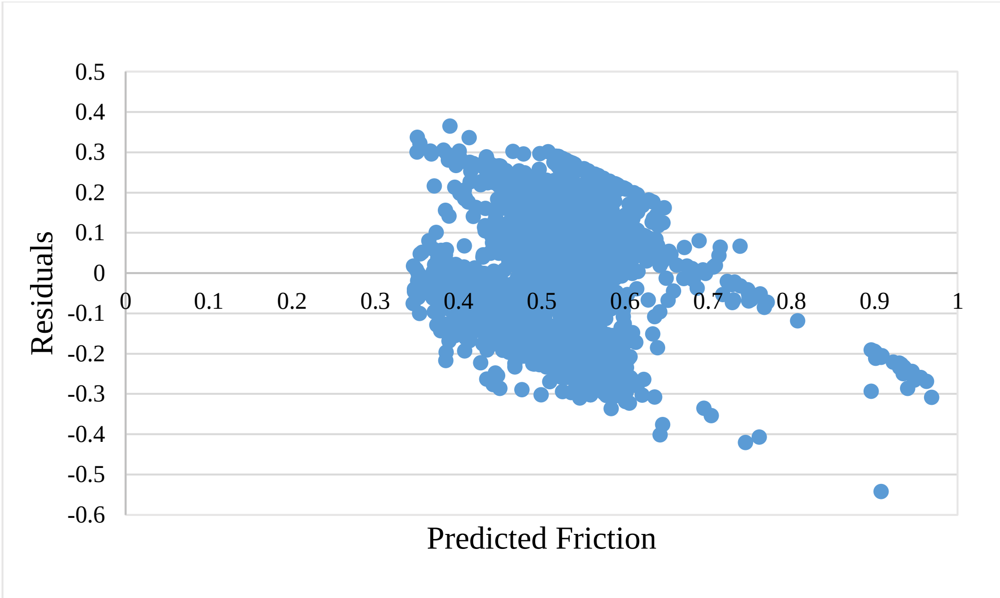


Figure 4.10: Plot of Residuals vs. Predicted Friction

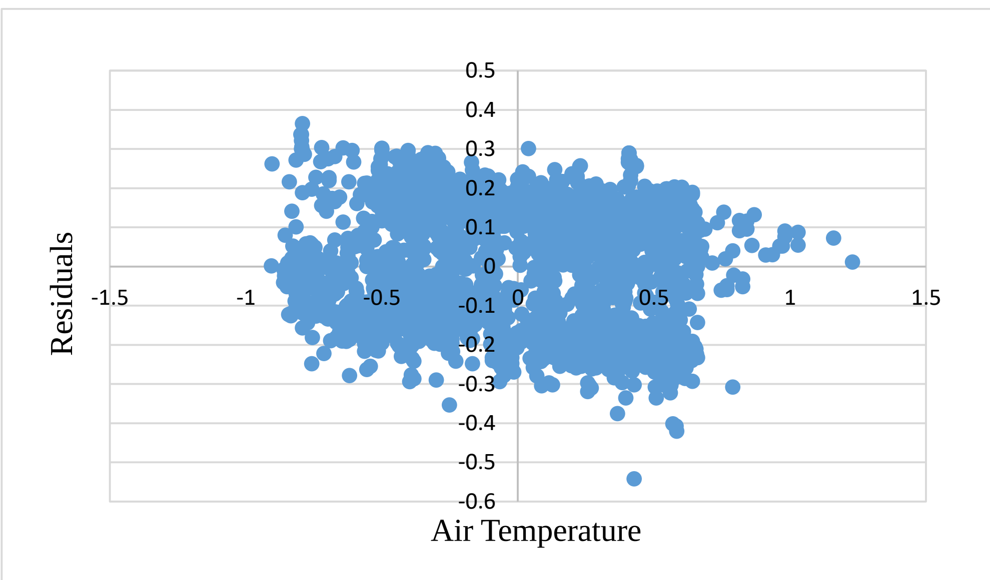


Figure 4.11: Plot of Residuals vs. Air Temperature

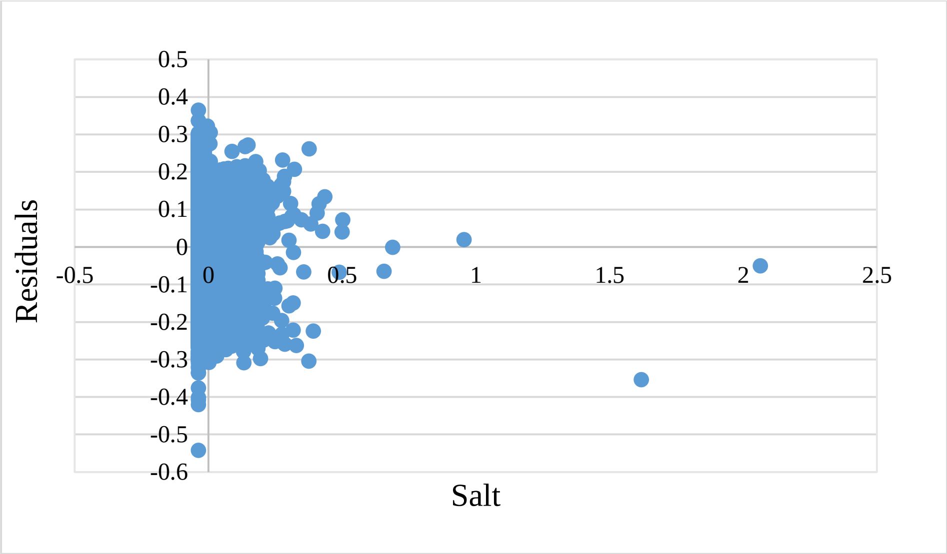


Figure 4.12: Plot of Residuals vs. Salt

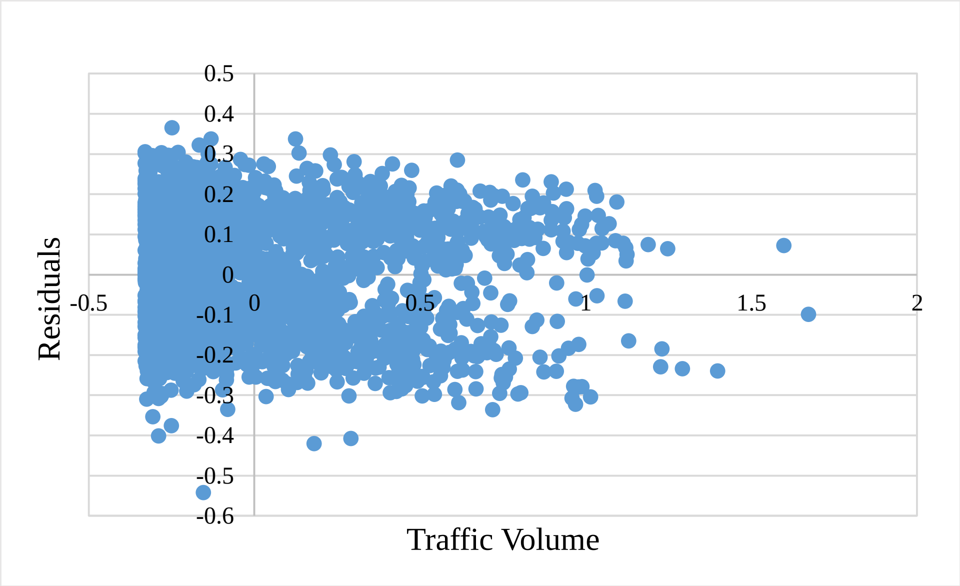


Figure 4.13: Plot of Residuals vs. Traffic Volume

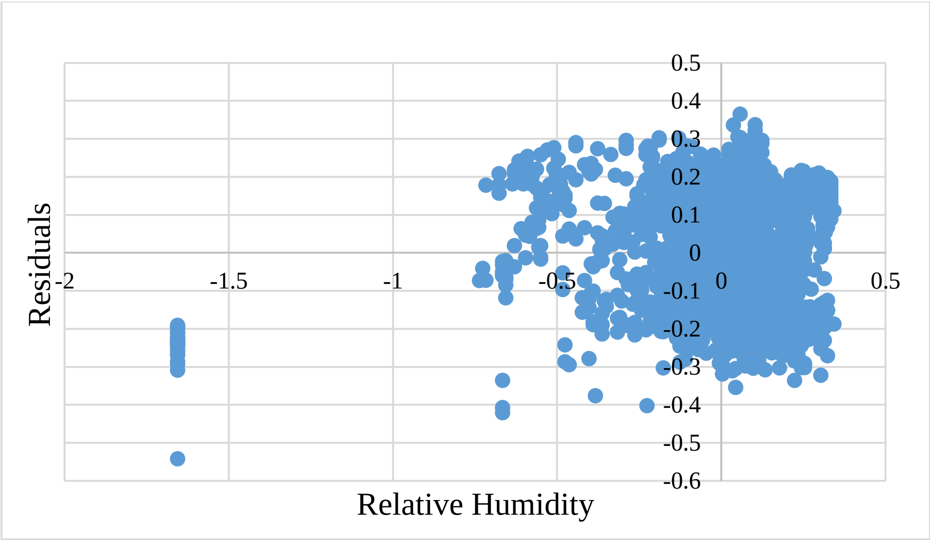


Figure 4.14: Plot of Residuals vs. Relative Humidity

4) Predicted Friction Values: The predicted friction values are plotted against observed friction values (Figure 4.15). The trend is scattered around the ideal 45° line.

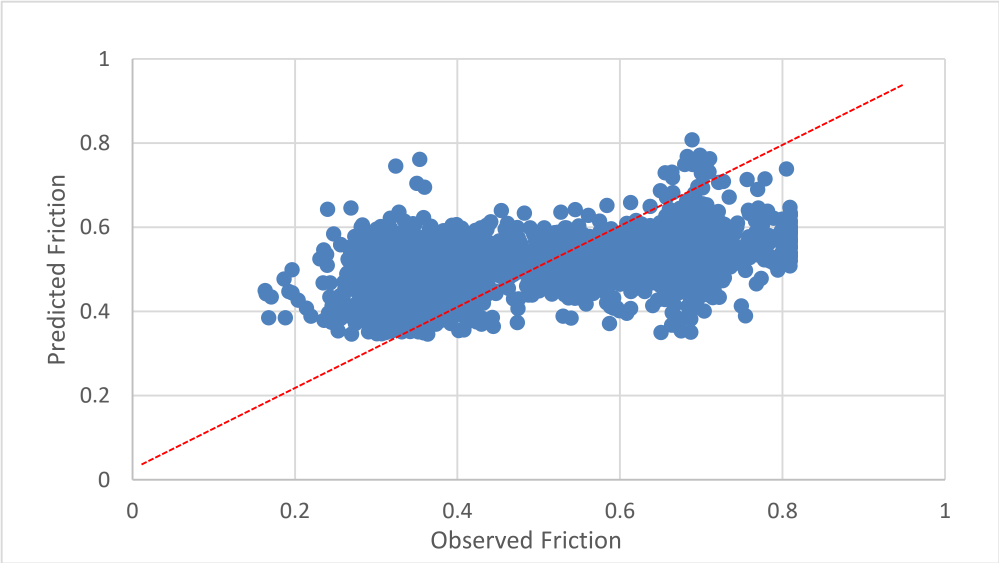


Figure 4.15: Plot of Predicted vs. Observed Friction Values

4.5.4 Model Application

This section demonstrates an application of the developed model to an assumed road section through an example, assuming the average values recorded during the field trials:

Air Temperature = -6.7 °C

Amount of salt = 0.022 tonnes/ 2-lane-km

Traffic Volume = 74.54

Relative Humidity = 82.82%

Modelling results shows that if the road section is treated with PW 5%, 10% and 20%, the corresponding friction vales will be 0.50, 0.52, 0.54 respectively (Figure 4.16). These outcomes show that PW 20% results in 8% improvement in friction as compared to PW 5% whereas PW 10% shows 4% increase in friction as compared to PW 5%, and these results are similar to the previous findings.

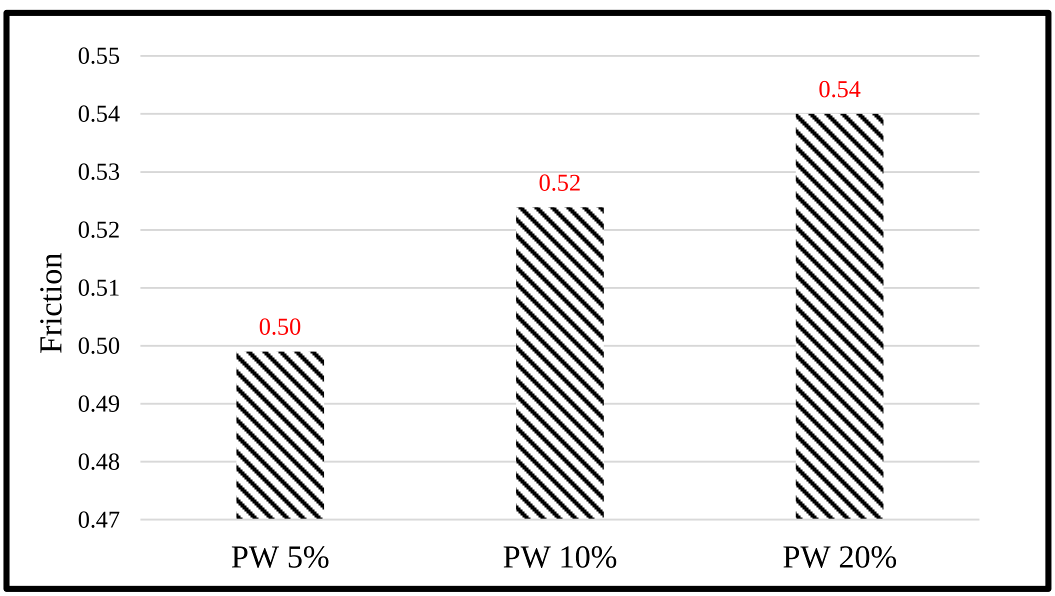


Figure 4.16: The friction levels attained for different pre-wet ratios of salt at controlled conditions

4.6 Other Models

This section presents the models that have been developed as an extra attempt to best learn the impact of significant factors on the effectiveness of different pre-wet ratios of salt.

4.6.1 Complete Model

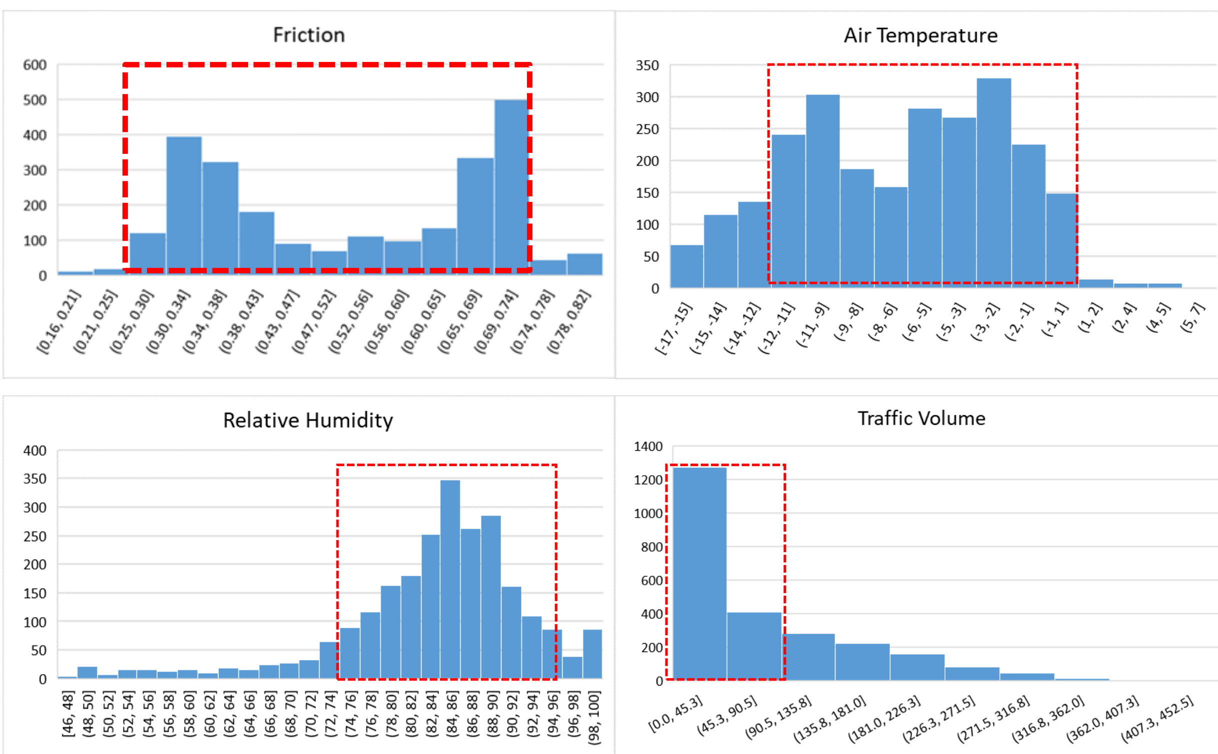
Following a process described in Section 4.5.1, a complete model which incorporates interaction terms was calibrated and results are shown in Table 4.11. Aside from the interaction terms and binary variables representing different treatments, the other four main factors – Air Temperature, Salt, Traffic Volume and Relative Humidity are statistically significant at the 95% confidence level and the adjusted R^2 value for the model is 0.26, which is slightly higher than the model developed in Section 4.5.1 involving only the effect of main factors with no interaction terms.

Table 4.11: Modeling Results – Complete Model

Friction	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.159	0.007	21.8	<0.015	0.145	0.173
Salt	0.125	0.032	3.95	<0.015	0.063	0.188
Traffic Volume	0.031	0.009	3.61	<0.015	0.014	0.048
Relative Humidity	-0.337	0.016	-20.88	<0.015	-0.369	-0.305
Air Temperature*Humidity	0.387	0.030	12.96	<0.015	0.329	0.446
Salt*Traffic Volume	-0.282	0.116	-2.42	0.015	-0.510	-0.054
PW 10%	0.026	0.007	3.71	<0.015	0.012	0.040
PW 20%	0.037	0.007	5.23	<0.015	0.023	0.052
Constant	0.494	0.005	101.69	<0.015	0.485	0.504

4.6.1.1 Model Interpretation – Complete Model

Due to the inclusion of the interaction terms, the interpretation of calibrated coefficients becomes complex. To help explain the model, the interaction terms - Air Temperature*Humidity and Salt*Traffic Volume are plotted for different treatments, i.e., PW 5%, PW 10% and PW 20% while fixing other independent variables in the model at their respective average values. Prior to the plotting, an exploratory data analysis was done to determine the effective data ranges of the recorded variables (Figure 4.17). Figure 4.17 implies that the effective ranges for friction, air temperature (°C), Relative Humidity (%), Traffic Volume, Wind Speed (km/hr) and Salt (tonnes/ 2-lane km) are (0.25 to 0.75), (-12 to 1), (75 to 95), (0 to100), (8 to 26) and (0 to 0.015), respectively.



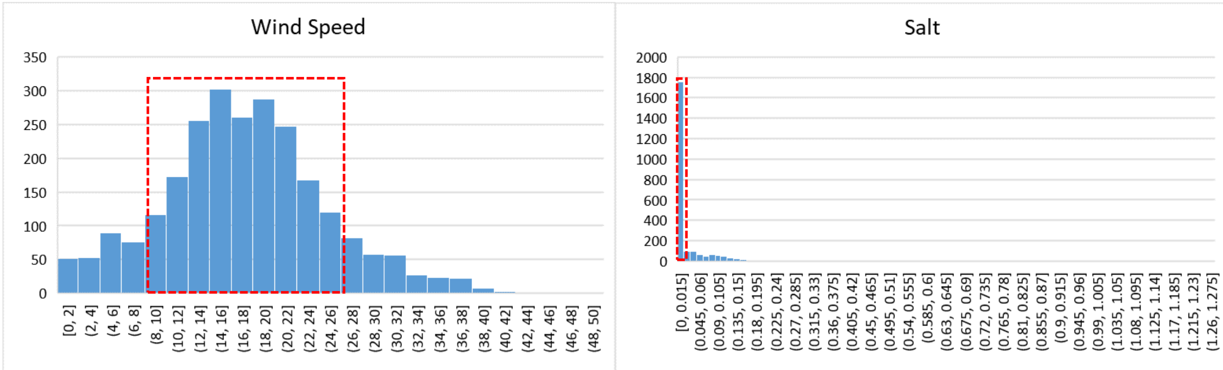
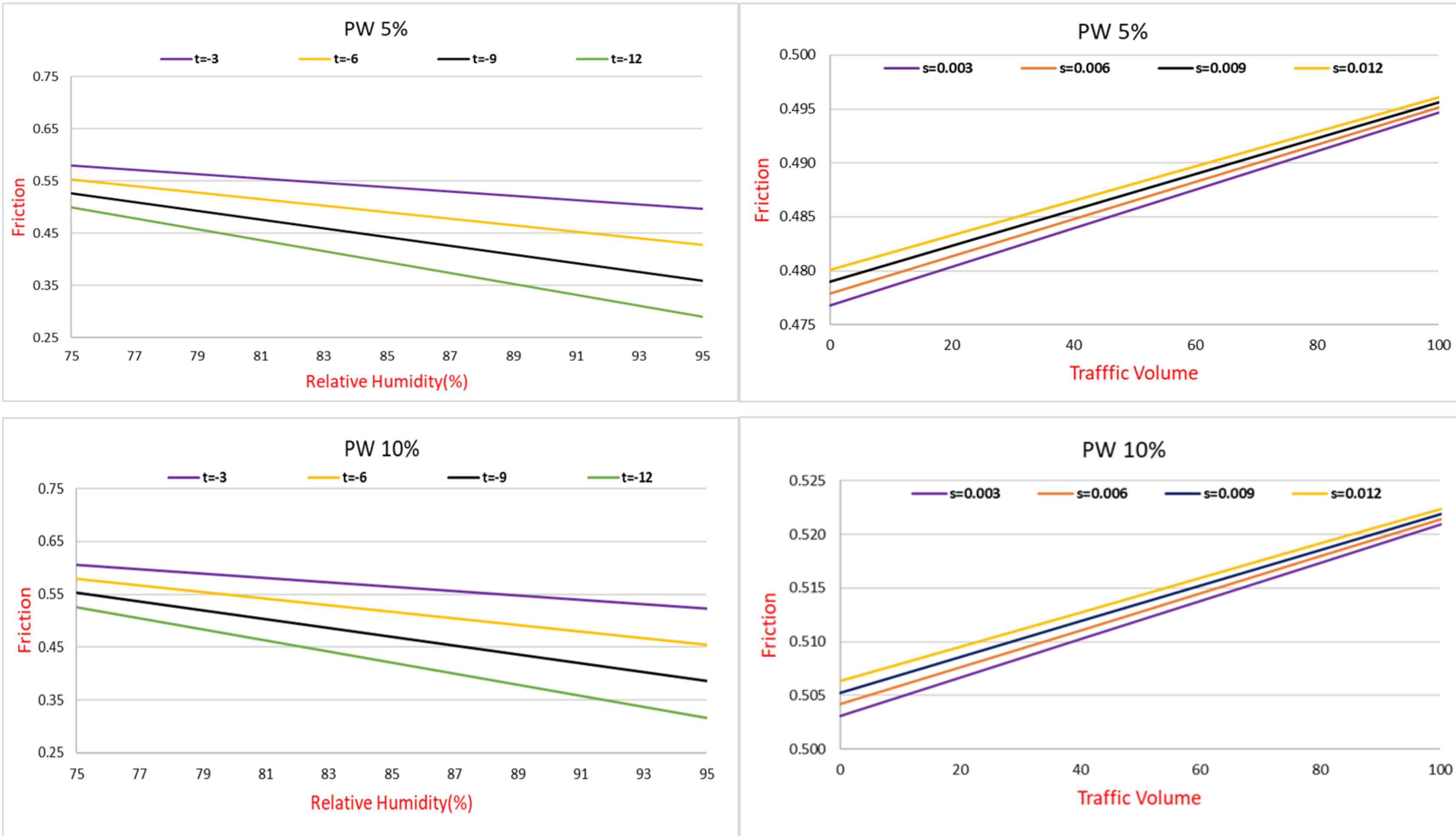
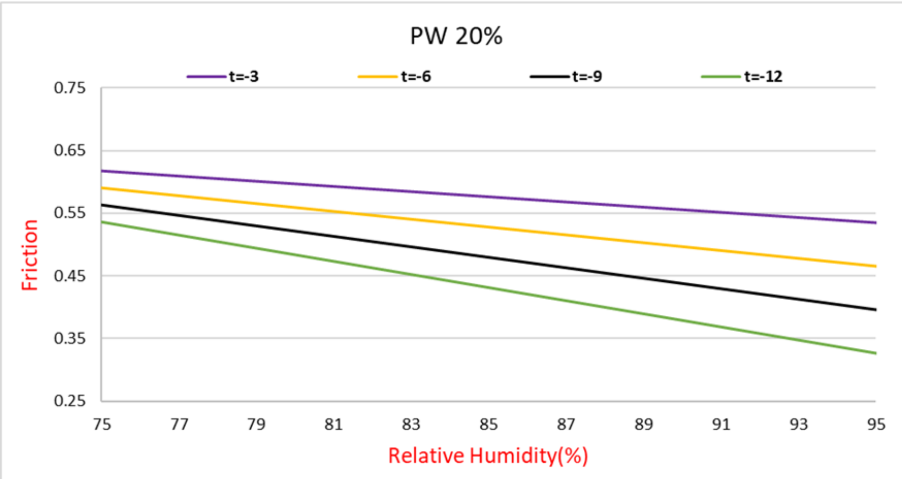


Figure 4.17: Exploratory Data Analysis

The interaction terms found significant in the model are analyzed at the effective ranges of independent variables (Figure 4.18). The impact of relative humidity and air temperature at -3, -6, -9, -12°C is determined for three different pre-wet ratios of salt. It can be inferred from Figure 4.18 that at any pre-wet ratio of salt, higher temperatures with lower relative humidity will generate a higher friction level. The relative difference between achieved friction levels for different temperatures is more prominent at higher humidity levels.

Similarly, the interaction term of traffic volume and salt is analyzed for three pre-wet ratios of salt, i.e., PW 1%, PW 3%, PW 5%, at four levels of salt application rate: 0.03, 0.06, 0.09 and 0.012 tonnes/ 2-lane-km (Figure 4.18). Figure 4.18 implies that salt applied in higher amounts with higher traffic volumes generates higher friction values. Also, the relative difference between friction values is more significant at lower traffic volumes for different amounts of salt used.


PW 5%
t=-3
t=-6
t=-9
t=-12
Friction
0.75
0.65
0.55
0.45
0.35
0.25
75
77
79
81
83
85
87
89
91
93
95
Relative Humidity(%)
PW 5%
s=0.003
s=0.006
s=0.009
s=0.012
Friction
0.500
0.495
0.490
0.485
0.480
0.475
0
20
40
60
80
100
Trafffic Volume
PW 10%
t=-3
t=-6
t=-9
t=-12
Friction
0.75
0.65
0.55
0.45
0.35
0.25
75
77
79
81
83
85
87
89
91
93
95
Relative Humidity(%)
PW 10%
s=0.003
s=0.006
s=0.009
s=0.012
Friction
0.525
0.520
0.515
0.510
0.505
0.500
0
20
40
60
80
100
Traffic Volume



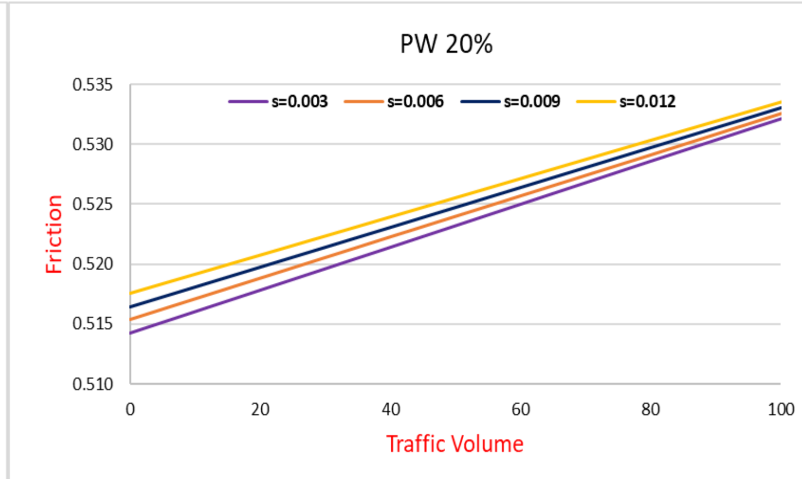


Figure 4.18: Plot of interaction terms (Air Temperature*Humidity, Salt*Traffic Volume) for the different pre-wet ratios of salt

4.6.1.2 Model Adequacy – Complete Model

An adequacy of the model is determined using the diagnostic checks shown in Figures 4.19 - 4.25

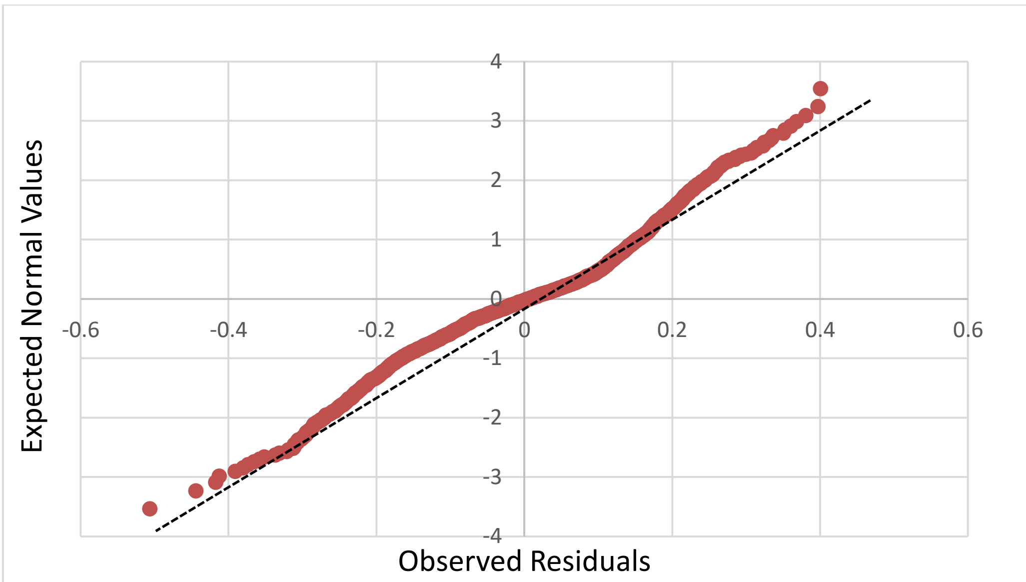


Figure 4.19: Normal Probability Plot – Complete Model

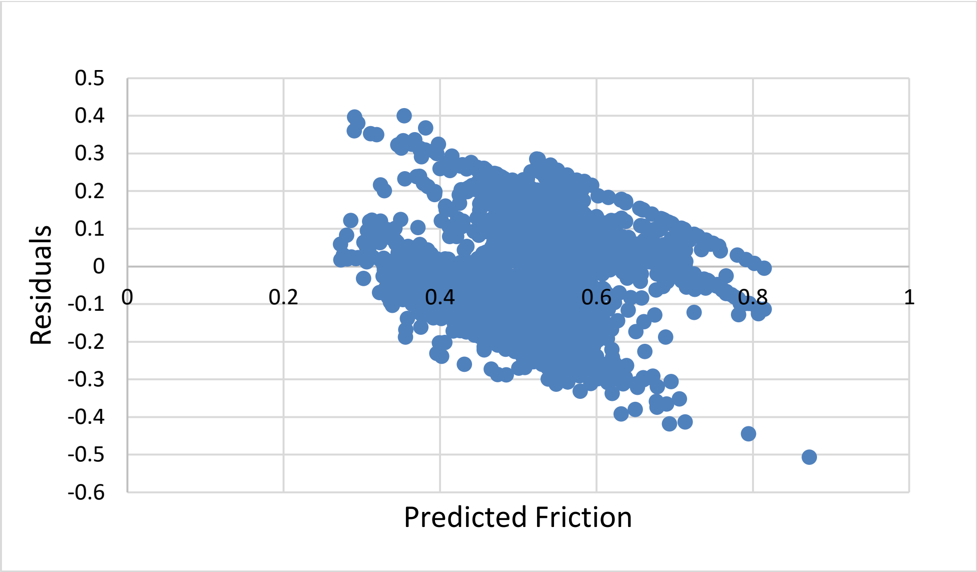


Figure 4.20: Plot of Residuals vs. Predicted Friction – Complete Model

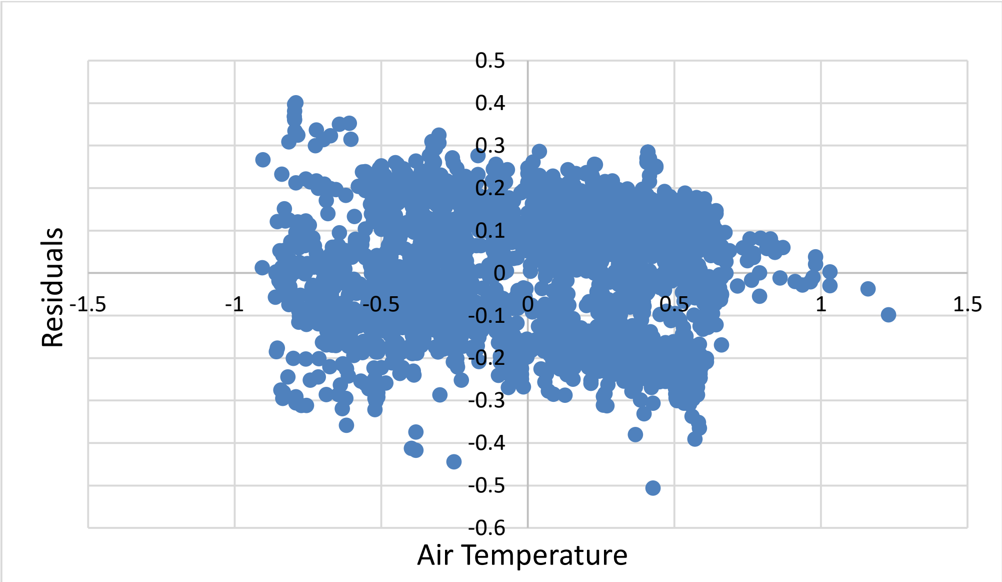


Figure 4.21: Plot of Residuals vs. Air Temperature – Complete Model

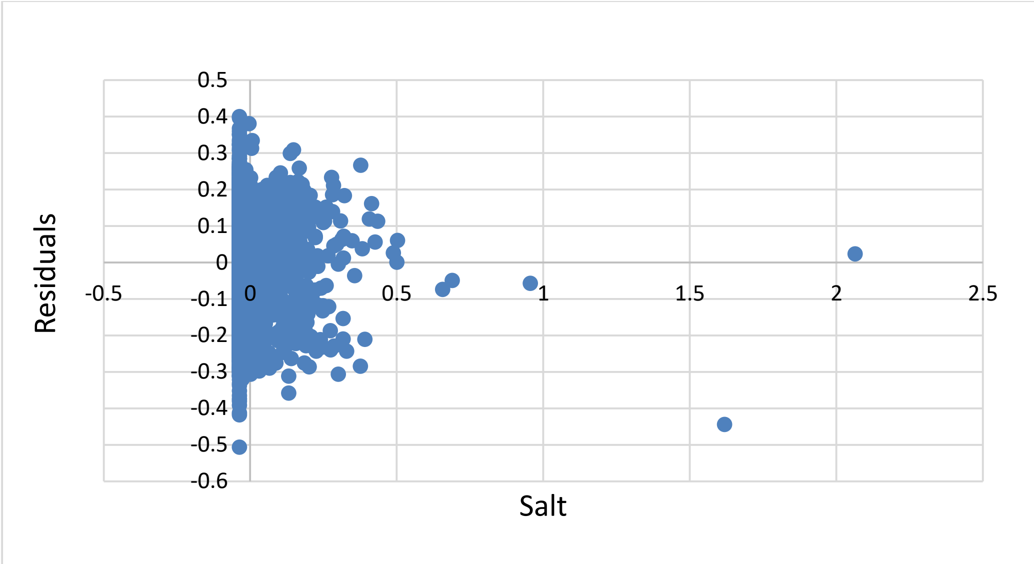


Figure 4.22: Plot of Residuals vs. Salt – Complete Model

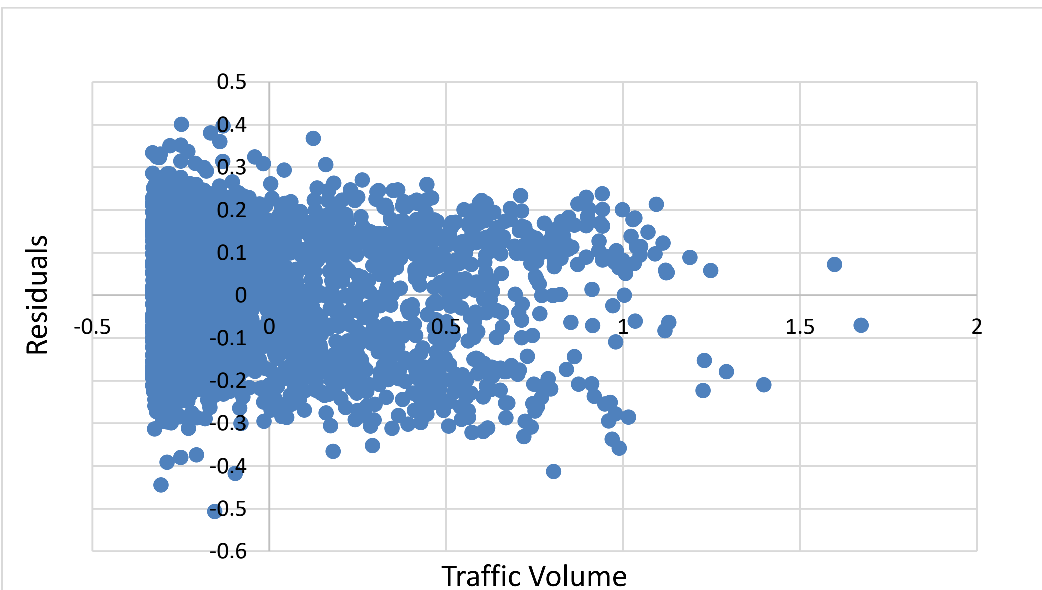


Figure 4.23: Plot of Residuals vs. Traffic Volume – Complete Model

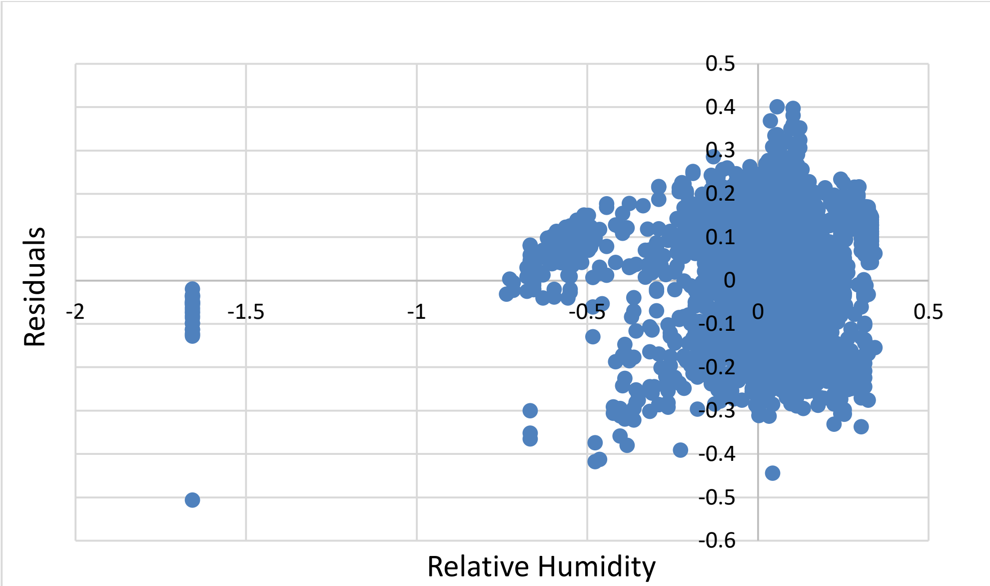


Figure 4.24: Plot of Residuals vs. Relative Humidity – Complete Model

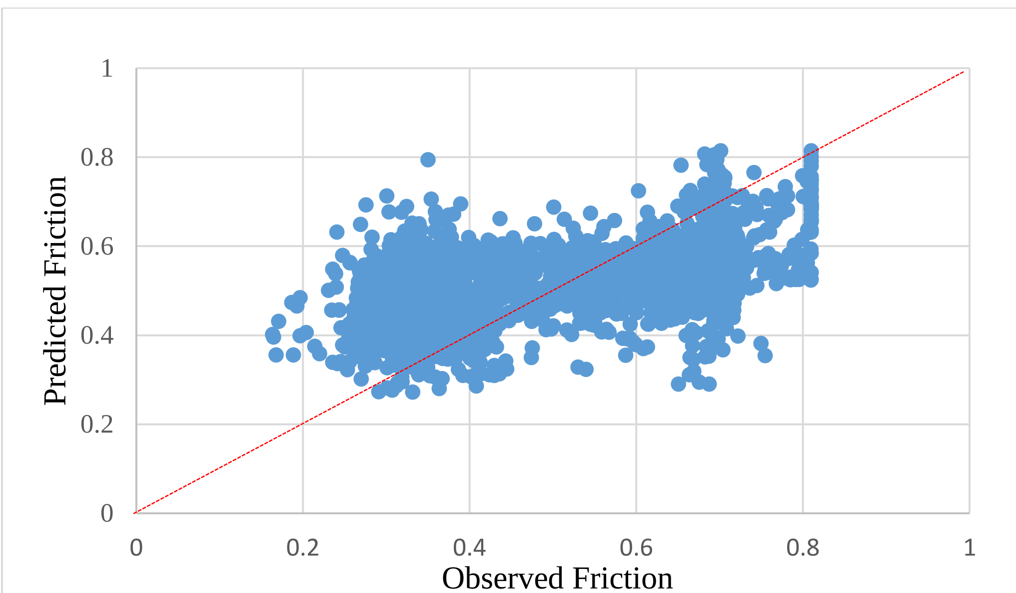


Figure 4.25: Plot of Predicted vs. Observed Friction Values – Complete Model

The residual plots (Figures 4.20 - 4.24) indicate some traits of the pattern being followed and that the model failed to pass the homoscedasticity test at the 5% level of significance. Therefore, non-linear models including logit models were tried to improve the fit of model.

4.6.2 Non-linear Models

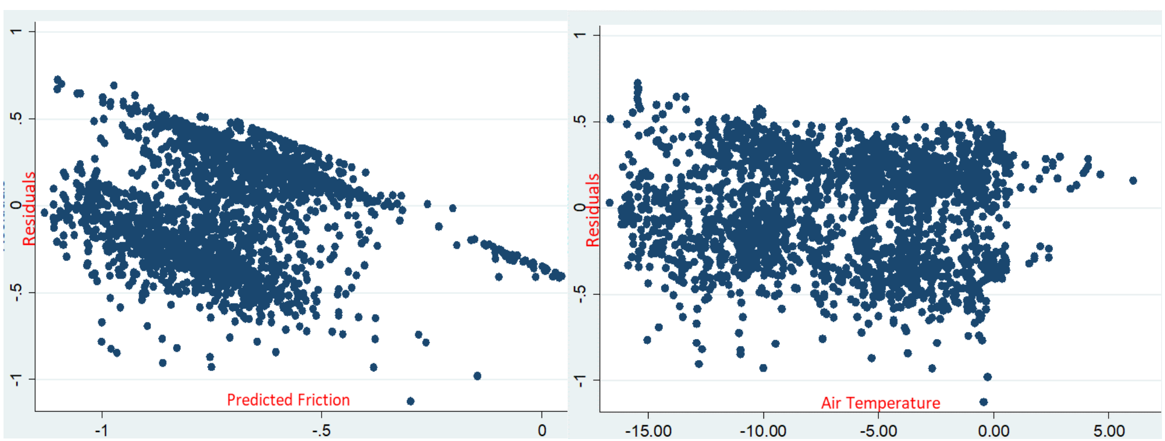
In order to remove heteroscedasticity, i.e., left or right skewness present in data, the variables were transformed using logarithm, inverse, roots or higher powers. These transformations may also help capture the non-linear relationship that may exist between the dependent and independent variables. Table 4.12 provides the results from seven non-linear models attempted in this research. The models include the variables that are statistically significant at 95% confidence level. Despite satisfying the homoscedasticity test of most of these models, the adjusted R^2 value could not be improved beyond 0.27 and no difference was observed in residual plots of non-linear models and linear models which were developed previously. The logit models failed to pass the homoscedasticity test (Table 4.12).

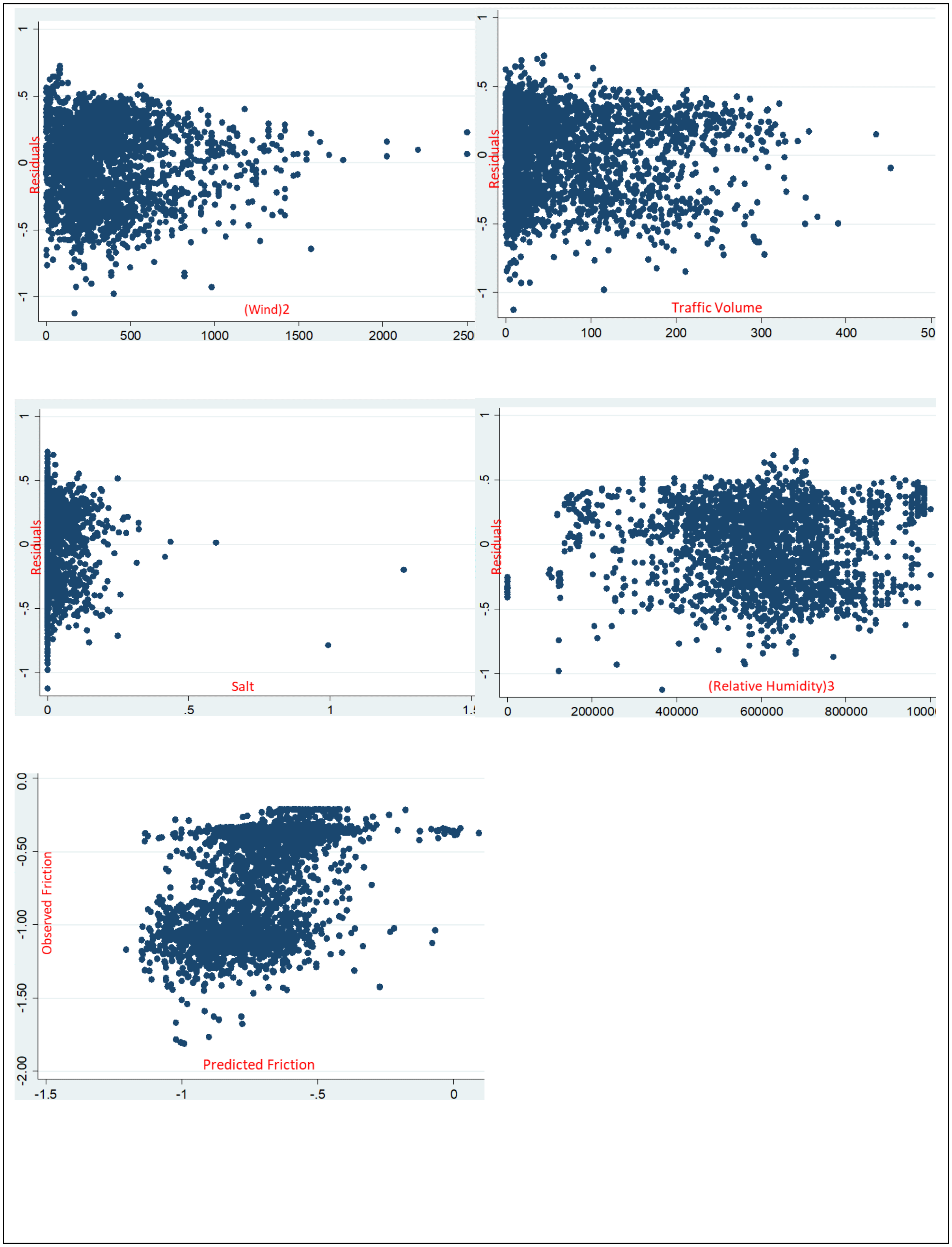
Table 4.12: Non-linear Models

Model #1
R^2 adj = 0.25 Homoskedastic ✓ Breusch-Pagan / Cook-Weisberg test for heteroskedasticity Ho: Constant variance chi2(1) = 0.71

Prob > chi2 = 0.3997

log(friction)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.033472	0.00148360	22.56	0	0.0305623	0.0363807
$(\text{Wind Speed})^2$	-0.000109	0.00002160	-5.04	0	-0.0001511	-0.0000665
Traffic Volume	0.000401	0.00008020	5	0	0.0002439	0.0005585
Salt	0.569371	0.10912940	5.22	0	0.3553706	0.7833712
$(\text{Relative Humidity})^3$	-0.000001	0.00000004	-19.4	0	-7.80E-07	-6.37E-07
PW 10%	0.055721	0.01467020	3.8	0	0.0269529	0.0844887
PW 20%	0.099221	0.01568200	6.33	0	0.0684689	0.1299729
Constant	-0.109780	0.03132880	-3.5	0	-0.1712155	-0.0483453




Residuals
(Wind)2
Residuals
Traffic Volume
Residuals
Salt
Residuals
(Relative Humidity)3
Observed Friction
Predicted Friction

Model #2

R^2 adj = 0.27

Homoskedastic ✓

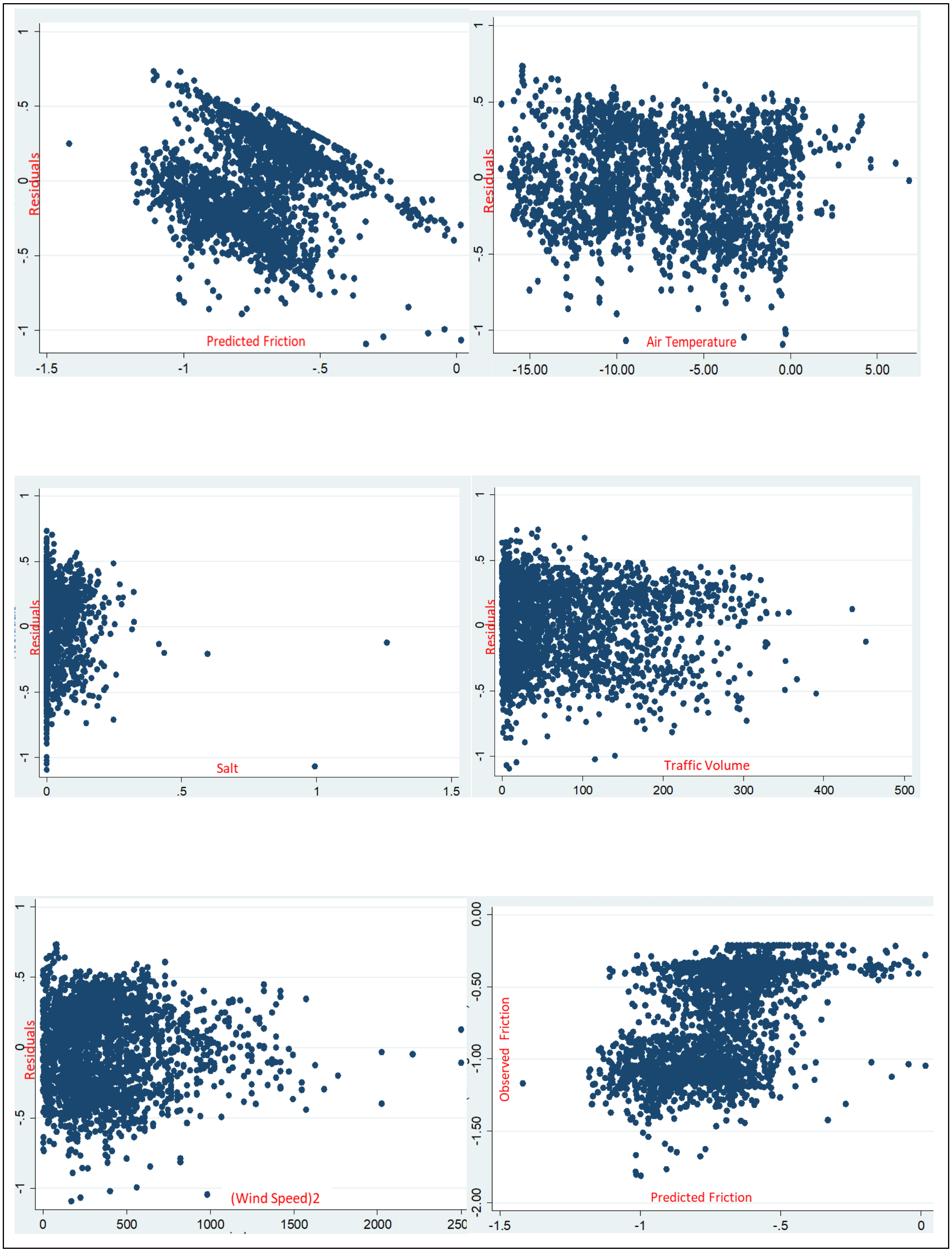
Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

Ho: Constant variance

chi2(1) = 1.36

Prob > chi2 = 0.2433

log(friction)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.036	0.002	23.67	0	0.0330	0.0389
Salt	0.882	0.161	5.47	0	0.5658	1.1982
Traffic Volume	0.000	0.000	5.82	0	0.0003	0.0007
(Wind Speed)^2	0.000	0.000	4.14	0	0.0001	0.0004
Salt*Traffic Volume	-0.004	0.002	-2.37	0.018	-0.0077	-0.0007
PW 10%	0.057	0.015	3.88	0	0.0281	0.0856
PW 20%	0.077	0.015	5.2	0	0.0481	0.1064
Constant	-0.218	0.045	-4.89	0	-0.3053	-0.1306


Residuals
Predicted Friction
Residuals
Air Temperature
Residuals
Salt
Residuals
Traffic Volume
Residuals
(Wind Speed)2
Observed Friction
Predicted Friction

Model #3

R^2 adj = 0.25

Homoskedastic ✓

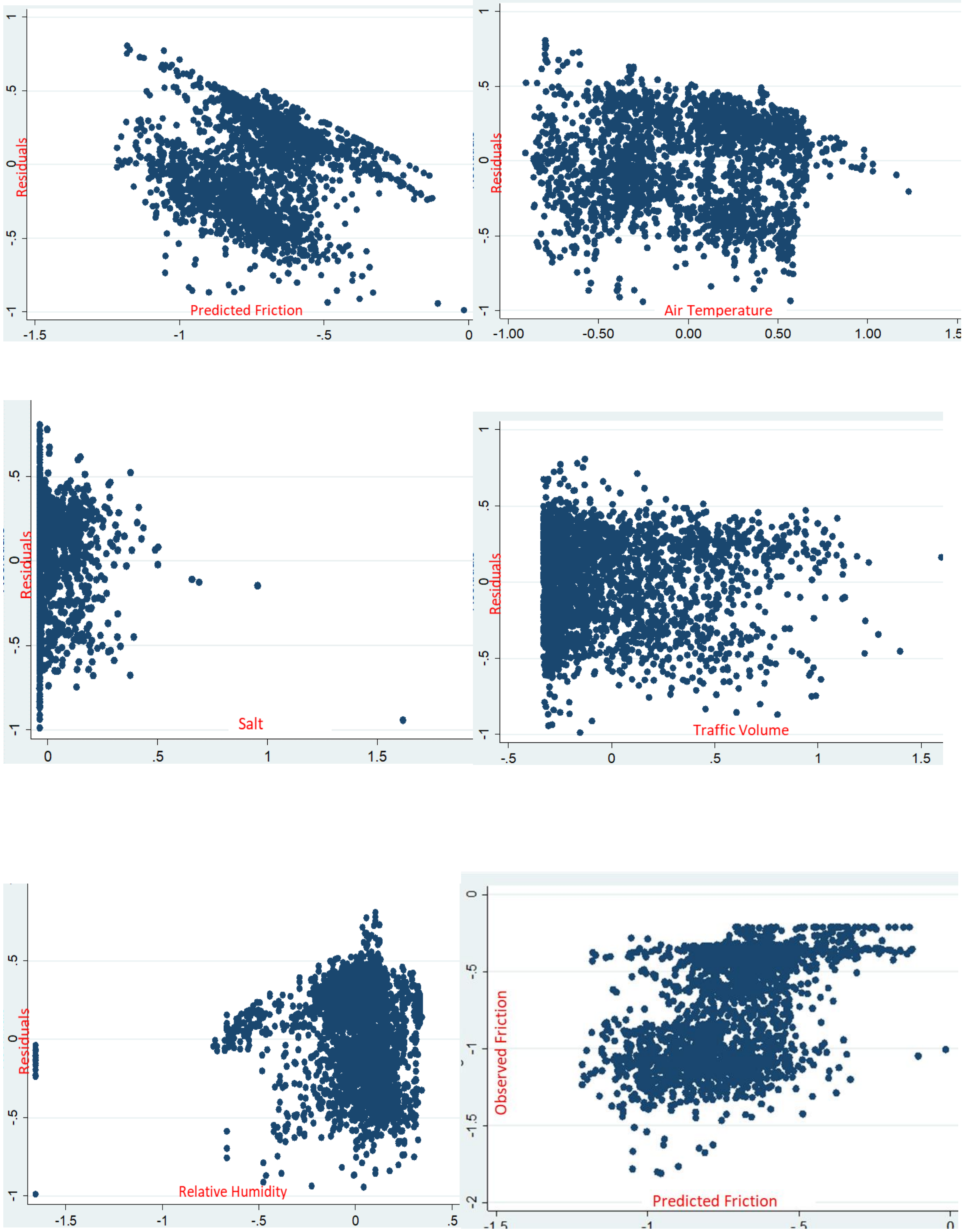
Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

Ho: Constant variance

chi2(1) = 0.38

Prob > chi2 = 0.5363

log(friction)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.327	0.015	21.53	0	0.297	0.357
salt	0.295	0.066	4.47	0	0.166	0.425
Traffic Volume	0.064	0.018	3.51	0	0.028	0.099
Relative Humidity	-0.668	0.034	-19.88	0	-0.733	-0.602
PW 10%	0.059	0.015	4.01	0	0.030	0.088
PW 20%	0.075	0.015	5.06	0	0.046	0.105
Temperature*Humidity	0.773	0.062	12.41	0	0.651	0.895
Salt*Traffic Volume	-0.530	0.242	-2.19	0.029	-1.005	-0.055
Constant	-0.767	0.010	-75.83	0	-0.787	-0.747


Residuals
Predicted Friction
Residuals
Air Temperature
Residuals
Salt
Residuals
Traffic Volume
Residuals
Relative Humidity
Observed Friction
Predicted Friction

Model # 4

R^2 adj = 0.26

Homoskedastic ✓

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

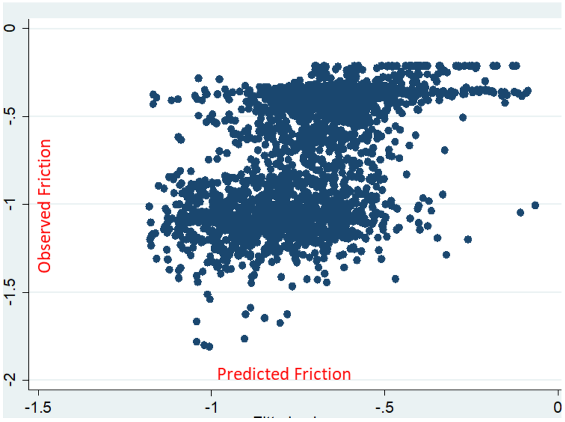
Ho: Constant variance

chi2(1) = 0.21

Prob > chi2 = 0.6455

log(friction)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.341	0.015	22.16	0	0.311	0.371
Wind Speed	-0.102	0.021	-4.87	0	-0.143	-0.061
salt	0.284	0.066	4.32	0	0.155	0.413
Traffic Volume	0.072	0.018	3.99	0	0.037	0.108
Relative Humidity	-0.694	0.034	-20.49	0	-0.760	-0.627
Salt*Traffic Volume	-0.560	0.241	-2.32	0.02	-1.033	-0.088
Temperature*Humidity	0.835	0.063	13.2	0	0.711	0.959
PW 10%	0.059	0.015	4.02	0	0.030	0.088
PW 20%	0.074	0.015	5.01	0	0.045	0.104
Constant	-0.767	0.010	-76.22	0	-0.787	-0.747


Residuals
Predicted Friction
-1.5 -1 -.5 0
Residuals
Air Temperature
-1.00 -0.50 0.00 0.50 1.00 1.5
Residuals
Wind Speed
-.5 0 .5 1
Residuals
Salt
0 .5 1 1.5
Residuals
Traffic Volume
-.5 0 .5 1 1.5
Residuals
Relative Humidity



Model # 5

R^2 adj = 0.27

Homoskedastic ✓

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

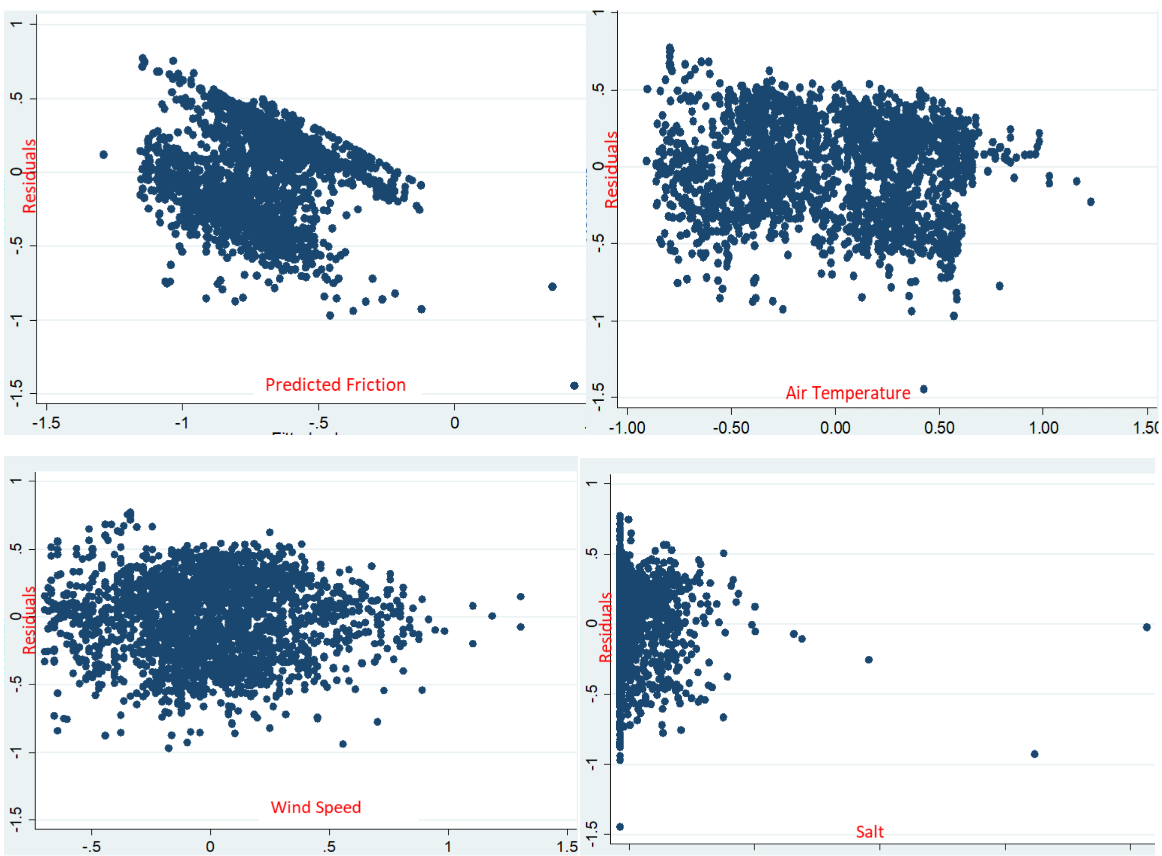
Ho: Constant variance

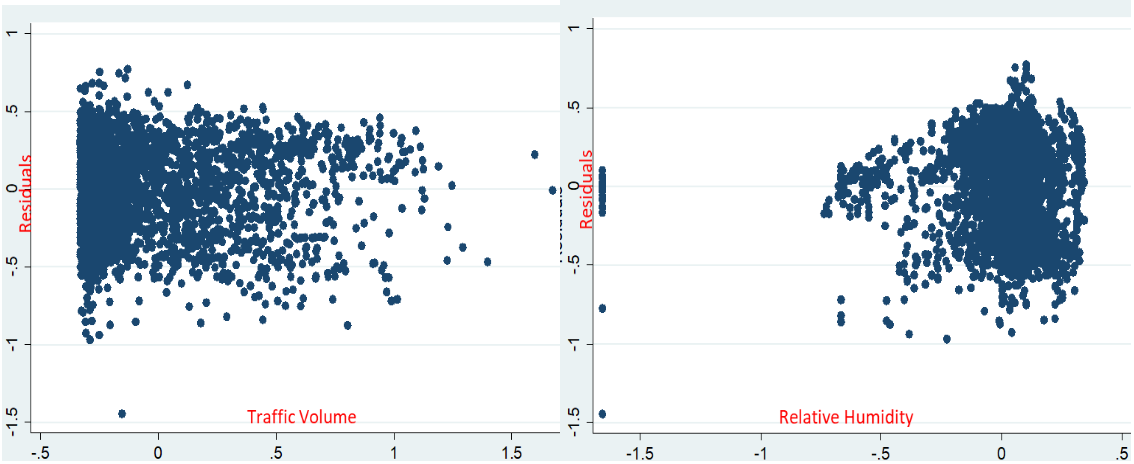
chi2(1) = 2.21

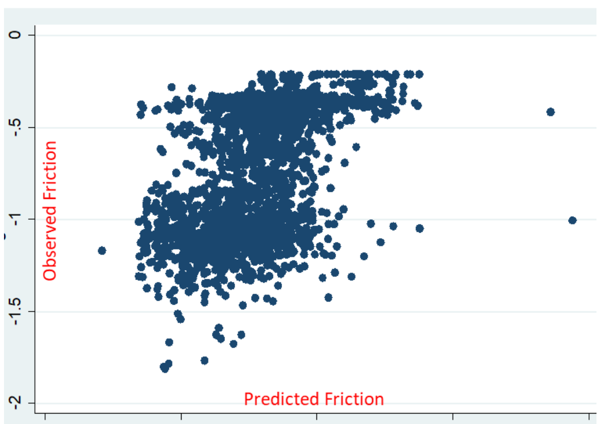
Prob > chi2 = 0.1367

log(friction)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.353	0.015	22.89	0.00	0.323	0.383
salt	0.290	0.065	4.45	0.00	0.162	0.418
Traffic Volume	0.082	0.018	4.51	0.00	0.046	0.117

Wind Speed	-0.113	0.021	-5.45	0.00	-0.154	-0.073
Relative Humidity	-0.693	0.034	-20.67	0.00	-0.759	-0.628
Temperature*Humidity	0.645	0.068	9.43	0.00	0.511	0.779
Salt*Traffic Volume	-0.515	0.239	-2.15	0.03	-0.984	-0.046
Wind*Traffic Volume	-0.132	0.063	-2.1	0.04	-0.255	-0.009
Wind*Humidity	-0.429	0.063	-6.76	0.00	-0.553	-0.305
PW 10%	0.059	0.015	4.07	0.00	0.031	0.088
PW 20%	0.076	0.015	5.2	0.00	0.048	0.105
Constant	-0.764	0.010	-76.25	0.00	-0.784	-0.744







Model # 6

R^2 adj = 0.26

Homoskedastic ×

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

Ho: Constant variance

chi2(1) = 40.75

Prob > chi2 = 0.000

ln(Y/1-Y)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.0312	0.0013	23.65	0	0.029	0.034
Wind Speed	-0.0039	0.0008	-5.05	0	-0.005	-0.002
Salt	0.4699	0.0976	4.81	0	0.279	0.661
Traffic Volume	0.0004	0.0001	5.31	0	0.000	0.001
Relative Humidity	-0.0137	0.0006	-21.36	0	-0.015	-0.012
PW 10%	0.0456	0.0132	3.46	0.001	0.020	0.071
PW 20%	0.0701	0.0133	5.25	0	0.044	0.096
Constant	1.3802	0.0627	22.03	0	1.257	1.503

Model # 7

R^2 adj = 0.26

Homoskedastic ×

Breusch-Pagan / Cook-Weisberg test for heteroskedasticity

Ho: Constant variance

chi2(1) = 25.12

Prob > chi2 = 0.000

ln(Y/1-Y)	Coef.	Std. Err.	t	P>t	95% Confidence Interval	
Air Temperature	0.033455	0.001355	24.68	0	0.030797	0.0361122
$(Wind)^2$	-0.0001	1.93E-05	-5.19	0	-0.00014	-0.0000625
Salt	0.477054	0.097604	4.89	0	0.285659	0.6684494
Traffic Volume	0.000373	7.07E-05	5.27	0	0.000234	0.0005113
$(Relative\ Humidity)^3$	-7.42E-07	3.48E-08	-21.32	0	-8.10E-07	-6.74E-07
PW 10%	0.044039	0.013187	3.34	0.001	0.01818	0.0698977
PW 20%	0.068777	0.013342	5.15	0	0.042614	0.0949394
_cons	0.672811	0.030772	21.86	0	0.612469	0.7331529

Chapter 5

Conclusions and Future Work

WRM operations such as plowing, salting and sanding play a critical role in countries like Canada by keeping their roads clear of snow and ice for safe and efficient transportation. Despite the critical importance for mobility and safety, WRM is also costly not just monetarily but also environmentally due to the deteriorating impact of the materials (salt, sand) being used on the environment. Transportation agencies have therefore constantly been seeking for innovative winter maintenance technologies and methods to reduce material applications and improve maintenance performance for sustainable winter road maintenance operations. This thesis research has focused on one of these WRM techniques, namely, pre-wetting. The specific objective of the research was to find out whether or not higher pre-wet ratios (10%, 20%) would result in any improvement in terms of friction levels and saving of material as compared to the current 5% pre-wet ratio. A field experiment was conducted to compare the performance of these three pre-wetting ratios. High resolution road condition, traffic and weather data were collected using both mobile and stationary sensors over a large number of snow events. A comparative analysis coupled with a visual analysis was conducted to determine the relative performance of the three pre-wetting ratios. A robust regression analysis was followed to quantify the impacts of different pre-wet ratios on snow-melting performance of salt. This chapter highlights the main contributions of this research with directions for future work.

5.1 Major Findings and Contributions

Based on three different types of analyses – Comparative Analysis, Visual Analysis and Regression Analysis on the data collected from the field experiment, the following major findings are obtained:

- Using PW 10% ratio results in 11% higher friction as compared to PW 5% and consumes 13% more salt and 22% less sand as compared to PW 5%.
- Using PW 20% ratio results in 15% higher friction as compared to PW 5% and utilize 19% less salt and 35% less sand as compared to PW 5%.
- PW 20% ratio outperforms PW 10% and PW 5% ratios by maintaining better road conditions with less snow coverage.
- PW 20% ratio generates higher friction levels as compared to PW 10% and PW 5% ratios at any controlled condition.

Based on these results it can be seen that sections treated with 20% pre-wet salt offers better results in terms of friction while utilizing the least amount of material.

The research has also made the following additional contributions:

- A survey was conducted to learn the pre-wetting practices across different jurisdictions. The survey has provided valuable information on current WRM practices, such as pre-wetting ratios, application rates and de-icers. It can be used to generate more research opportunities in the area of WRM and shed lights on new alternatives as compared to the adopted practices.

- This research has resulted in a comprehensive database incorporating variables such as traffic counts, friction, road surface conditions and weather-related variables. This data set can be used by other research projects such as assessments of impacts of snow storms on safety and mobility. Particularly, the images of road conditions collected during field trials are currently being used for road condition recognition by artificial intelligence that will be used for providing safety related information to travelers.

- This research resulted in the generation of a measure - the snow index number, representing road surface condition. The Snow Index Number is simpler and easier to use than the categorical description of road surface conditions.

- This research was able to generate a statistical model showing impacts of different pre-wetting ratio of salt on a performance measure, i.e., friction. The developed model can support the further research investigating the performance difference between 5%, 10% and 20% pre-wet ratios of salt.

5.2 Future Work

While this research has yielded statistically valid findings on the relative performance of the alternative pre-wetting ratios, further research is needed before the new ratios can be adopted in practice.

- The current analysis was conducted using data from one winter season. In the future research, it would be interesting to incorporate data of more winter seasons so that the stability of results over time could be assessed.

- This analysis was conducted using data from MTO's Class 2 Highway only. A similar analysis should be conducted on other classes of highways with different WRM standards.

- A comprehensive cost benefit analysis should be conducted, ensuring that the implementation costs as well as safety and mobility benefits are fully accounted for.

Bibliography

1. Agricultural by-products for Anti-icing and Deicing use in Michigan, 2002, Research Report R 1418, Michigan Department of Transportation.
2. Brine Fact Sheet, APWA Winter Maintenance Sub-Committee.
3. Blomqvist, G. (2001), Long Term Effects of De-icing Salt on Roadside Environment. Part-I: Forestry, Transportation Research Board Conference Proceedings 23: 179-185.
4. Best Practices for Winter Maintenance Roadway Deicer Applications in the State of Nebraska, 2015, Spring 4-27-2015, Tregan PD Albers II.
5. Current Deicing Practices and Alternate Deicing Materials, Michigan Department of Transportation, Chapter-2, 14-23.
6. Comfort, G. and Dinovitzer, A. Traction Enhancement Provided by Sand Application on Packed Snow and Bare Ice: Summary Report. Report MAT-97-02. Ontario Ministry of Transportation, 1997.
7. Department of Transportation (MDT). White Paper, Prepared December 2001, updated December 2003.
8. Denby, B.R., Ketzel, M., Ellermann, T., Stojiljkovic, A., Kupiainen, K., Niemi, J.V., Norman, M., Johansson, C., Gustafsson, M., Blomqvist, G., Janhall, S. and Sundvor, I., (2016), Road salt emissions, a comparison of measurements and modelling using the NORTRIP road dust emission model.
9. Environment and Climate Change Canada. http://ec.gc.ca/sels-salts/Default.asp?lang=En&n=45D464B1-1#sec_appa
10. Environment Canada (2002). Winter Road Maintenance Activities and the Use of Road Salts in Canada: A Compendium of Costs and Benefits Indicators.

11. Fonnesbech, J. K. Ice Control Technology with 20 Percent Brine on Highways, Transportation Research Record 1741, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 54-59.

12. Fortin, C. and Dindorf, C., (2005). Minnesota Snow and Ice Control: Field Handbook for Snowplow Operators. Minnesota Local Road Research Board, Manual Number 2005-01, August 2005.

13. Fu, L. and Omer, R. (2011), Field Performance of Organic Deicing /Anti-icing Products for Snow and Ice Control.

14. Gray, D. M. and Male, D. H. Handbook of Snow: Principles, Processes, Management and Use. Pergamon Press, 1981.

15. Hyman, W. A. and Vary, D. (1999). Best Management Practices for Environmental Issues Related to Highway and Street Maintenance. Transportation Research Board, National Academy Press, Washington, D.C. National Cooperative Highway Research Program synthesis report # 272.

16. Ketcham, S.A., Minsk, D., Blackburn, R. R., and Fleege, E.J. (1996). FHWA, Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel, Hanover, New Hamspire: US Army Cold Regions Research and Engineering Laboratory.

17. Manual of Practise for an effective Anti-Icing Program, Federal Highway Administration, U.S. Department of Transportation.

18. Mendenhall, W. and Sincich, T., “Coding Quantitative Independedent Variables”, A second course in statistics: Regression Analysis, 2012, Seventh Edition, 281-83

19. Minsk, L.D., (1998). Snow and Ice Control Manual for Transportation Facilities, McGraw-Hill, New York.

20. MTO, 1994. Field Trials of Pre-wetted Sand for Winter Maintenance. Report, MAT-94-10, Research and Development Branch, Ontario Ministry of Transportation, Downsview.

21. MTO 2003, Maintenance Best Practices, Maintenance Manual.
22. MTO 2003, Maintenance Quality Standards, Maintenance Manual.
23. MTO 2012, Ontario Provincial Standard Specification, METRIC OPSS.PROV 1004.
24. MTO 2017, Ontario Provincial Standard Specification, METRIC OPSS.PROV 2502.
25. NCHRP Project 25-25, Task 4 (2004). Environmental Stewardship Practices, Procedures, and Policies for Highway Construction and Maintenance.
26. Nilsson, G. and Obrenovic, A. (1998). Road Accident Risk Twice as High in the winter. Swedish Road and Traffic Research Institute (VTI), Report No. 435.
27. Nixon, W. A. (2001). Use of Abrasives in Winter Maintenance at the County Level. Transportation Research Record 1741. p. 42-46. Paper No. S00 -0025.
28. O'Keefe, K. and Shi, X. (2006). Anti-icing and Pre-wetting: Improved Methods for Winter Highway Maintenance in North America. TRB 2006 Annual Meeting CD-ROM.
29. Perchanok, M., Manning, D. G. and Armstrong, J. J. (1991). "Highway deicers: Standards, practice, and research in the province of Ontario". Ministry of Transportation Ontario. November 1991.
30. Peden, M., Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E. and Mathers, C. (2004). World Report on Road Traffic Injury Prevention, WHO.
31. Pisano, P., Goodwin, L. and Stern, A. (2004). Surface Transportation Safety and Operations: The Impacts of Weather within the Context of Climate Change. TRB annual meeting, 2004.
32. Ramakrishna, D.M. and Viraraghavan, T., (2005), Environmental Impacts of Chemical de-icers.
33. Sooklall, R., Fu, L. and Perchanok, M. (2006), Effectiveness of Pre-wetting strategy for Snow and Ice Control on Highways, Annual Conference of Transportation Association of Canada.
34. Sustainability insight (2009), An Innovative Strategy for Ontario's Ministry of Transportation.
35. Special Report (2015), Winter Highway Maintenance, Office of Auditor General of Ontario.
36. The Snowfighter's Handbook, "Safe and Sustainable Snowfightng", The Salt Institute, 2016.

37. Usman, T., Fu, L., Jiang, C., Perchanok, M., (2017). Sustainable Traction with Winter Sand, 96th Annual Meeting of the Transportation Research Board.

38. Williams, D (2003). Past and Current Practices of Winter Maintenance at the Montana.

39. White, S. P., Thornes, J. E. and Chapman, L. (2006). A Guide to Road Weather Information Systems. University of Birmingham, Birmingham, UK.

40. Winter Sanding Guidelines (2012), Stantec, Regina, Saskatoon.

41. Wisconsin Transportation Bulletin No. 6

42. Wisconsin Transportation Bulletin No. 22

Appendix A

Questionnaire for Pre-wetting Best Practices

The following questionnaire was prepared to determine the pre-wet practices being followed in different jurisdictions:

1. Does your company pre-wet either salt or sand or both?
2. What liquid chemical/additive does your company use in the pre-wetting process of either salt or sand?
3. What percentage (by mass or volume) of this liquid chemical/additive does your company use in pre-wetting?
4. What are your company's application rates of this pre-wetted material? Please include weather conditions such as temperature range or type of precipitation (i.e. light, normal, heavy) if applicable.
5. What are your company's opinions on the effectiveness of using pre-wetting?

Appendix B

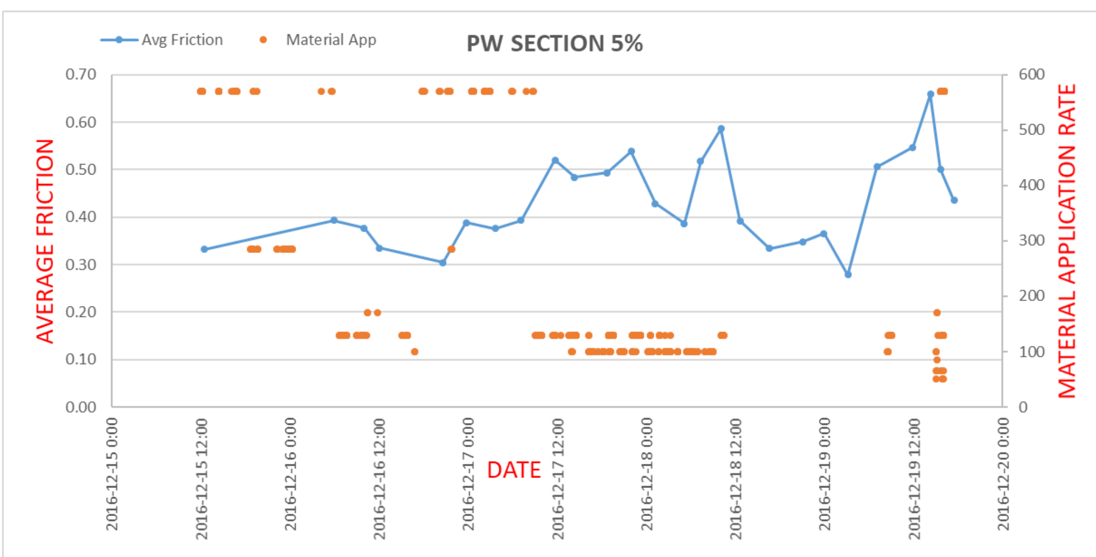
Event-wise Plots

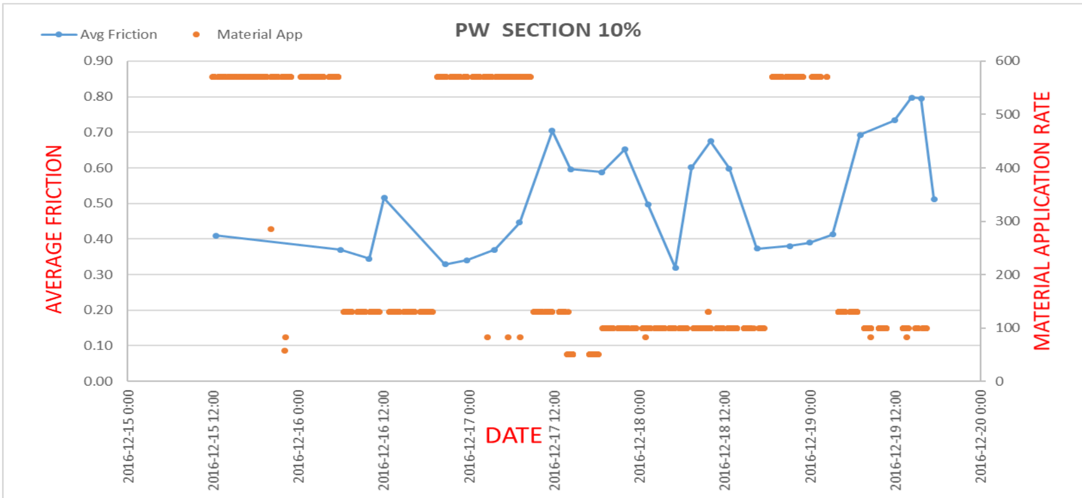
For each of the 25 events, the friction levels and material were plotted for different pre-wet ratios of salt against the time of an event. Also, the comparison of friction levels attained using different treatments were also plotted.

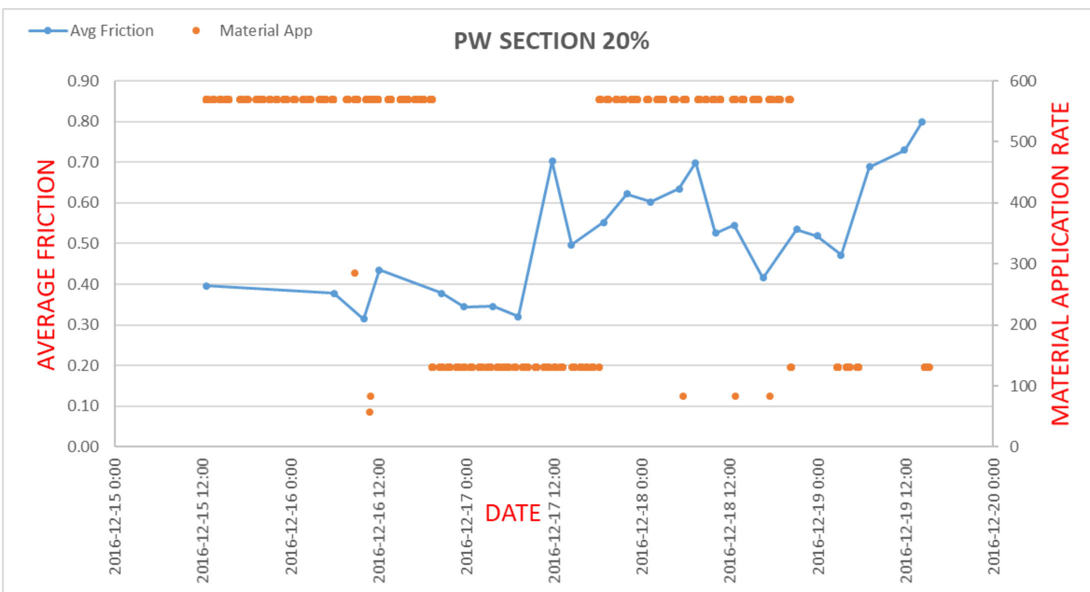
EVENT- 1

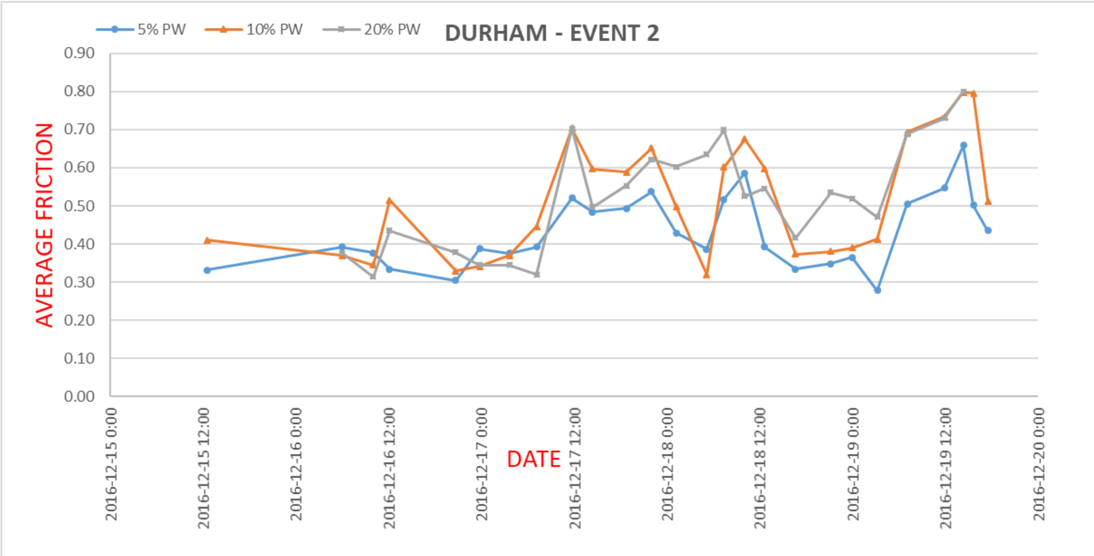
Event 1 constituted the training of equipment and was not a part of the analysis.

EVENT – 2

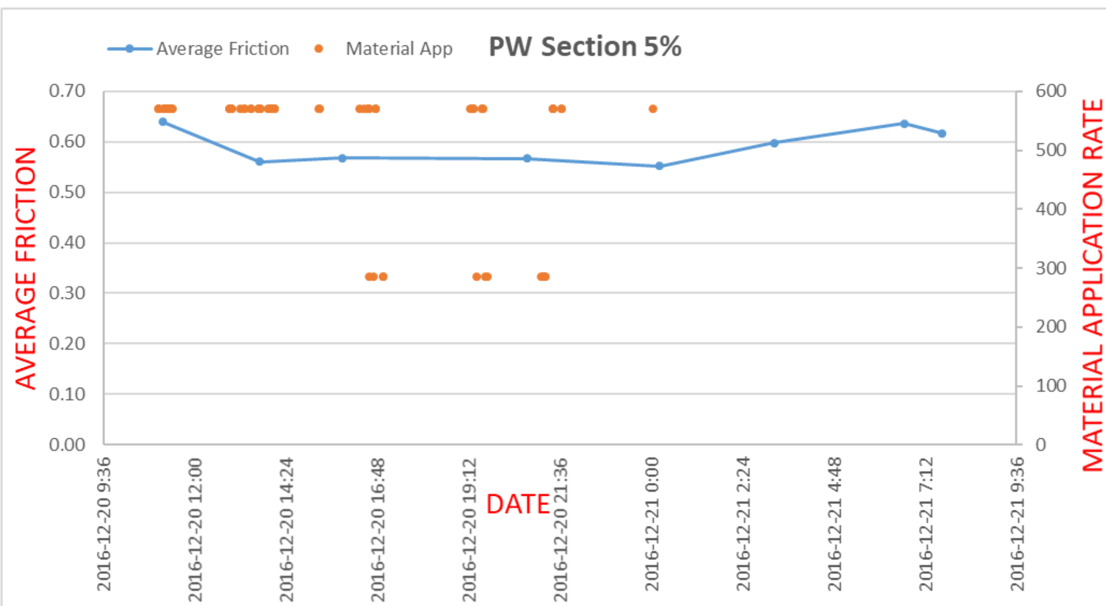


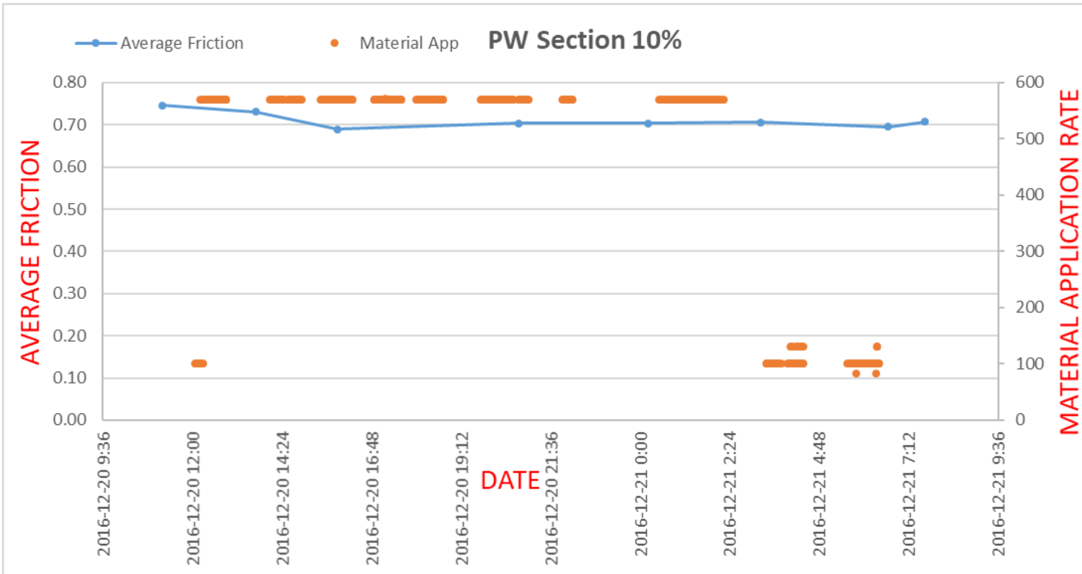

Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2016-12-15 0:00
2016-12-15 12:00
2016-12-16 0:00
2016-12-16 12:00
2016-12-17 0:00
2016-12-17 12:00
2016-12-18 0:00
2016-12-18 12:00
2016-12-19 0:00
2016-12-19 12:00
2016-12-20 0:00

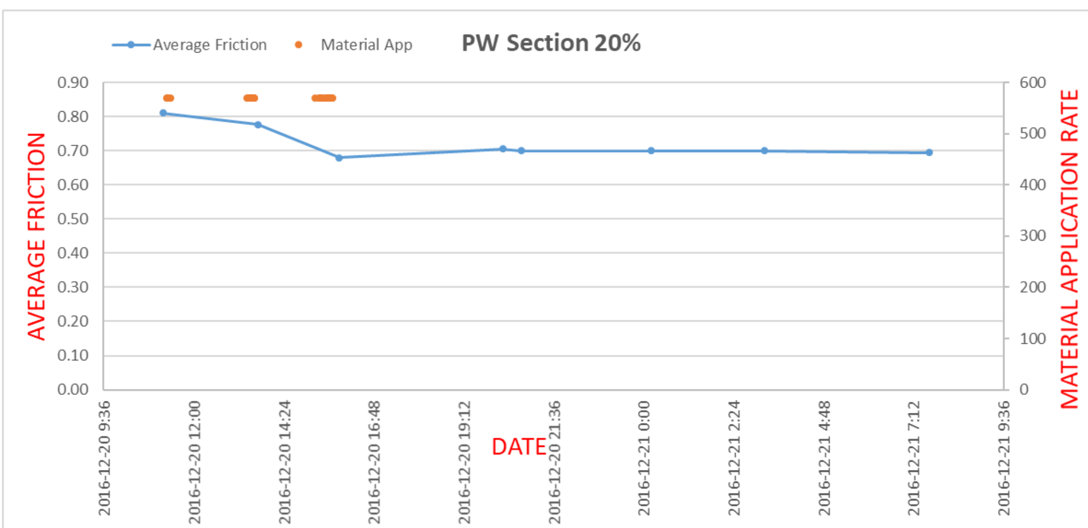

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2016-12-15 0:00
2016-12-15 12:00
2016-12-16 0:00
2016-12-16 12:00
2016-12-17 0:00
2016-12-17 12:00
2016-12-18 0:00
2016-12-18 12:00
2016-12-19 0:00
2016-12-19 12:00
2016-12-20 0:00

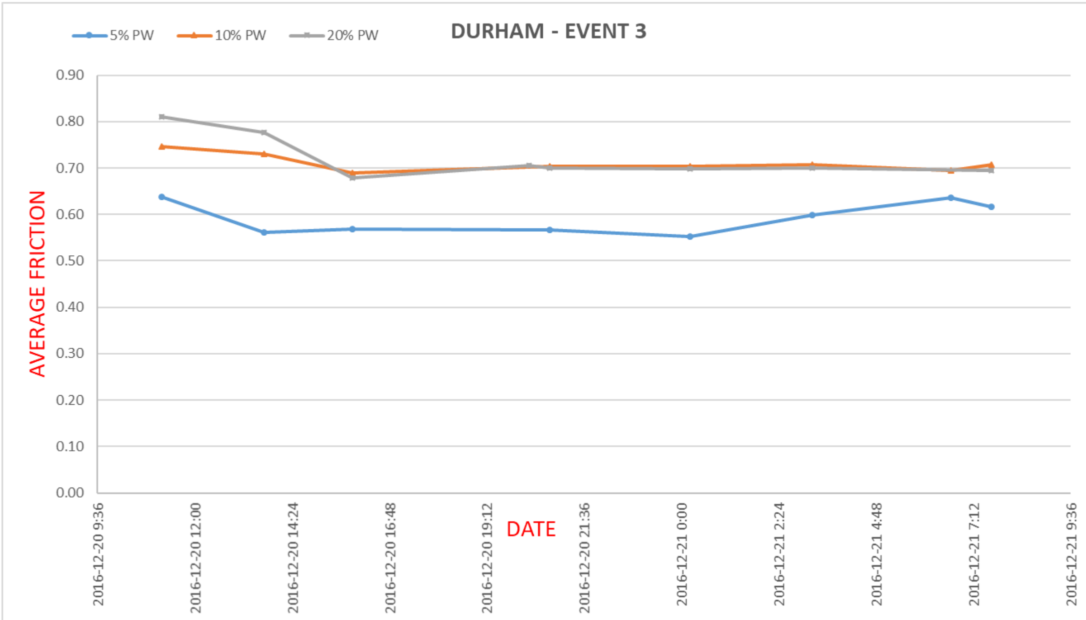

5% PW
10% PW
20% PW
DURHAM - EVENT 2
AVERAGE FRICTION
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2016-12-15 0:00
2016-12-15 12:00
2016-12-16 0:00
2016-12-16 12:00
2016-12-17 0:00
2016-12-17 12:00
2016-12-18 0:00
2016-12-18 12:00
2016-12-19 0:00
2016-12-19 12:00
2016-12-20 0:00
DATE

EVENT – 3


Average Friction
Material App
PW Section 5%
AVERAGE FRICTION
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
MATERIAL APPLICATION RATE
2016-12-20 9:36
2016-12-20 12:00
2016-12-20 14:24
2016-12-20 16:48
2016-12-20 19:12
2016-12-20 21:36
2016-12-21 0:00
2016-12-21 2:24
2016-12-21 4:48
2016-12-21 7:12
2016-12-21 9:36
DATE

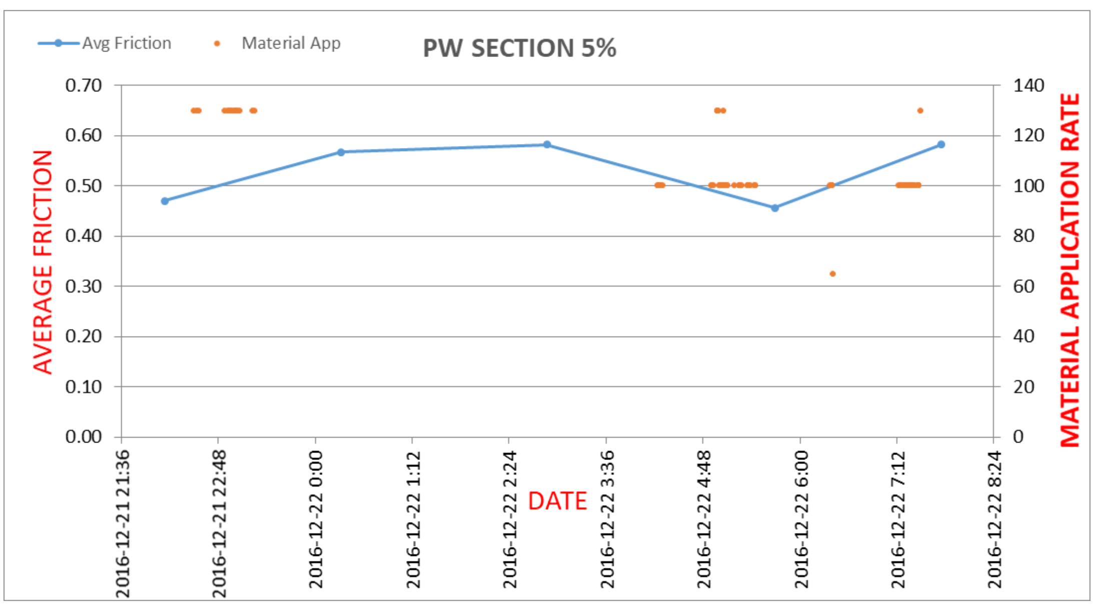

Average Friction
Material App
PW Section 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2016-12-20 9:36
2016-12-20 12:00
2016-12-20 14:24
2016-12-20 16:48
2016-12-20 19:12
2016-12-20 21:36
2016-12-21 0:00
2016-12-21 2:24
2016-12-21 4:48
2016-12-21 7:12
2016-12-21 9:36


Average Friction
Material App
PW Section 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2016-12-20 9:36
2016-12-20 12:00
2016-12-20 14:24
2016-12-20 16:48
2016-12-20 19:12
2016-12-20 21:36
2016-12-21 0:00
2016-12-21 2:24
2016-12-21 4:48
2016-12-21 7:12
2016-12-21 9:36

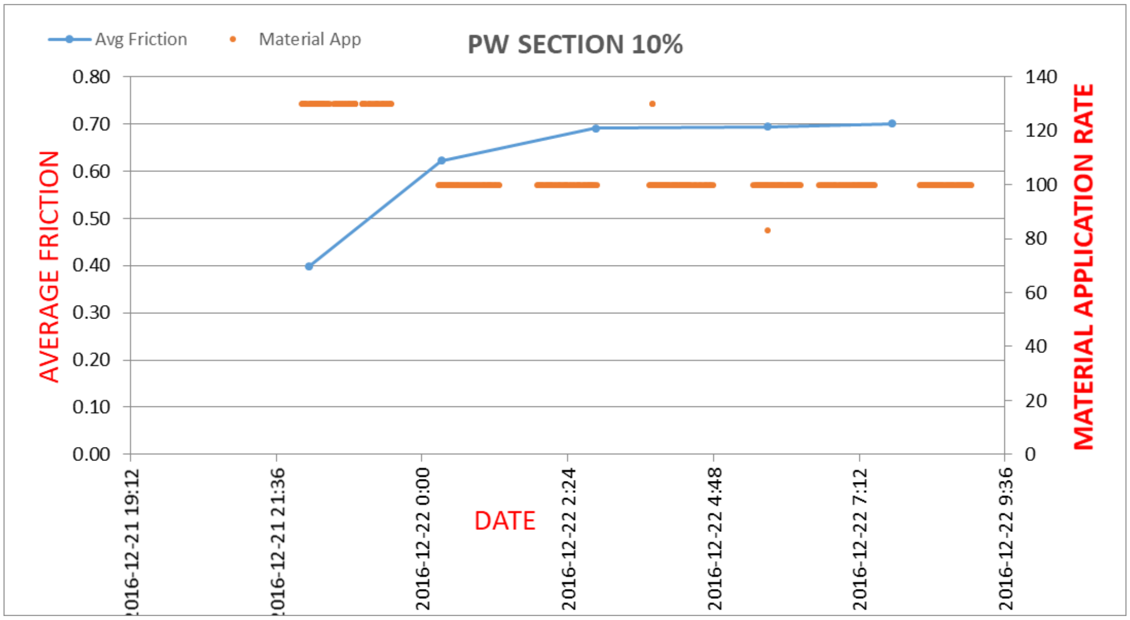


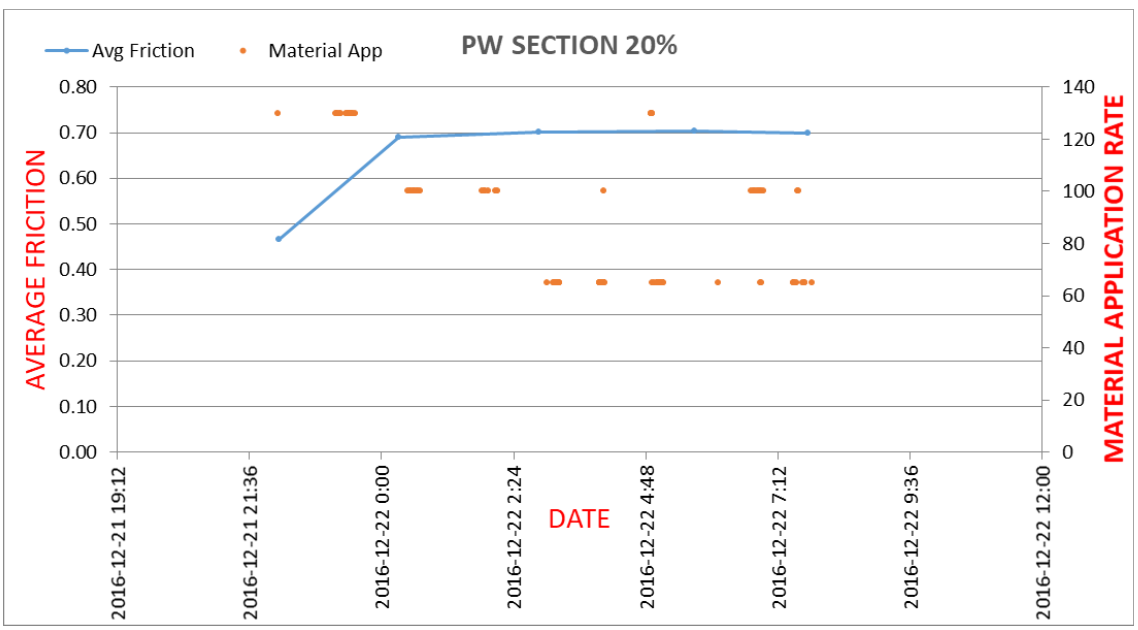
DURHAM - EVENT 3
5% PW
10% PW
20% PW
AVERAGE FRICTION
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2016-12-20 9:36
2016-12-20 12:00
2016-12-20 14:24
2016-12-20 16:48
2016-12-20 19:12
2016-12-20 21:36
2016-12-21 0:00
2016-12-21 2:24
2016-12-21 4:48
2016-12-21 7:12
2016-12-21 9:36

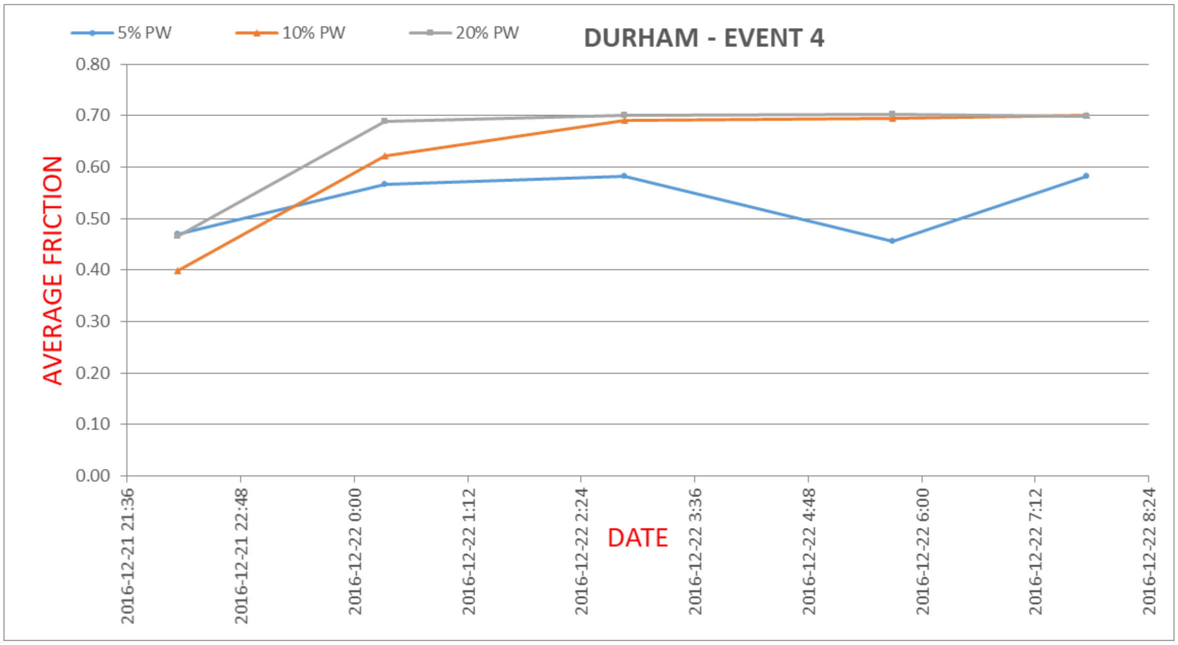
EVENT – 4



PW SECTION 5%
Avg Friction
Material App
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
2016-12-21 21:36
2016-12-21 22:48
2016-12-22 0:00
2016-12-22 1:12
2016-12-22 2:24
2016-12-22 3:36
2016-12-22 4:48
2016-12-22 6:00
2016-12-22 7:12
2016-12-22 8:24

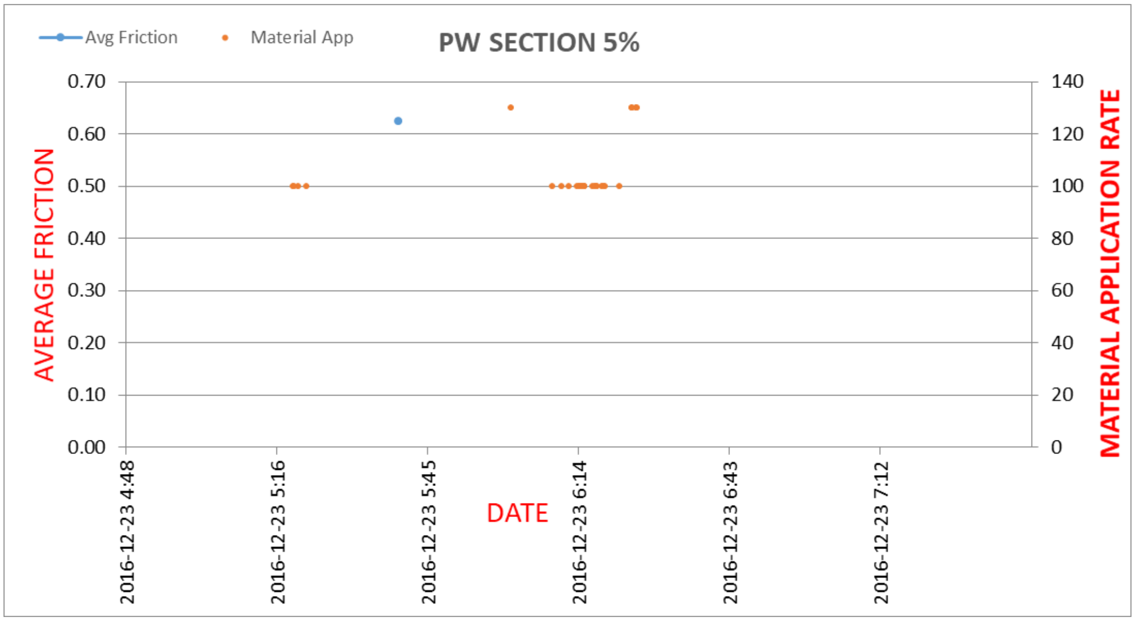

Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
2016-12-21 19:12
2016-12-21 21:36
2016-12-22 0:00
2016-12-22 2:24
2016-12-22 4:48
2016-12-22 7:12
2016-12-22 9:36

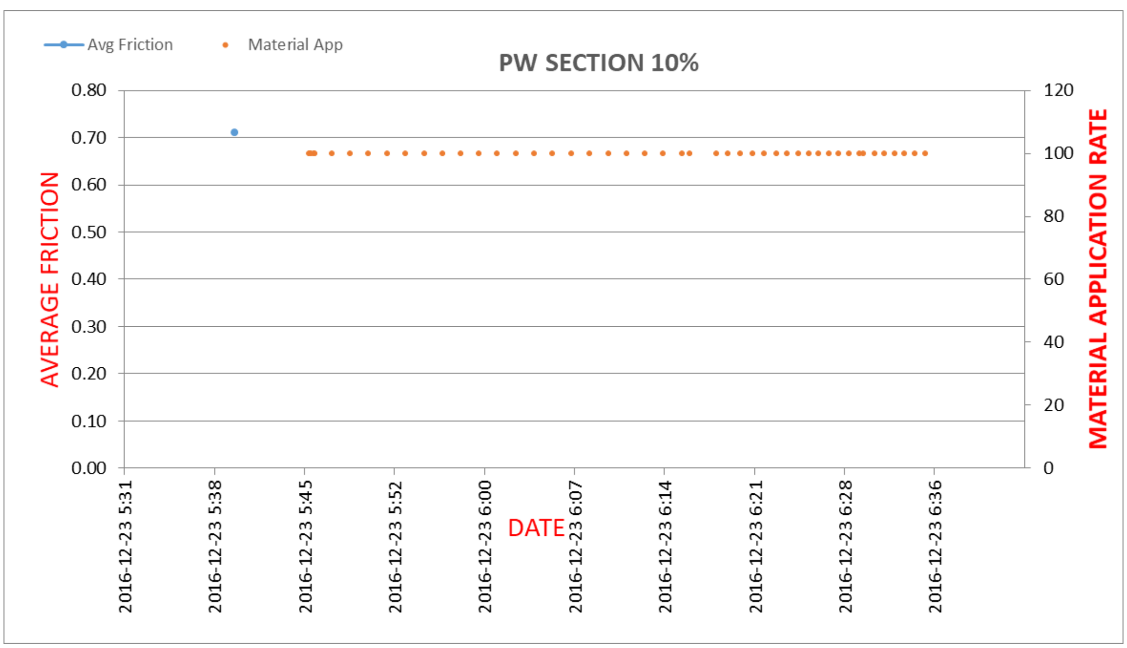

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICITION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
2016-12-21 19:12
2016-12-21 21:36
2016-12-22 0:00
2016-12-22 2:24
2016-12-22 4:48
2016-12-22 7:12
2016-12-22 9:36
2016-12-22 12:00

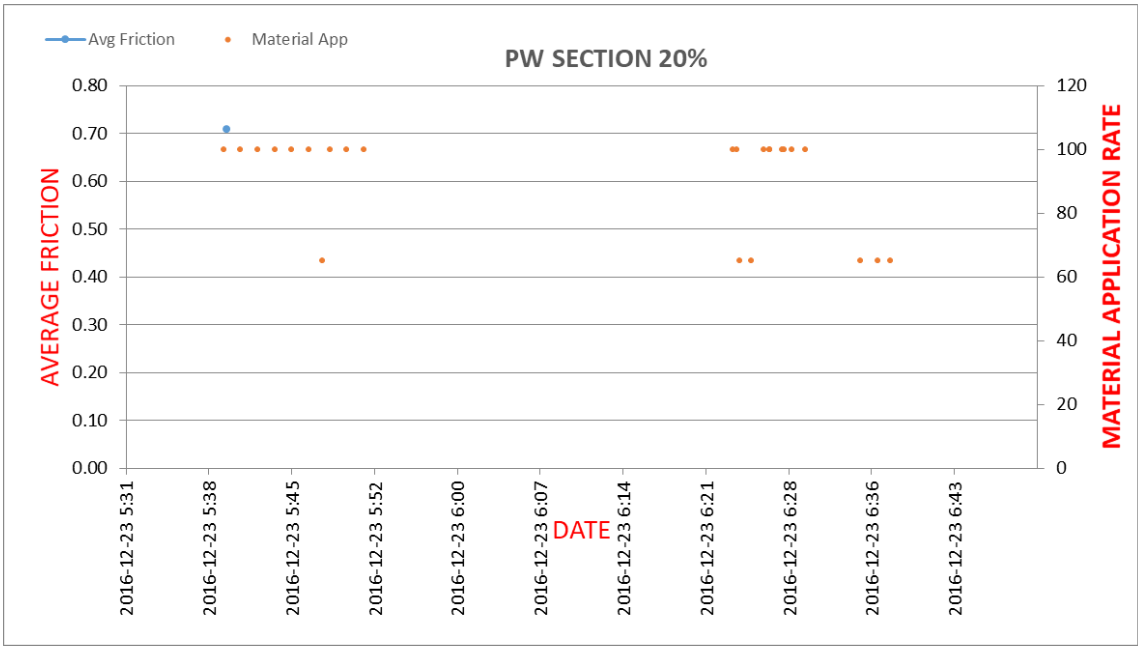


EVENT – 5

Event 5 comprises only single run, hence the plot showing comparison between friction levels attained by different treatments is not shown.

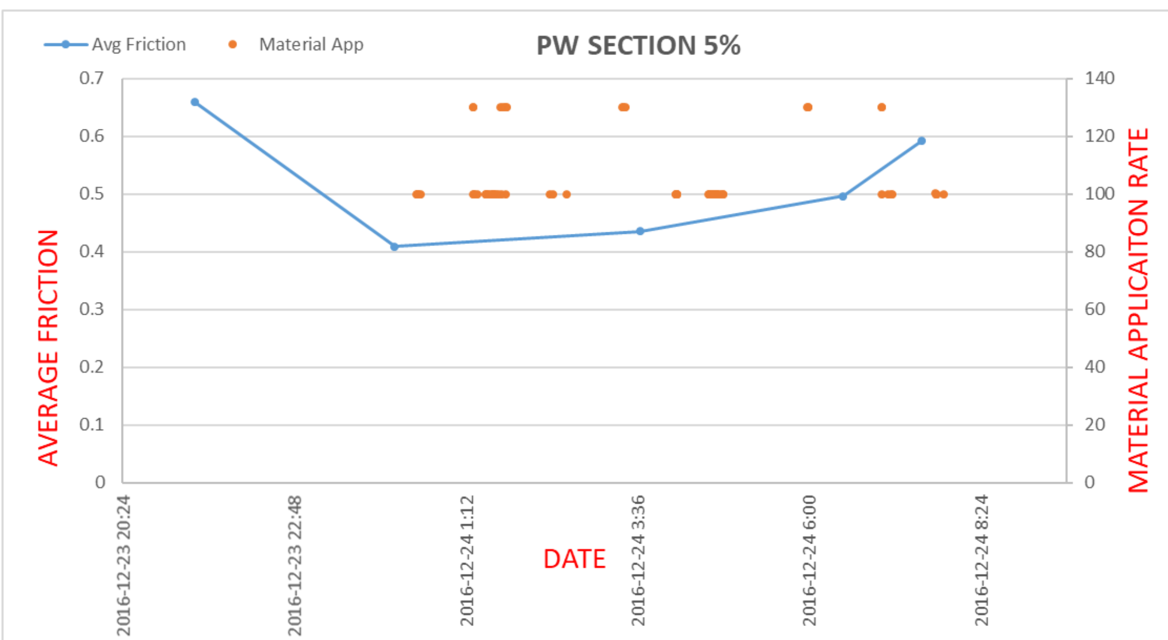

Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
MATERIAL APPLICATION RATE
2016-12-23 4:48
2016-12-23 5:16
2016-12-23 5:45
DATE
2016-12-23 6:14
2016-12-23 6:43
2016-12-23 7:12


Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
120
100
80
60
40
20
0
MATERIAL APPLICATION RATE
2016-12-23 5:31
2016-12-23 5:38
2016-12-23 5:45
2016-12-23 5:52
2016-12-23 6:00
DATE
2016-12-23 6:07
2016-12-23 6:14
2016-12-23 6:21
2016-12-23 6:28
2016-12-23 6:36

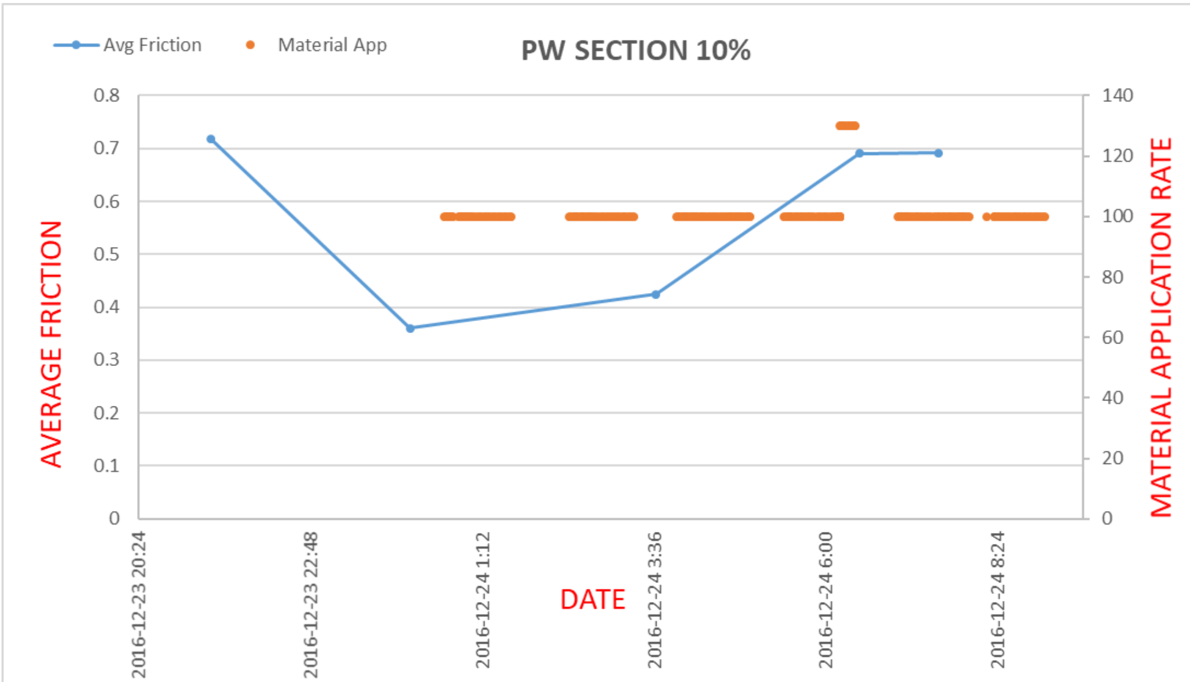


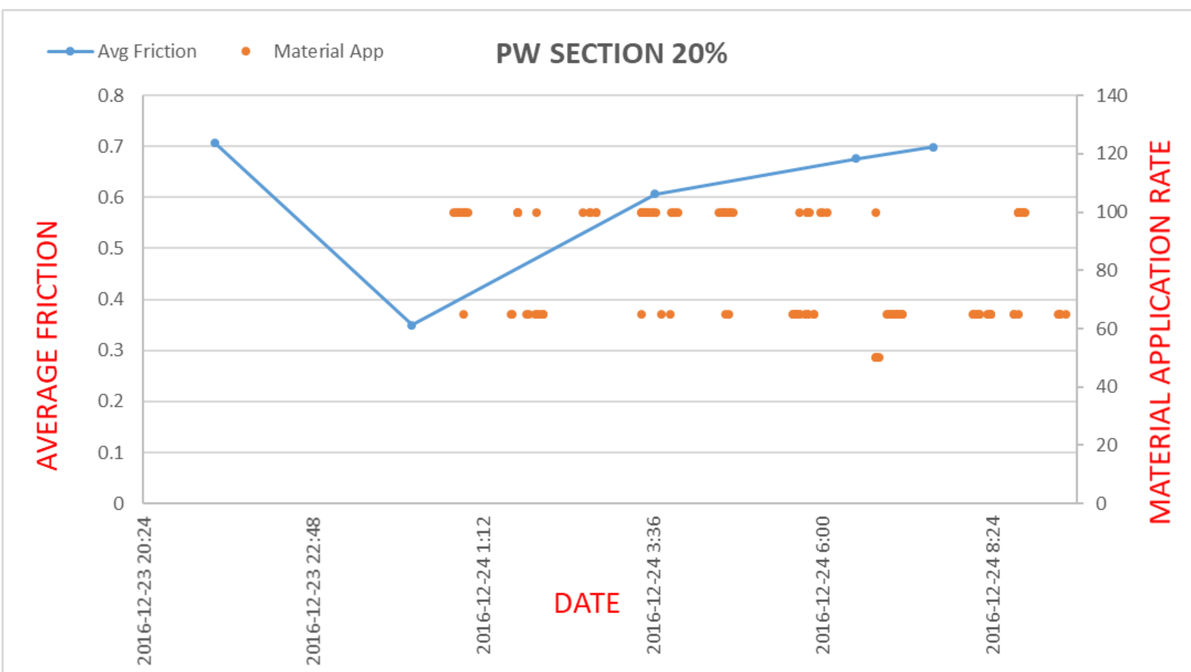
Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
120
100
80
60
40
20
0
MATERIAL APPLICATION RATE
2016-12-23 5:31
2016-12-23 5:38
2016-12-23 5:45
2016-12-23 5:52
2016-12-23 6:00
2016-12-23 6:07
2016-12-23 6:14
2016-12-23 6:21
2016-12-23 6:28
2016-12-23 6:36
2016-12-23 6:43
DATE

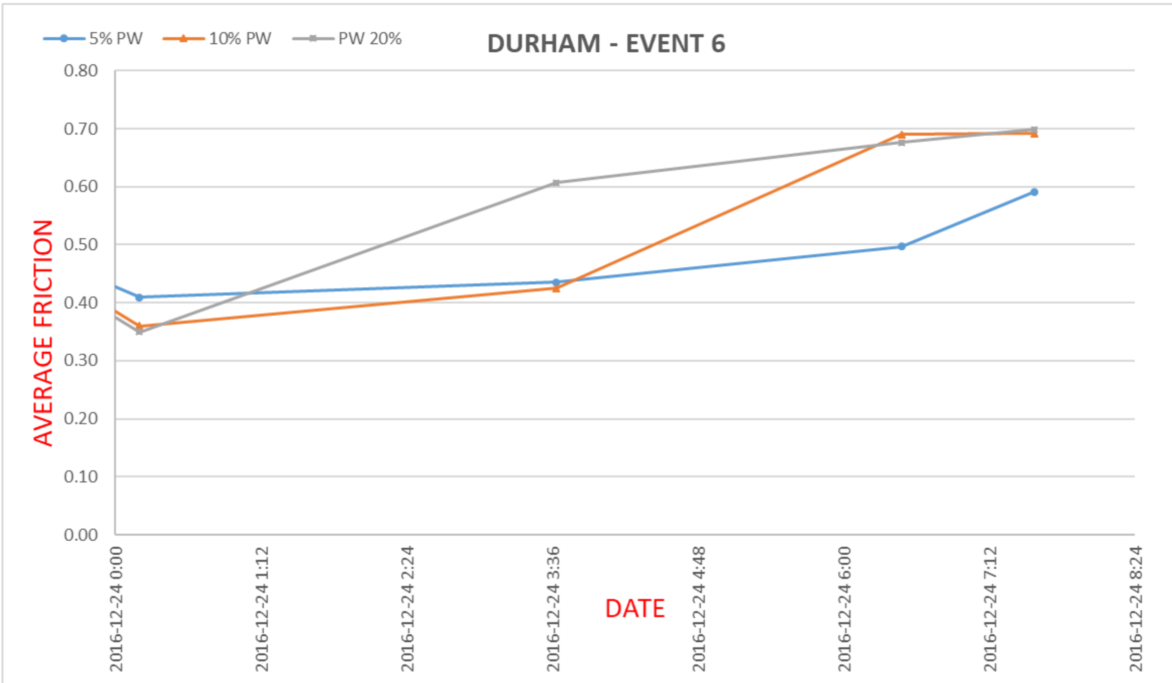
EVENT – 6



Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
140
120
100
80
60
40
20
0
MATERIAL APPLICAITON RATE
2016-12-23 20:24
2016-12-23 22:48
2016-12-24 1:12
2016-12-24 3:36
2016-12-24 6:00
2016-12-24 8:24
DATE


Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
140
120
100
80
60
40
20
0
2016-12-23 20:24
2016-12-23 22:48
2016-12-24 1:12
2016-12-24 3:36
2016-12-24 6:00
2016-12-24 8:24

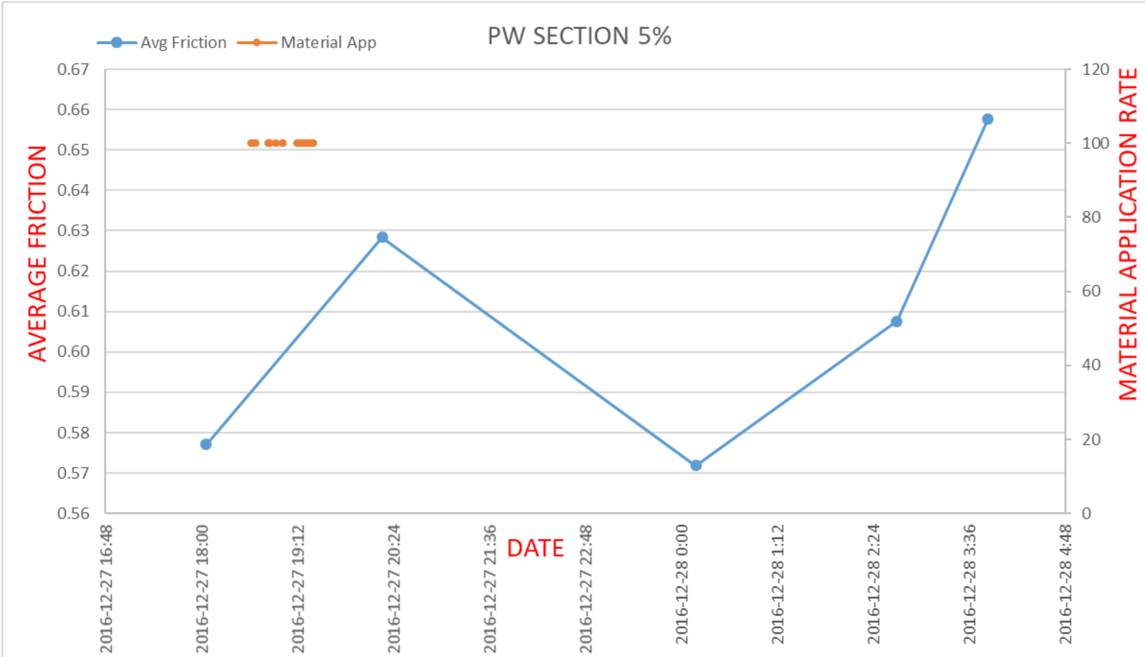

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
140
120
100
80
60
40
20
0
2016-12-23 20:24
2016-12-23 22:48
2016-12-24 1:12
2016-12-24 3:36
2016-12-24 6:00
2016-12-24 8:24

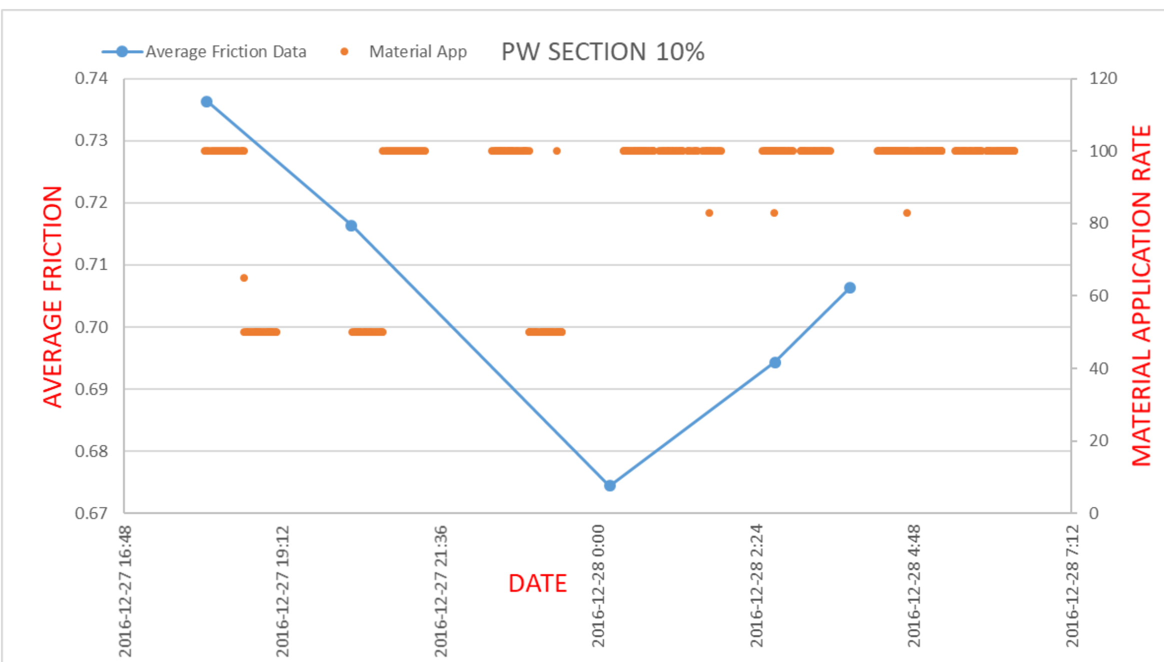


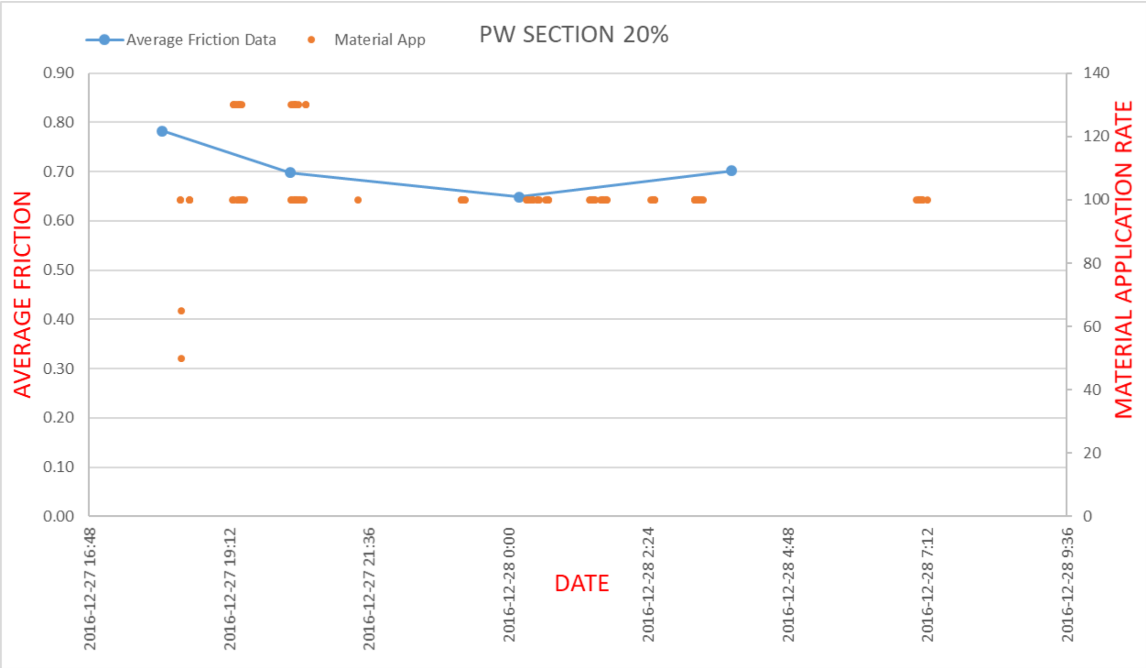
EVENT – 7

Friction Data was not available for Event 7

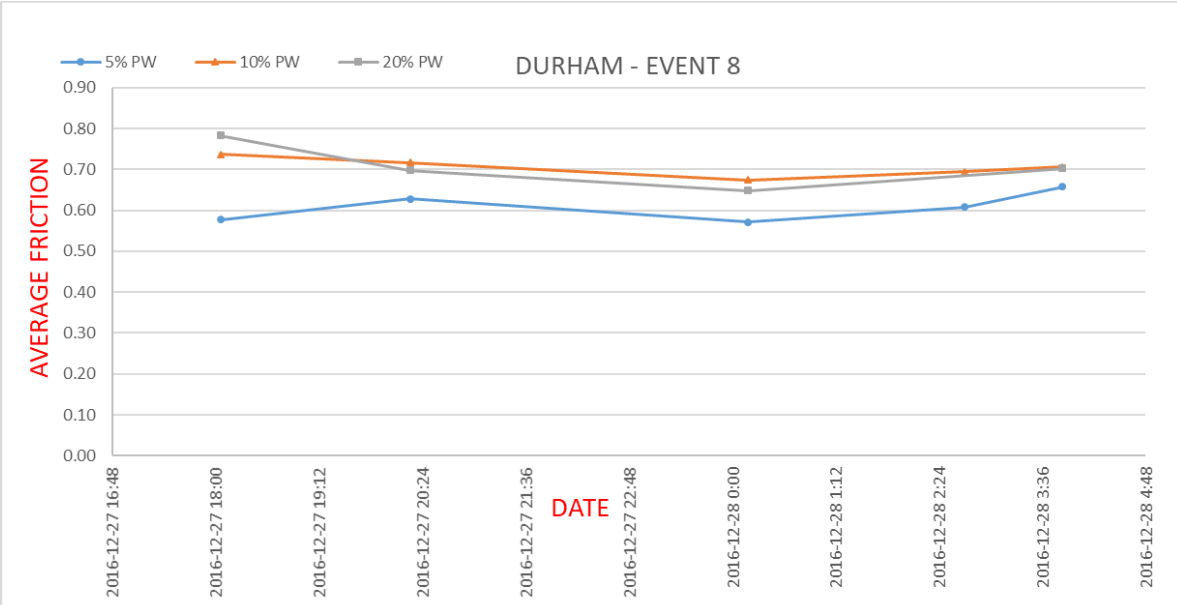
EVENT – 8


Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.67
0.66
0.65
0.64
0.63
0.62
0.61
0.60
0.59
0.58
0.57
0.56
120
100
80
60
40
20
0
2016-12-27 16:48
2016-12-27 18:00
2016-12-27 19:12
2016-12-27 20:24
2016-12-27 21:36
2016-12-27 22:48
2016-12-28 0:00
2016-12-28 1:12
2016-12-28 2:24
2016-12-28 3:36
2016-12-28 4:48


Average Friction Data
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.74
0.73
0.72
0.71
0.70
0.69
0.68
0.67
120
100
80
60
40
20
0
2016-12-27 16:48
2016-12-27 19:12
2016-12-27 21:36
2016-12-28 0:00
2016-12-28 2:24
2016-12-28 4:48
2016-12-28 7:12

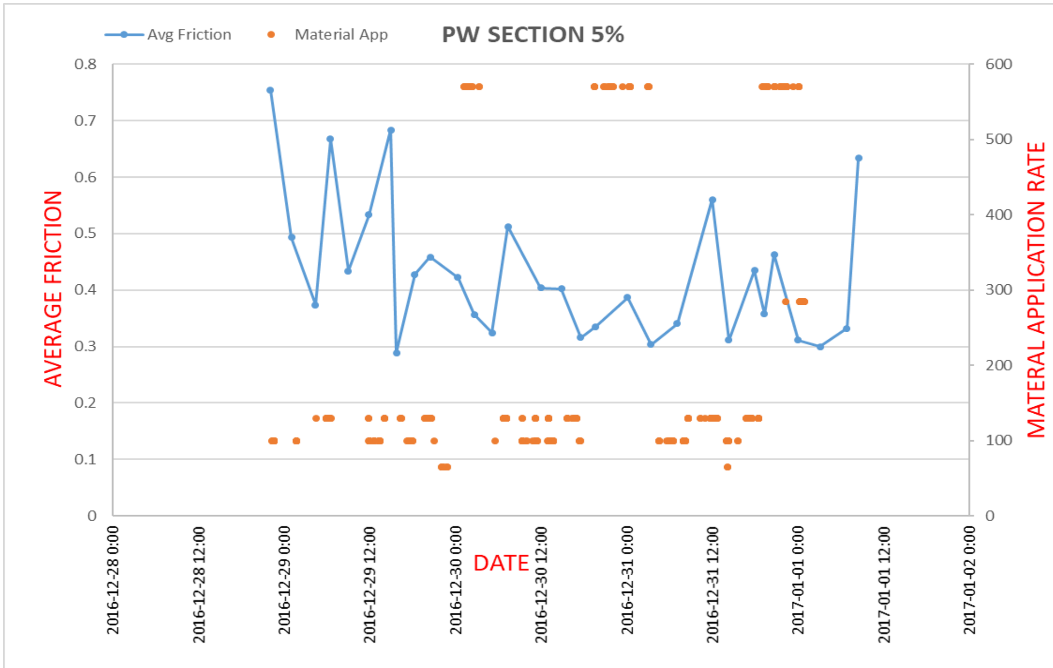


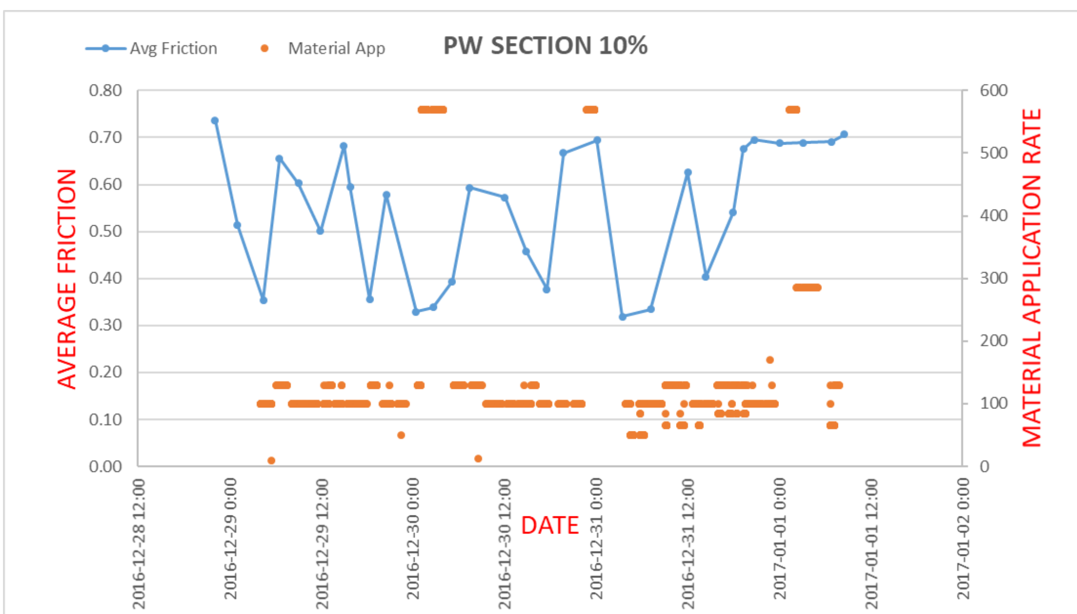
Average Friction Data
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE

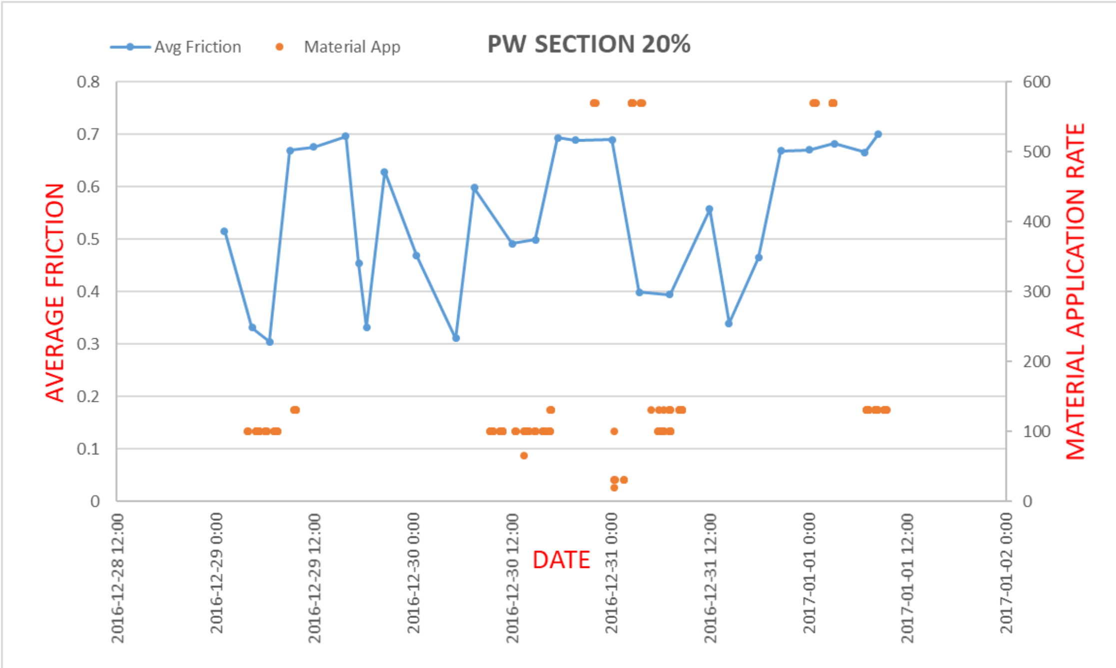


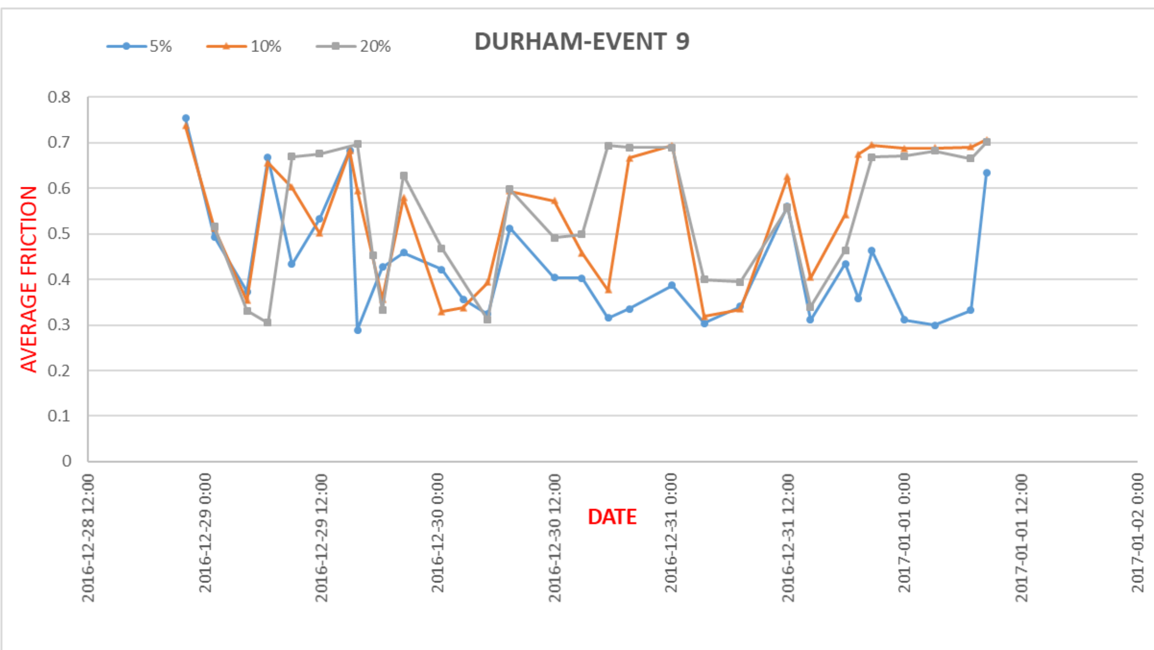
5% PW
10% PW
20% PW
DURHAM - EVENT 8
AVERAGE FRICTION
DATE

EVENT – 9

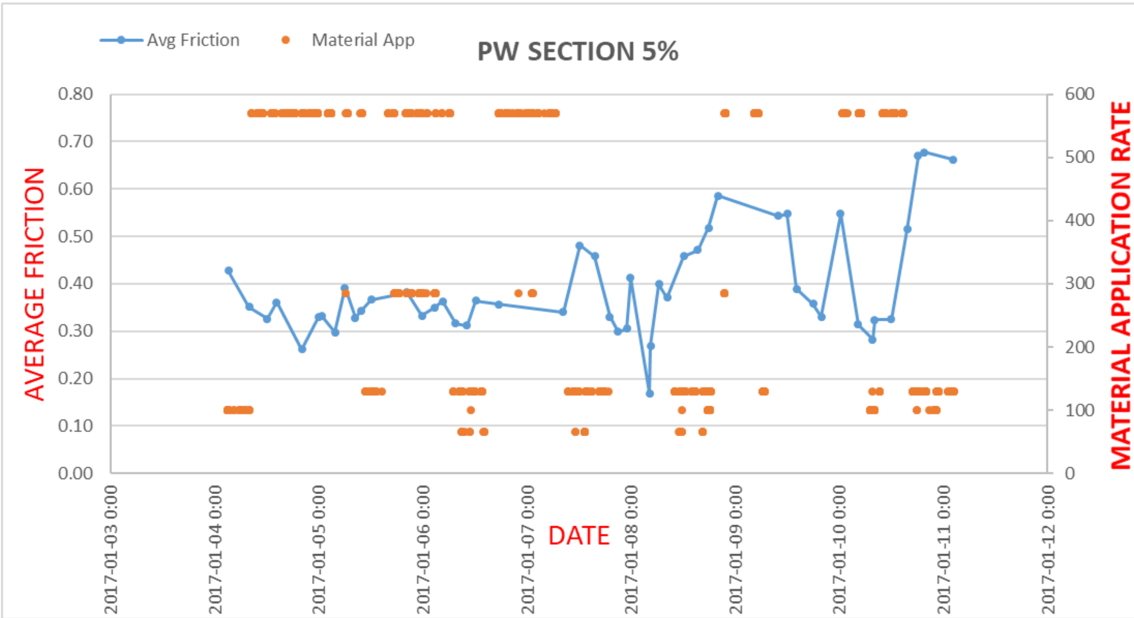

Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
600
500
400
300
200
100
0
2016-12-28 0:00
2016-12-28 12:00
2016-12-29 0:00
2016-12-29 12:00
2016-12-30 0:00
2016-12-30 12:00
2016-12-31 0:00
2016-12-31 12:00
2017-01-01 0:00
2017-01-01 12:00
2017-01-02 0:00


Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2016-12-28 12:00
2016-12-29 0:00
2016-12-29 12:00
2016-12-30 0:00
2016-12-30 12:00
2016-12-31 0:00
2016-12-31 12:00
2017-01-01 0:00
2017-01-01 12:00
2017-01-02 0:00

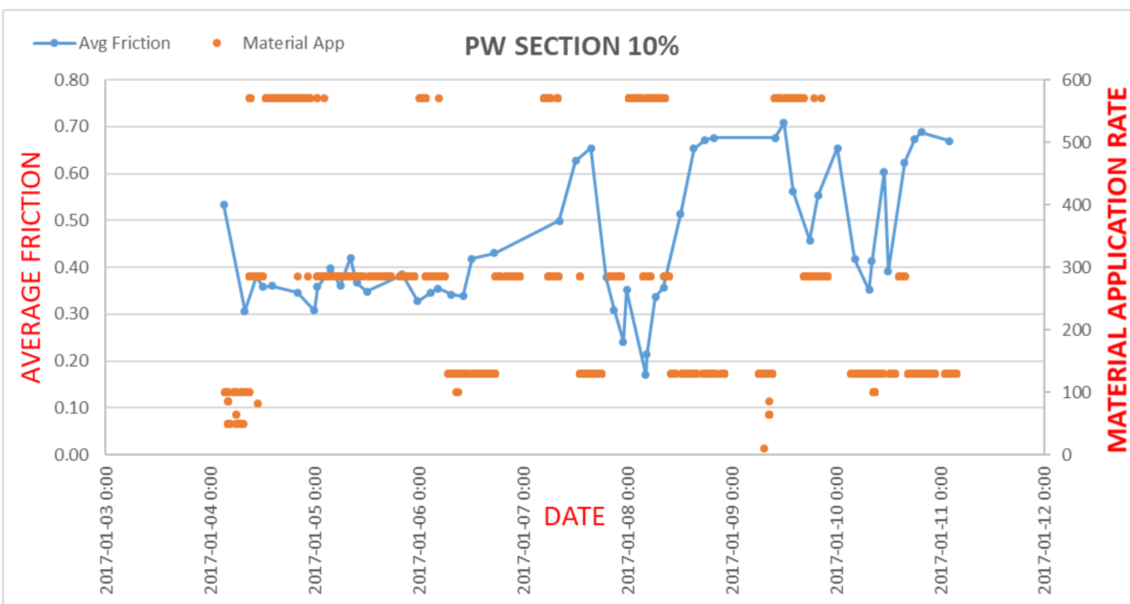

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
600
500
400
300
200
100
0
2016-12-28 12:00
2016-12-29 0:00
2016-12-29 12:00
2016-12-30 0:00
2016-12-30 12:00
2016-12-31 0:00
2016-12-31 12:00
2017-01-01 0:00
2017-01-01 12:00
2017-01-02 0:00


5%
10%
20%
DURHAM-EVENT 9
AVERAGE FRICTION
DATE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2016-12-28 12:00
2016-12-29 0:00
2016-12-29 12:00
2016-12-30 0:00
2016-12-30 12:00
2016-12-31 0:00
2016-12-31 12:00
2017-01-01 0:00
2017-01-01 12:00
2017-01-02 0:00

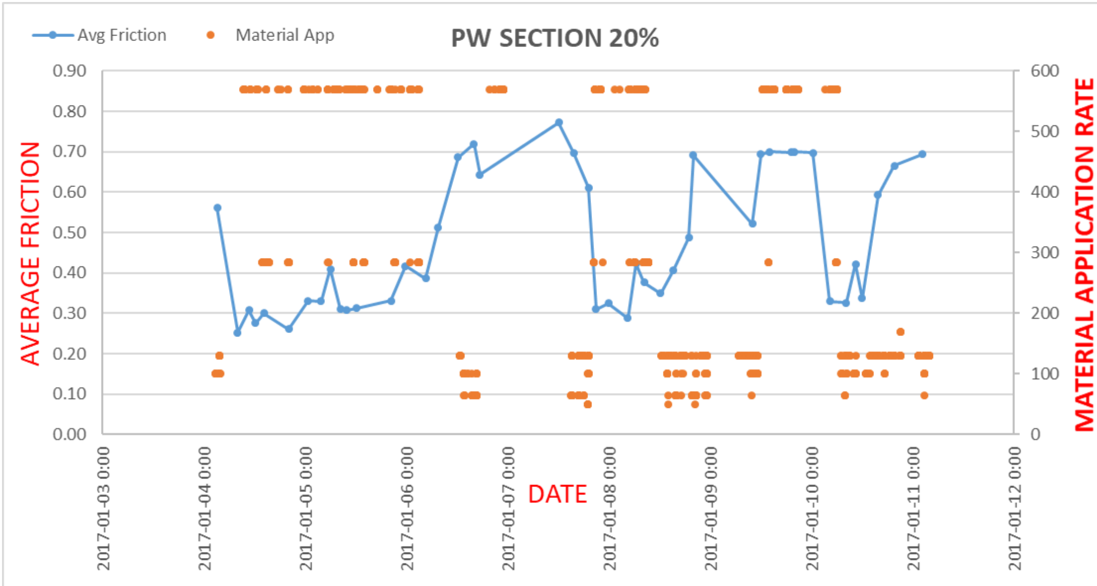
EVENT – 10

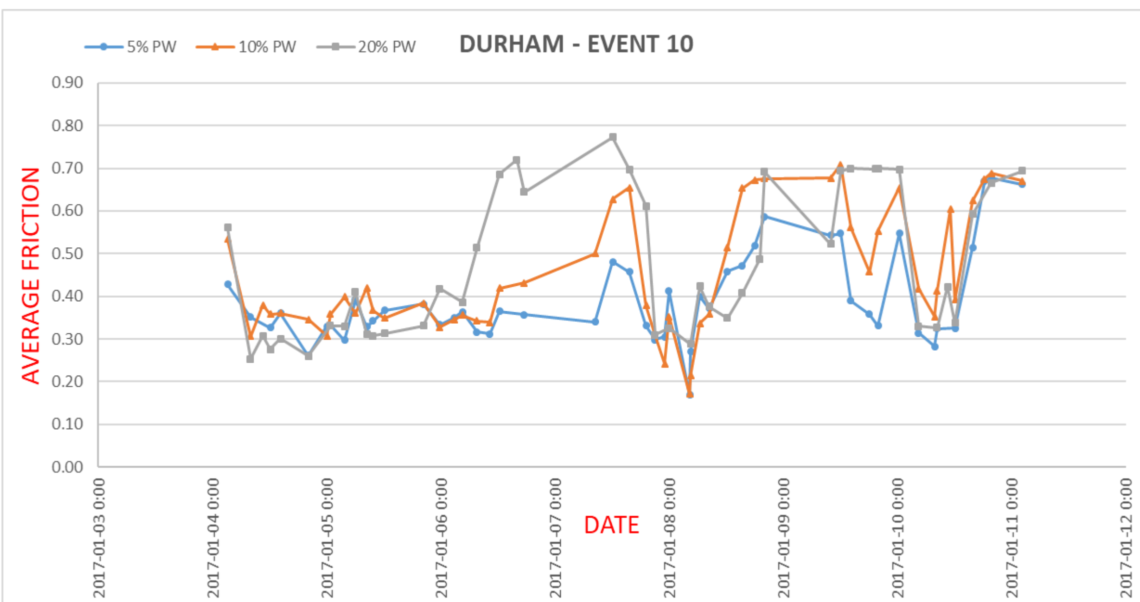


Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0
100
200
300
400
500
600
2017-01-03 0:00
2017-01-04 0:00
2017-01-05 0:00
2017-01-06 0:00
2017-01-07 0:00
2017-01-08 0:00
2017-01-09 0:00
2017-01-10 0:00
2017-01-11 0:00
2017-01-12 0:00



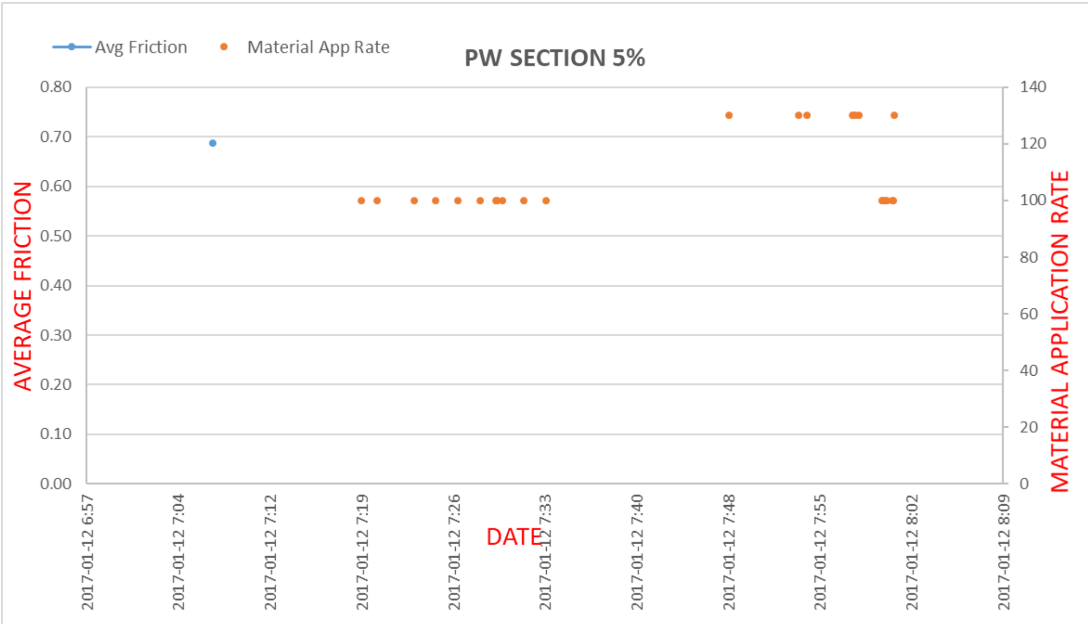
Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0
100
200
300
400
500
600
2017-01-03 0:00
2017-01-04 0:00
2017-01-05 0:00
2017-01-06 0:00
2017-01-07 0:00
2017-01-08 0:00
2017-01-09 0:00
2017-01-10 0:00
2017-01-11 0:00
2017-01-12 0:00

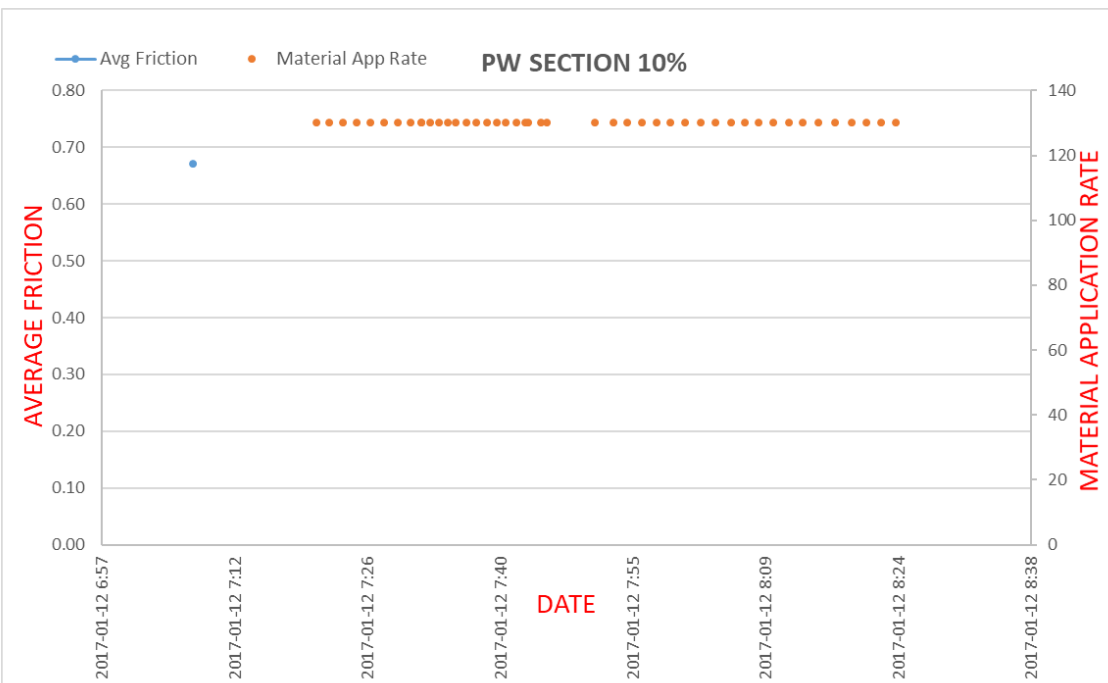

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-03 0:00
2017-01-04 0:00
2017-01-05 0:00
2017-01-06 0:00
2017-01-07 0:00
2017-01-08 0:00
2017-01-09 0:00
2017-01-10 0:00
2017-01-11 0:00
2017-01-12 0:00

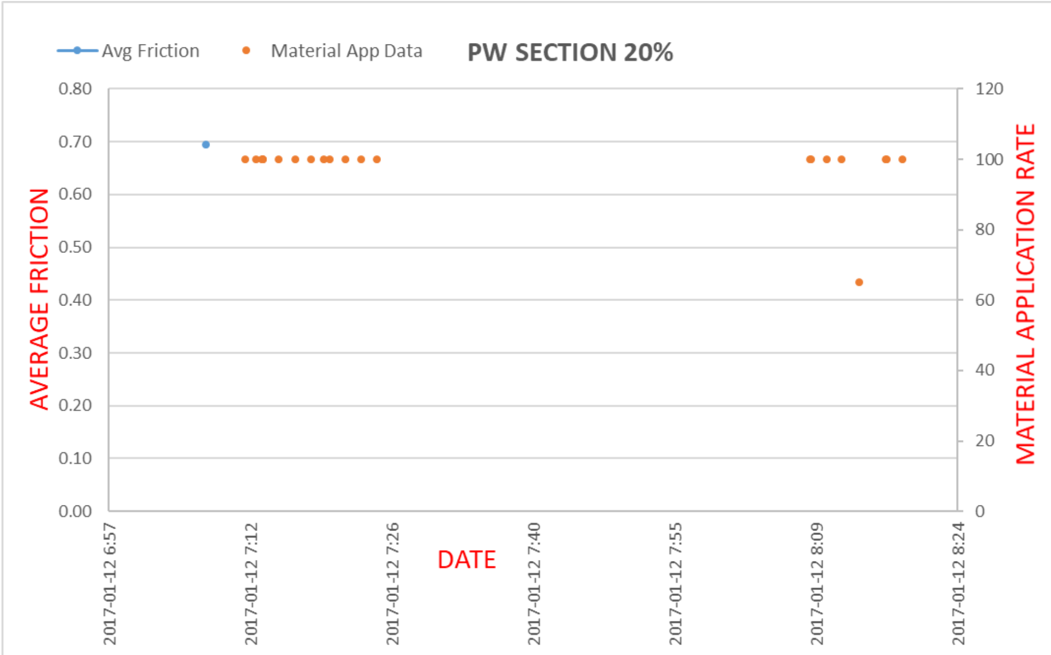

5% PW
10% PW
20% PW
DURHAM - EVENT 10
AVERAGE FRICTION
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-01-03 0:00
2017-01-04 0:00
2017-01-05 0:00
2017-01-06 0:00
2017-01-07 0:00
2017-01-08 0:00
2017-01-09 0:00
2017-01-10 0:00
2017-01-11 0:00
2017-01-12 0:00

EVENT – 11

Event 11 was comprised of one run, so the plot showing comparison between friction levels of three pre-wet ratios is not shown.

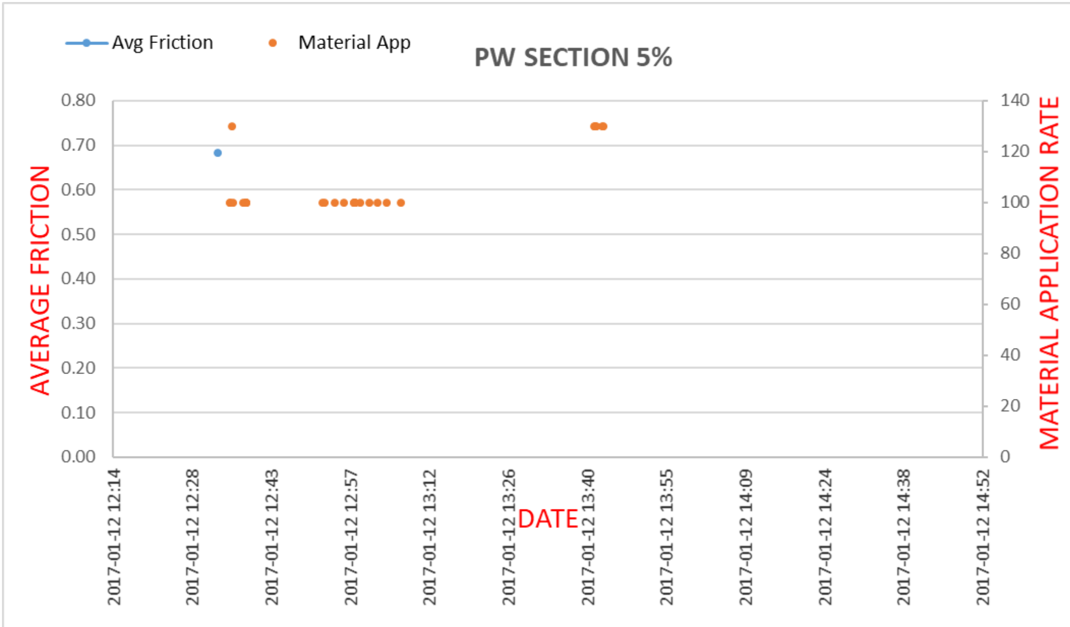


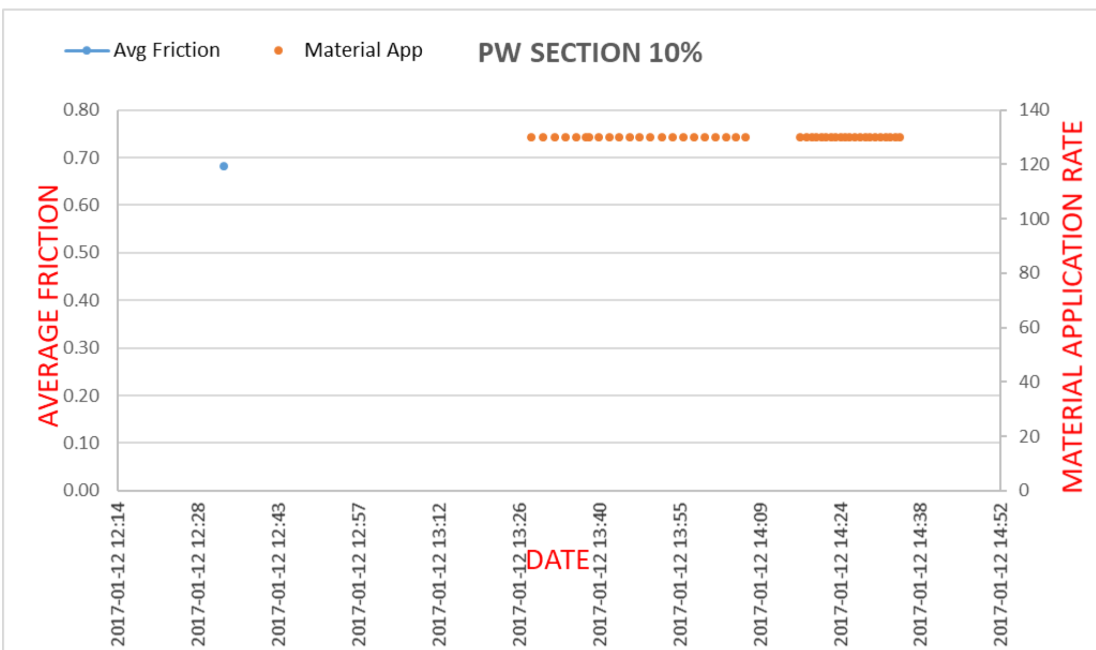


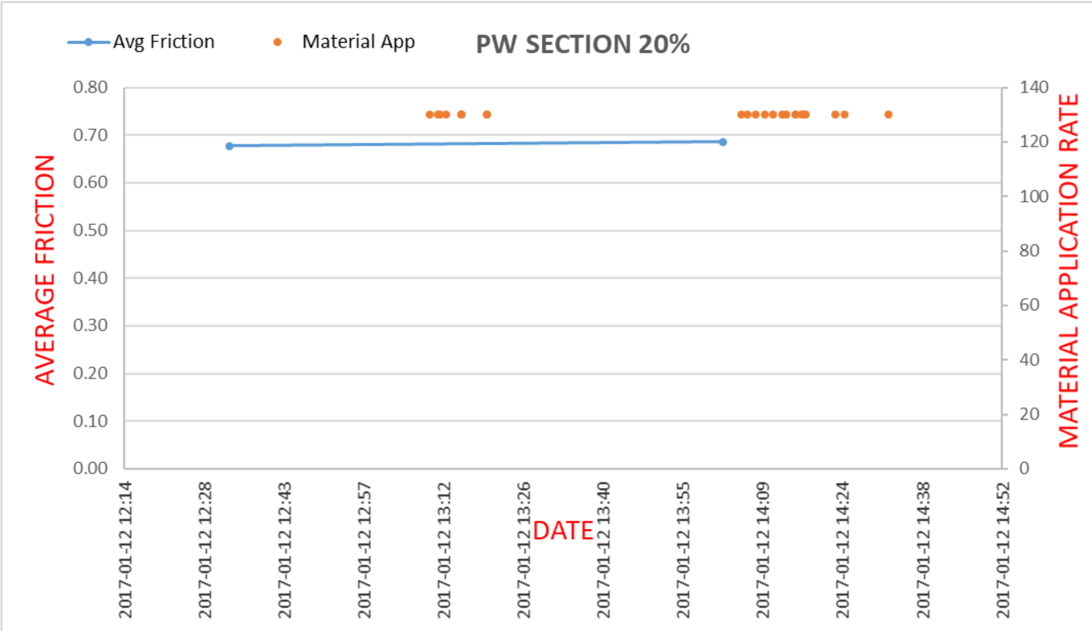


EVENT – 12

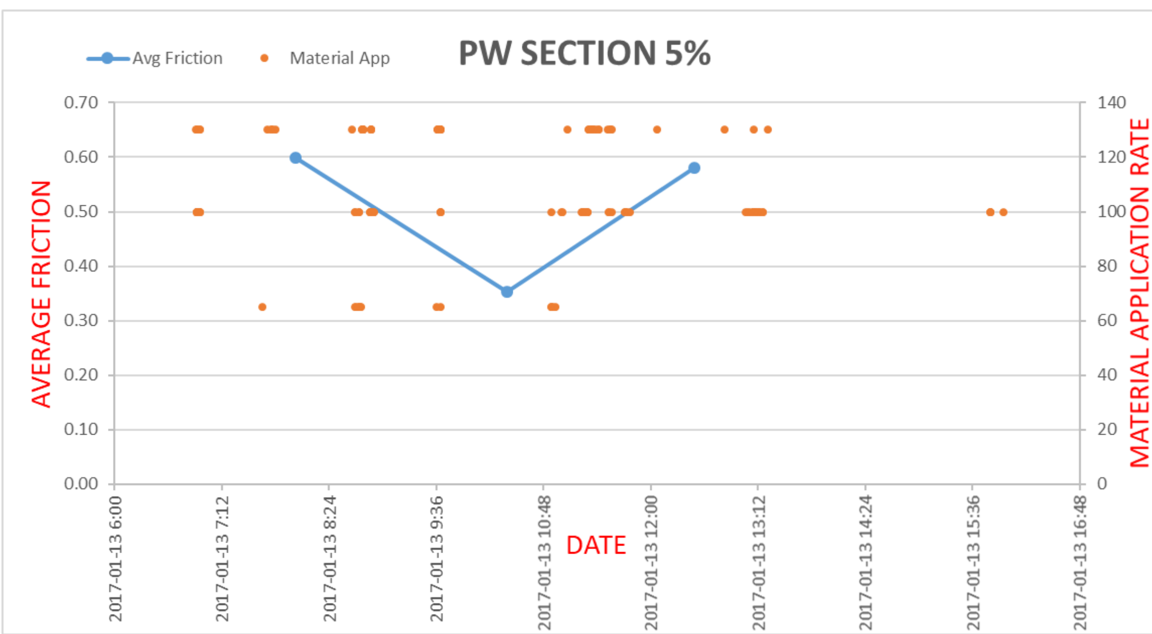
Since only one run was recorded for PW 5% and PW 10% Section, hence the plot showing comparison between friction levels attained using different pre-wet ratios is not shown.

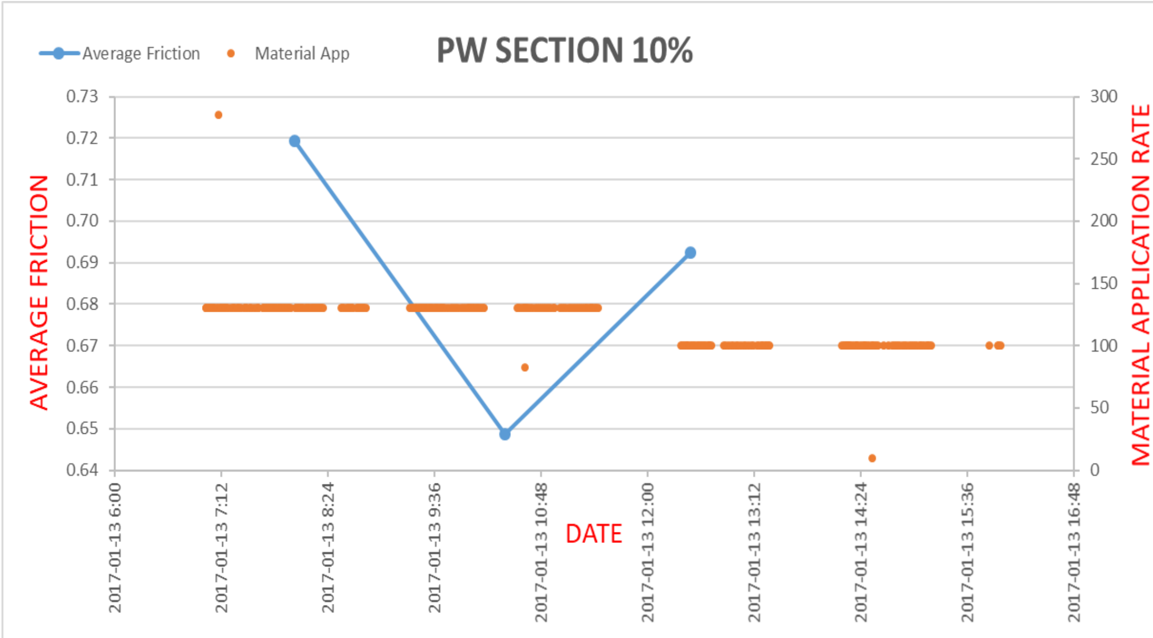

Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
MATERIAL APPLICATION RATE
140
120
100
80
60
40
20
0
DATE
2017-01-12 12:14
2017-01-12 12:28
2017-01-12 12:43
2017-01-12 12:57
2017-01-12 13:12
2017-01-12 13:26
2017-01-12 13:40
2017-01-12 13:55
2017-01-12 14:09
2017-01-12 14:24
2017-01-12 14:38
2017-01-12 14:52


Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
MATERIAL APPLICATION RATE
140
120
100
80
60
40
20
0
DATE
2017-01-12 12:14
2017-01-12 12:28
2017-01-12 12:43
2017-01-12 12:57
2017-01-12 13:12
2017-01-12 13:26
2017-01-12 13:40
2017-01-12 13:55
2017-01-12 14:09
2017-01-12 14:24
2017-01-12 14:38
2017-01-12 14:52

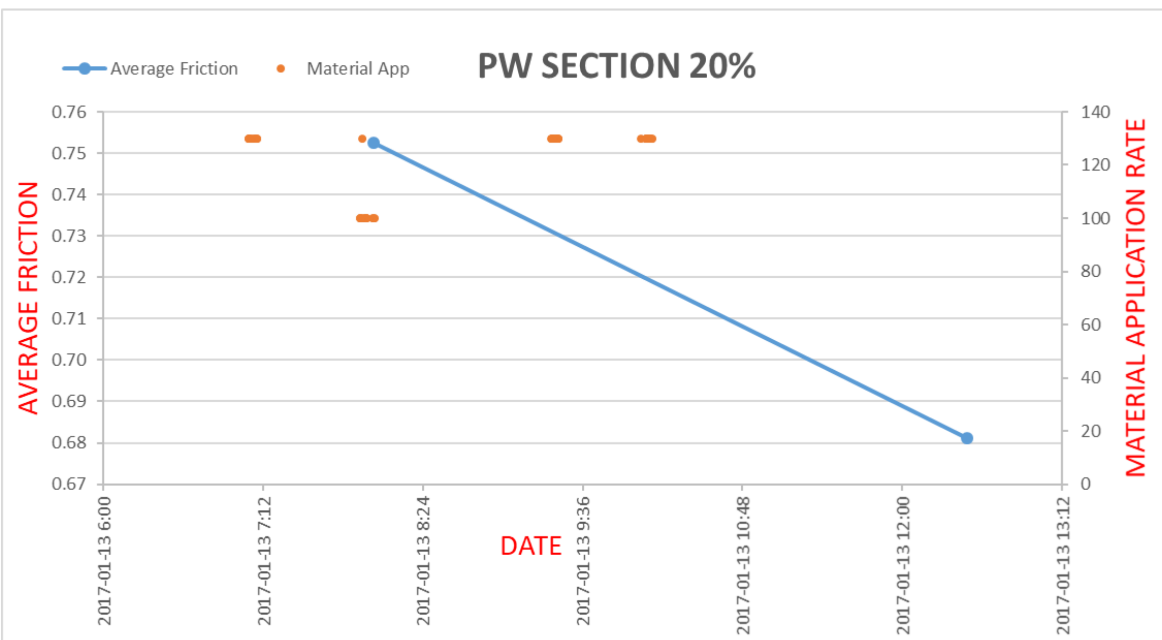

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
2017-01-12 12:14
2017-01-12 12:28
2017-01-12 12:43
2017-01-12 12:57
2017-01-12 13:12
2017-01-12 13:26
2017-01-12 13:40
2017-01-12 13:55
2017-01-12 14:09
2017-01-12 14:24
2017-01-12 14:38
2017-01-12 14:52
DATE

EVENT – 13

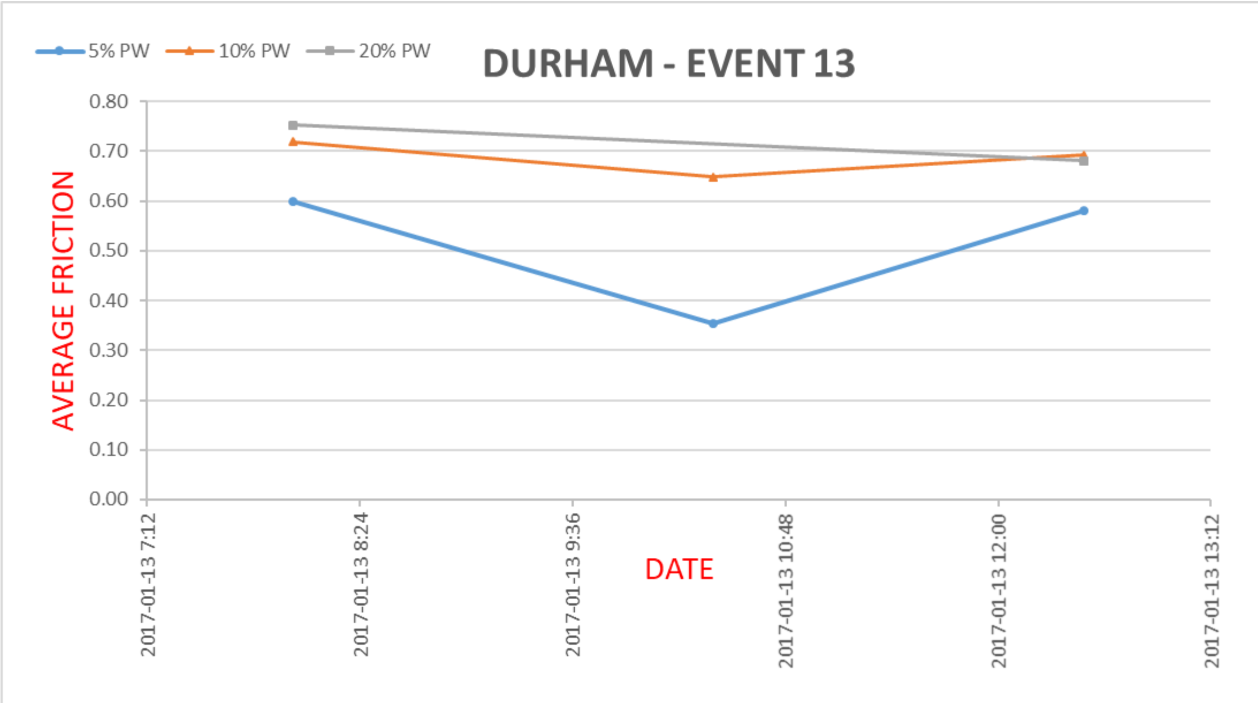

Avg Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
140
120
100
80
60
40
20
0
2017-01-13 6:00
2017-01-13 7:12
2017-01-13 8:24
2017-01-13 9:36
2017-01-13 10:48
2017-01-13 12:00
2017-01-13 13:12
2017-01-13 14:24
2017-01-13 15:36
2017-01-13 16:48
DATE



Average Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
0.73
0.72
0.71
0.70
0.69
0.68
0.67
0.66
0.65
0.64
MATERIAL APPLICATION RATE
300
250
200
150
100
50
0
2017-01-13 6:00
2017-01-13 7:12
2017-01-13 8:24
2017-01-13 9:36
2017-01-13 10:48
2017-01-13 12:00
2017-01-13 13:12
2017-01-13 14:24
2017-01-13 15:36
2017-01-13 16:48
DATE



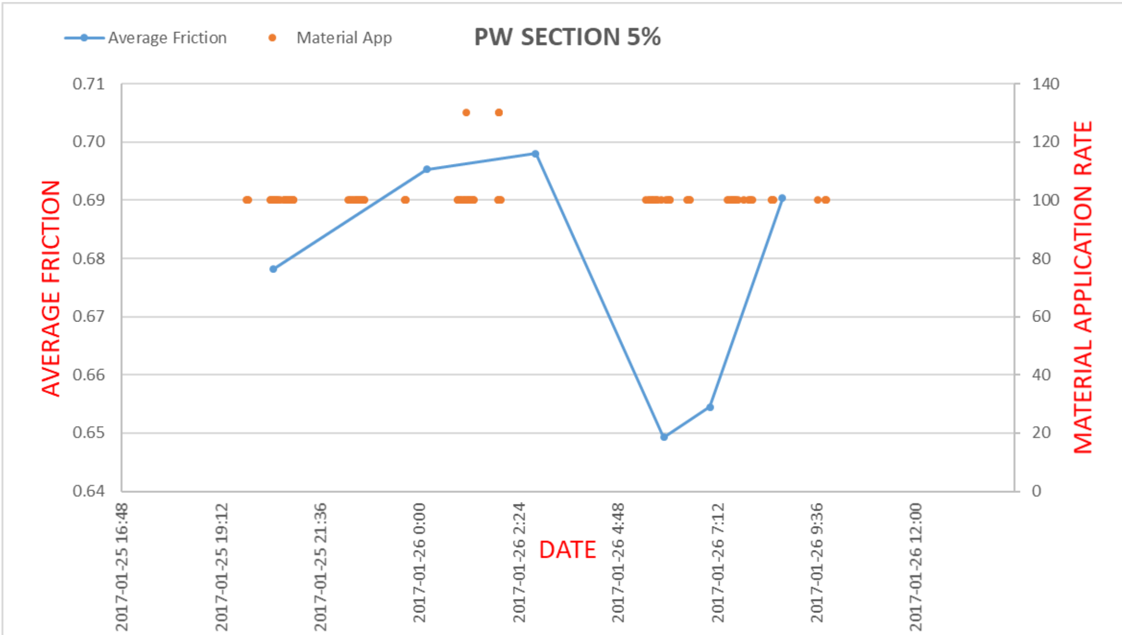
Average Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
0.76
0.75
0.74
0.73
0.72
0.71
0.70
0.69
0.68
0.67
MATERIAL APPLICATION RATE
140
120
100
80
60
40
20
0
2017-01-13 6:00
2017-01-13 7:12
2017-01-13 8:24
2017-01-13 9:36
2017-01-13 10:48
2017-01-13 12:00
2017-01-13 13:12
DATE

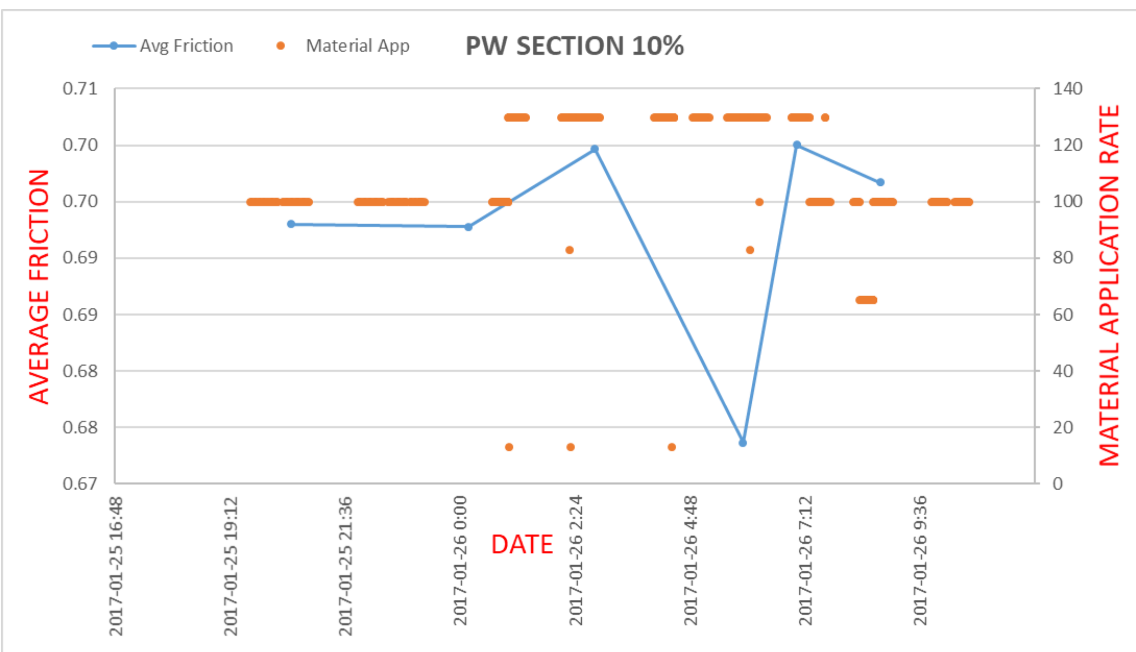


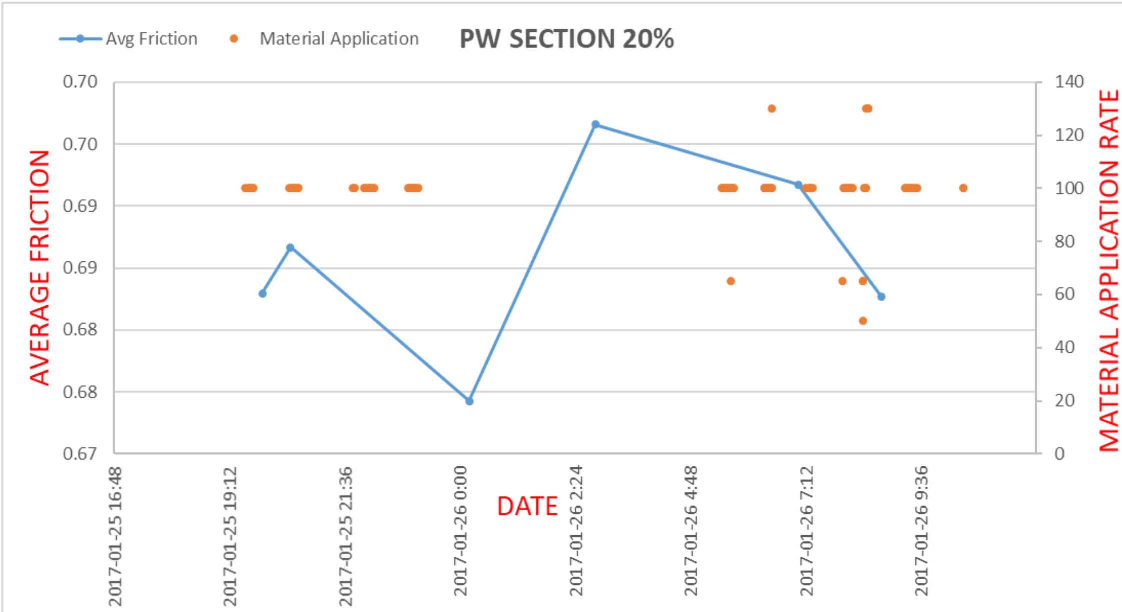
EVENT – 14

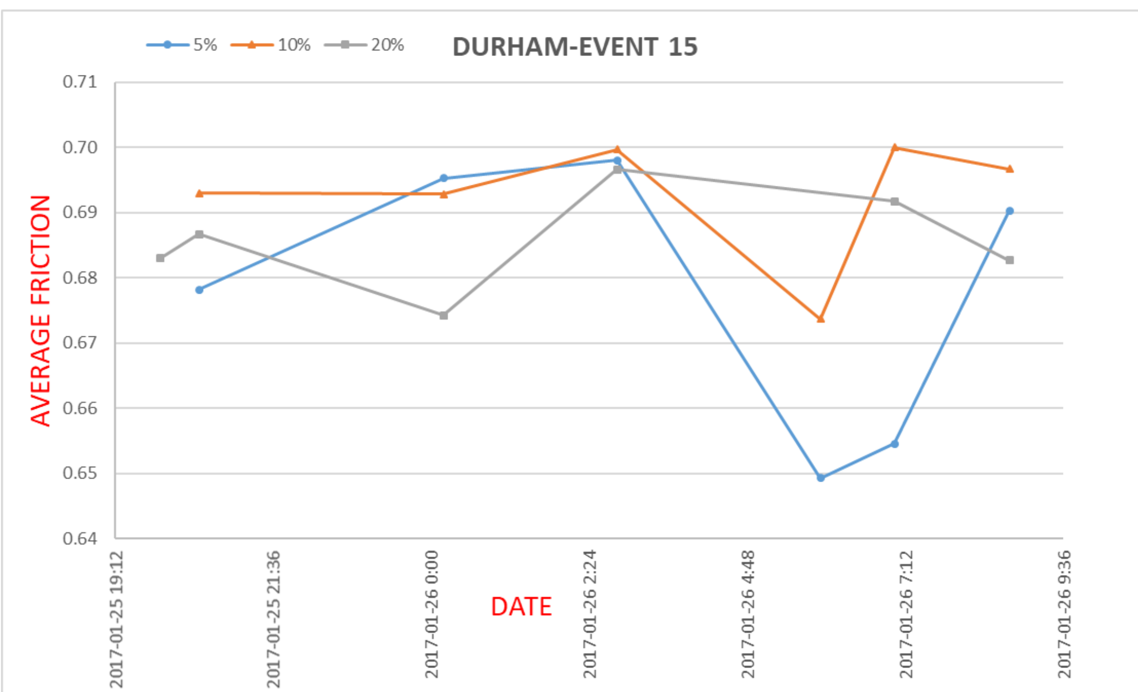
Friction data is not available for Event 14

EVENT – 15

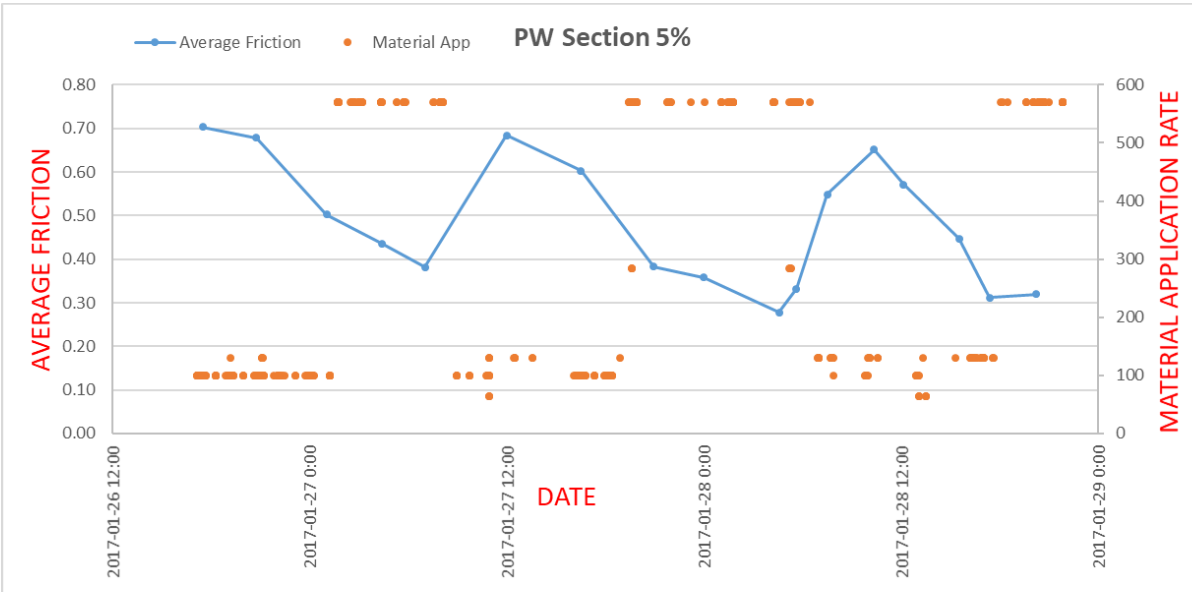

Average Friction
Material App
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.71
0.70
0.69
0.68
0.67
0.66
0.65
0.64
140
120
100
80
60
40
20
0
2017-01-25 16:48
2017-01-25 19:12
2017-01-25 21:36
2017-01-26 0:00
2017-01-26 2:24
2017-01-26 4:48
2017-01-26 7:12
2017-01-26 9:36
2017-01-26 12:00


Avg Friction
Material App
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.71
0.70
0.70
0.69
0.69
0.68
0.68
0.67
140
120
100
80
60
40
20
0
2017-01-25 16:48
2017-01-25 19:12
2017-01-25 21:36
2017-01-26 0:00
2017-01-26 2:24
2017-01-26 4:48
2017-01-26 7:12
2017-01-26 9:36

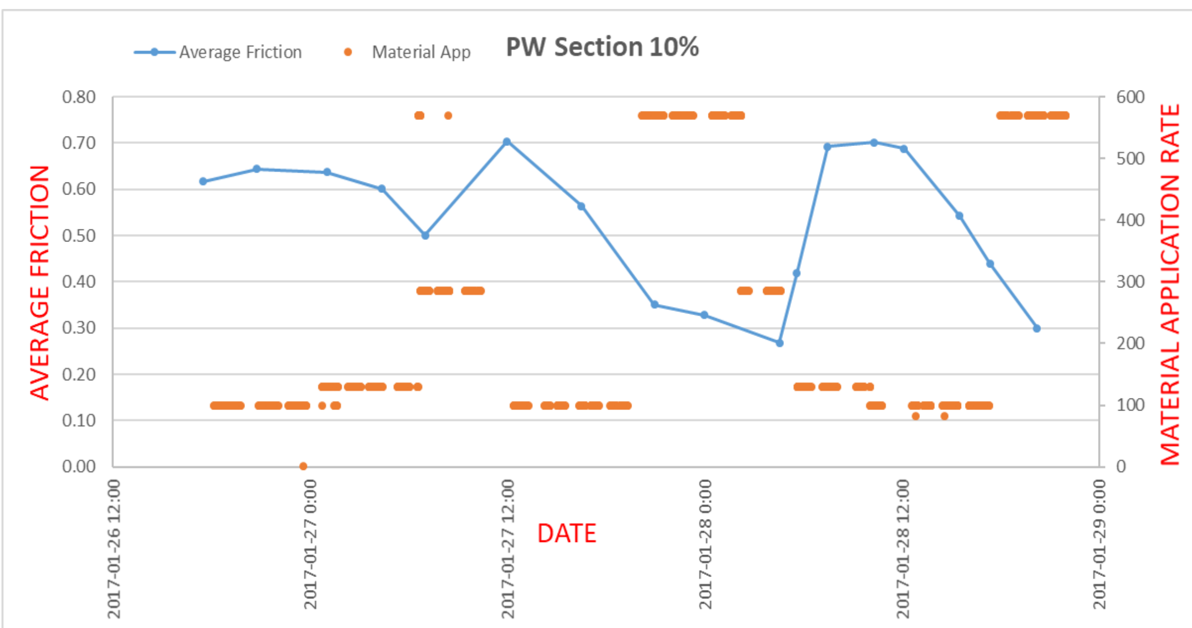

Avg Friction
Material Application
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.70
0.70
0.69
0.69
0.68
0.68
0.67
140
120
100
80
60
40
20
0
2017-01-25 16:48
2017-01-25 19:12
2017-01-25 21:36
2017-01-26 0:00
2017-01-26 2:24
2017-01-26 4:48
2017-01-26 7:12
2017-01-26 9:36
DATE


5%
10%
20%
DURHAM-EVENT 15
AVERAGE FRICTION
0.71
0.70
0.69
0.68
0.67
0.66
0.65
0.64
2017-01-25 19:12
2017-01-25 21:36
2017-01-26 0:00
2017-01-26 2:24
2017-01-26 4:48
2017-01-26 7:12
2017-01-26 9:36
DATE

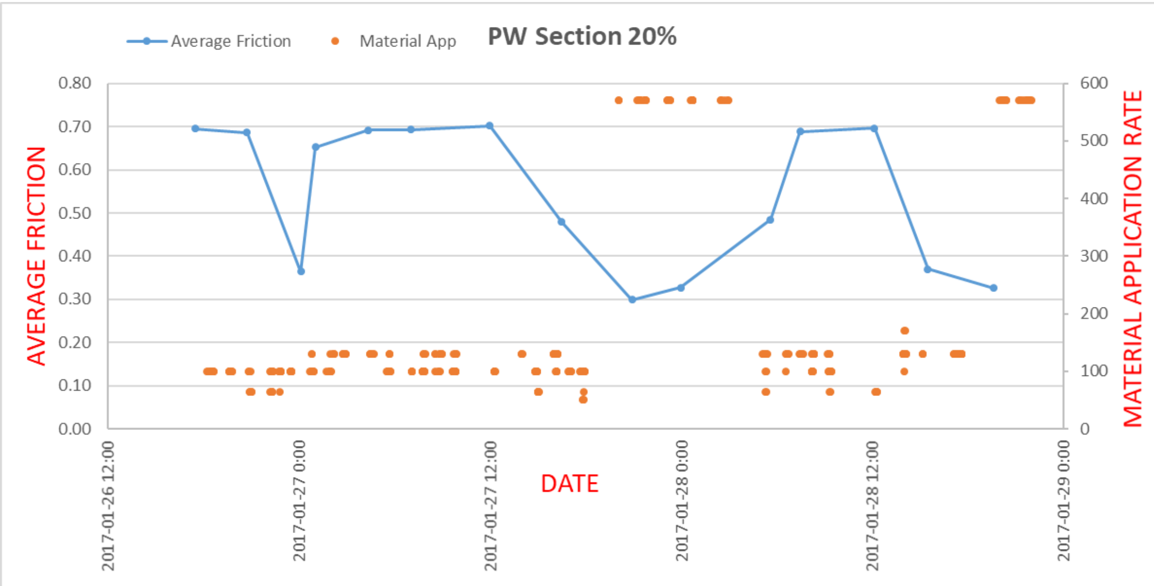
EVENT – 16

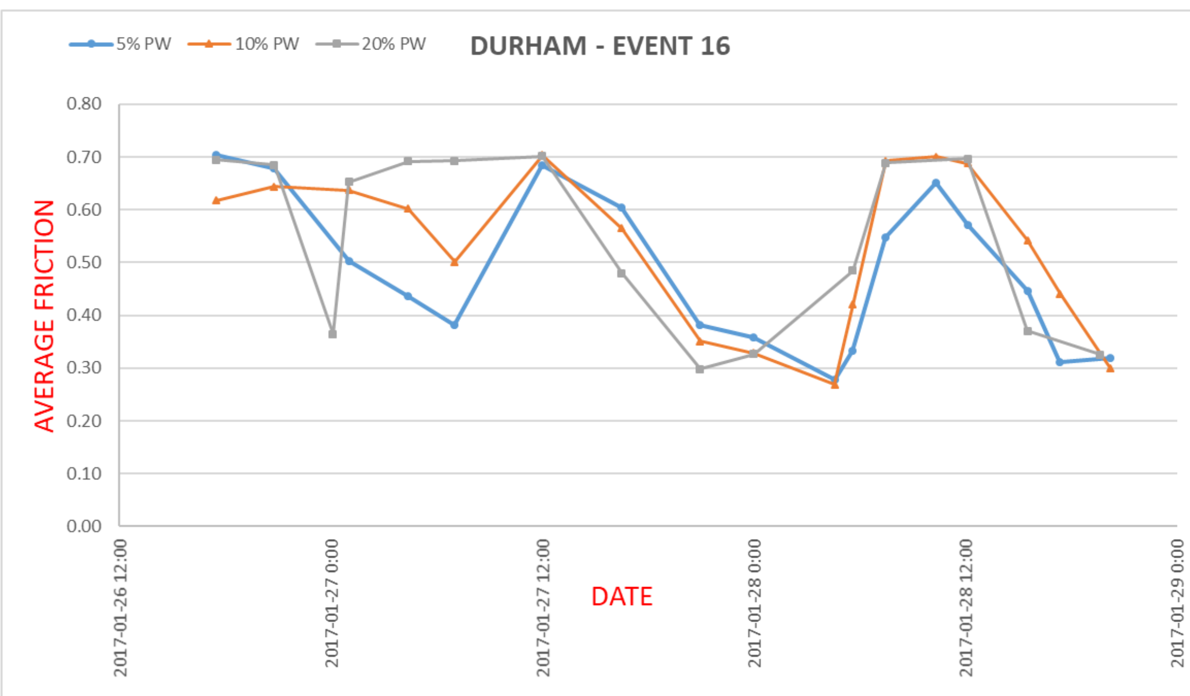


Average Friction
Material App
PW Section 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-26 12:00
2017-01-27 0:00
2017-01-27 12:00
2017-01-28 0:00
2017-01-28 12:00
2017-01-29 0:00
DATE



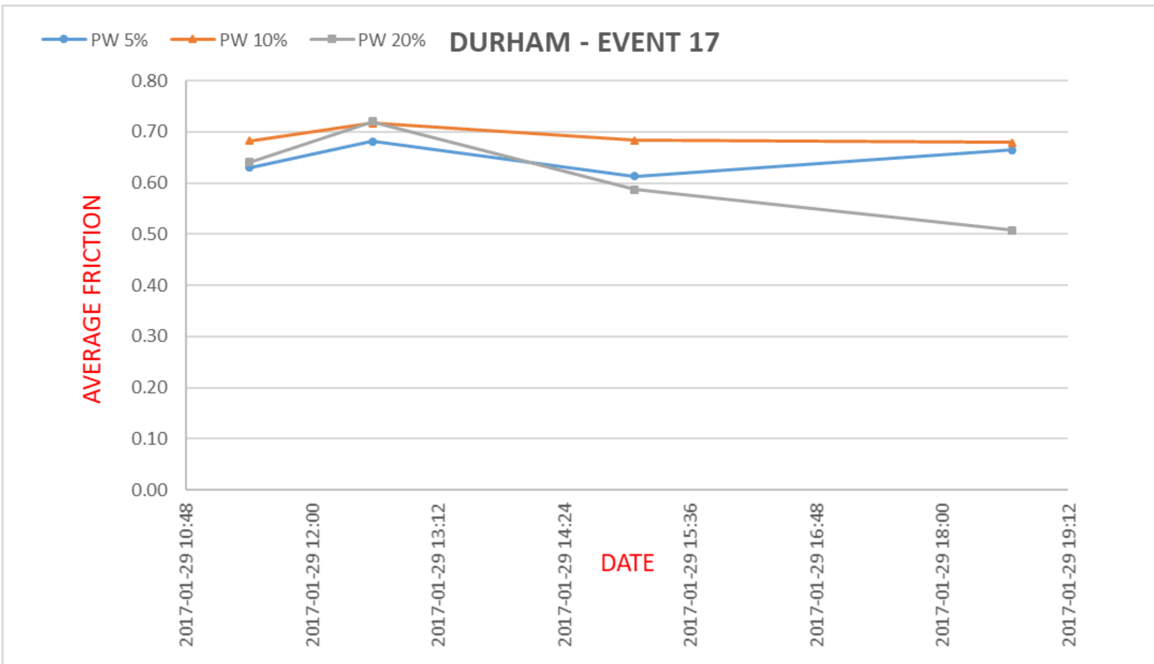
Average Friction
Material App
PW Section 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-26 12:00
2017-01-27 0:00
2017-01-27 12:00
2017-01-28 0:00
2017-01-28 12:00
2017-01-29 0:00
DATE


Average Friction
Material App
PW Section 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-26 12:00
2017-01-27 0:00
2017-01-27 12:00
2017-01-28 0:00
2017-01-28 12:00
2017-01-29 0:00


5% PW
10% PW
20% PW
DURHAM - EVENT 16
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-01-26 12:00
2017-01-27 0:00
2017-01-27 12:00
2017-01-28 0:00
2017-01-28 12:00
2017-01-29 0:00

EVENT – 17

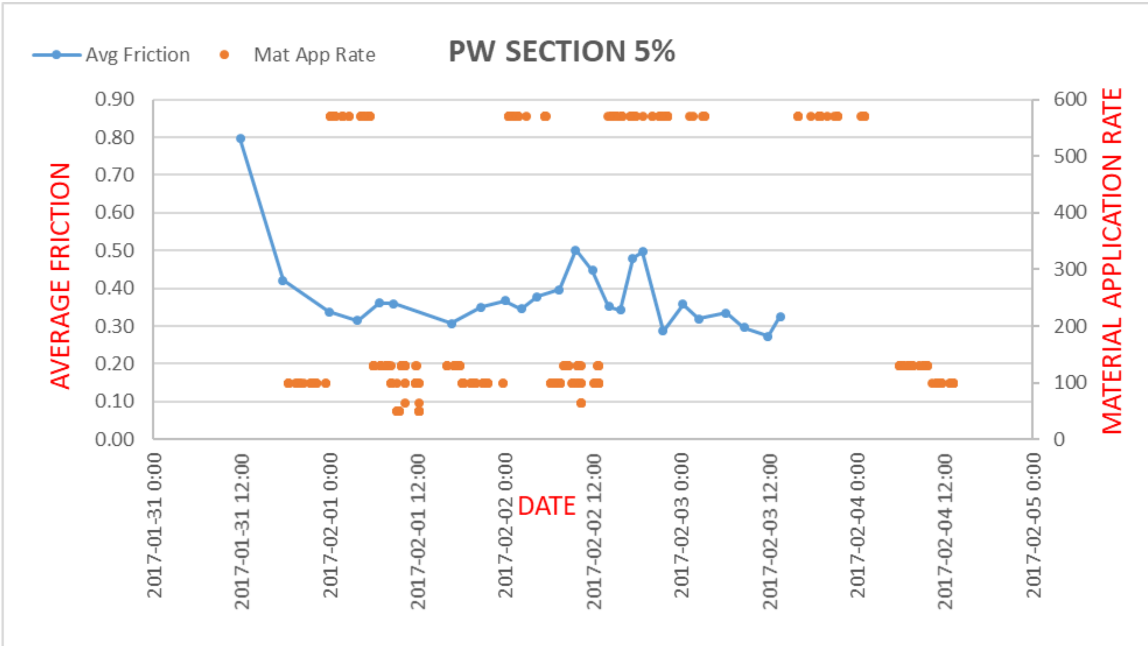
Material data was not available for Event 17.

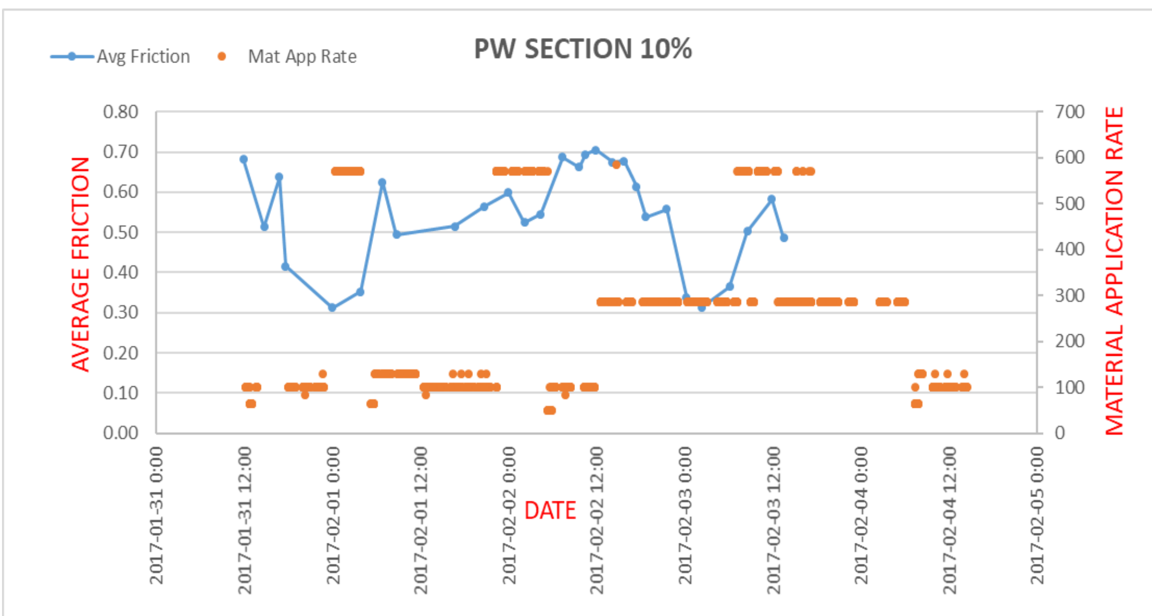


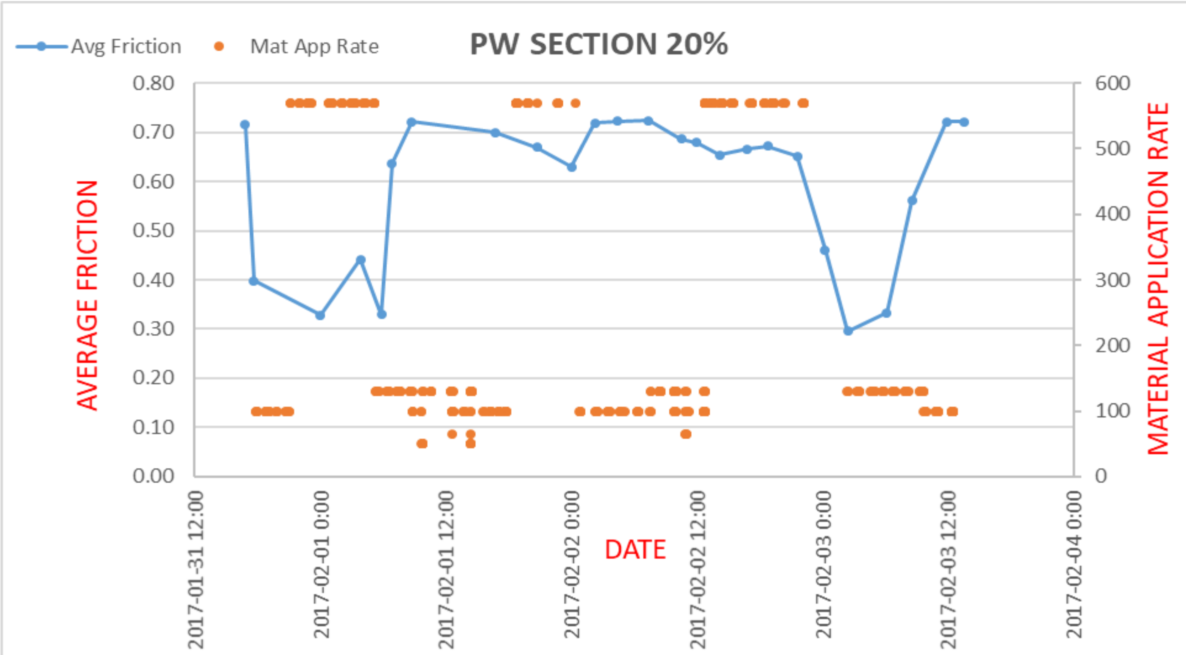
EVENT – 18

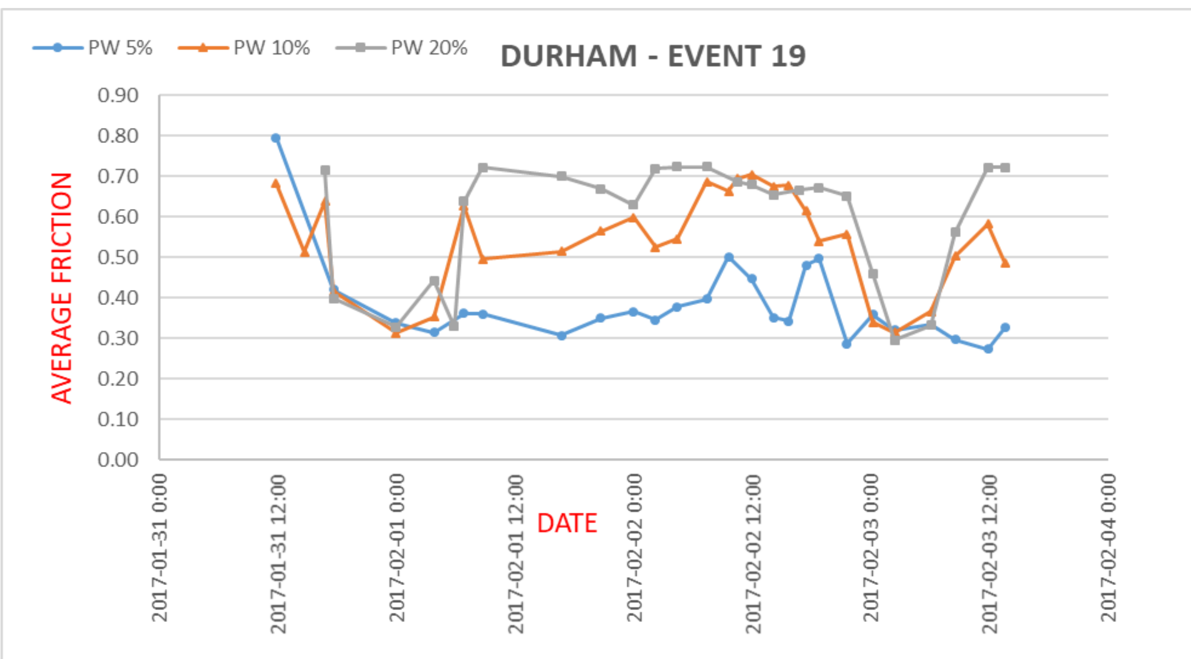
Friction data was not available for Event 18

EVENT – 19

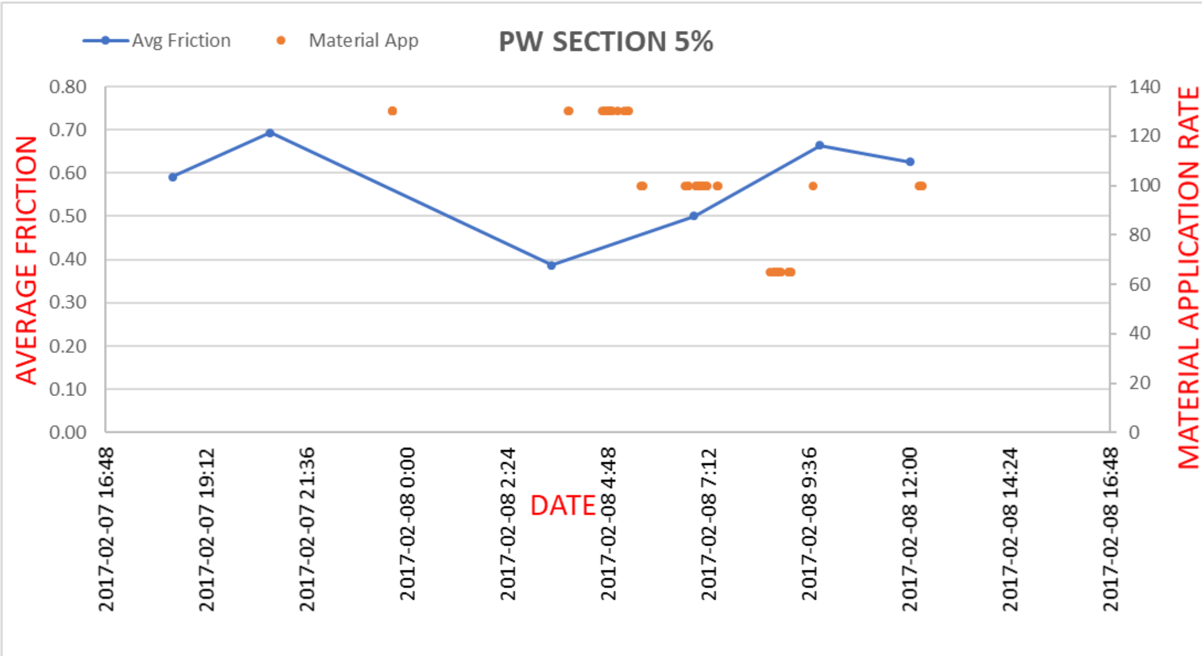

PW SECTION 5%
Avg Friction
Mat App Rate
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-31 0:00
2017-01-31 12:00
2017-02-01 0:00
2017-02-01 12:00
2017-02-02 0:00
2017-02-02 12:00
2017-02-03 0:00
2017-02-03 12:00
2017-02-04 0:00
2017-02-04 12:00
2017-02-05 0:00

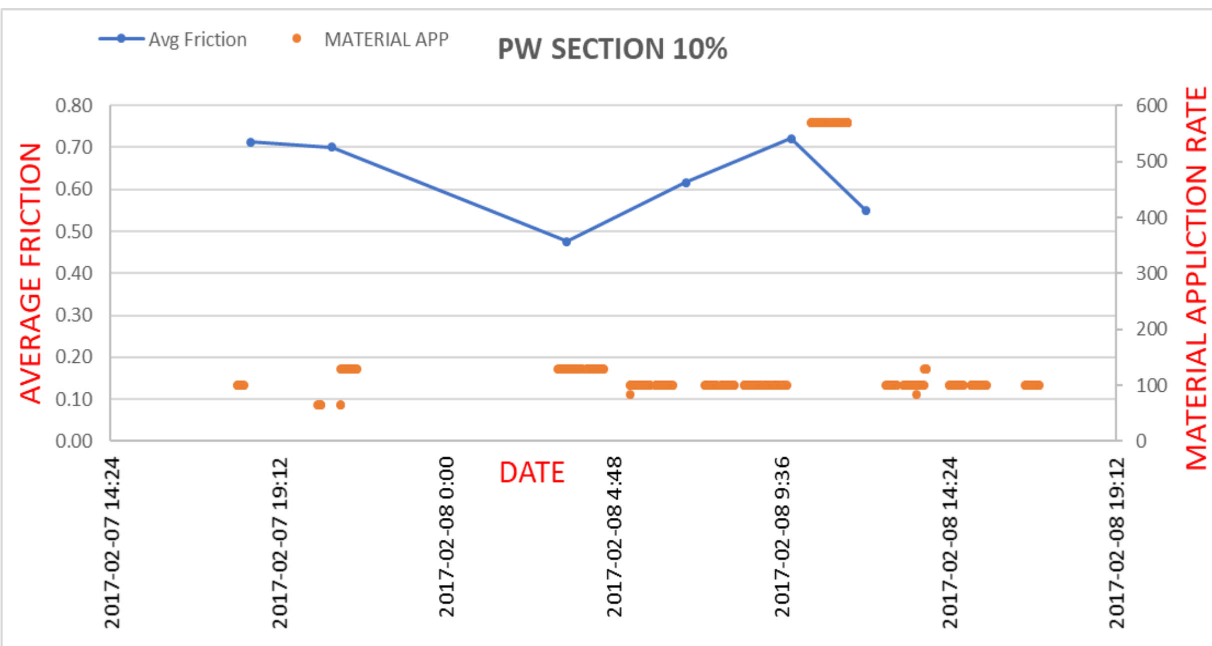

PW SECTION 10%
Avg Friction
Mat App Rate
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
700
600
500
400
300
200
100
0
2017-01-31 0:00
2017-01-31 12:00
2017-02-01 0:00
2017-02-01 12:00
2017-02-02 0:00
2017-02-02 12:00
2017-02-03 0:00
2017-02-03 12:00
2017-02-04 0:00
2017-02-04 12:00
2017-02-05 0:00

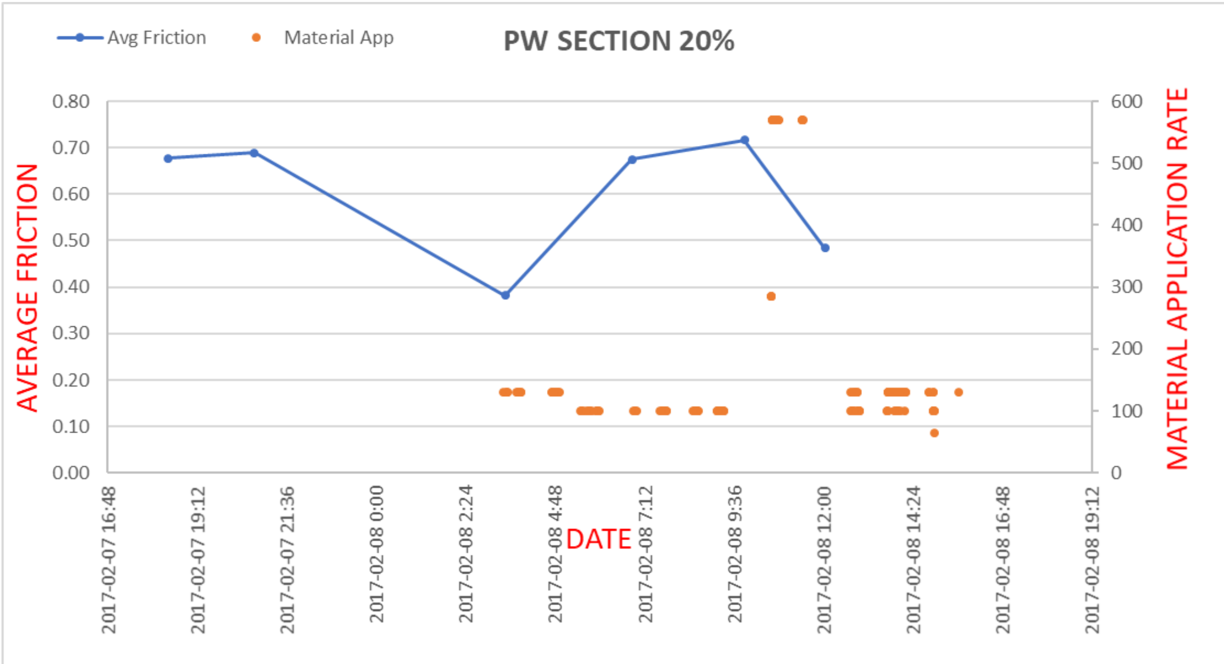

Avg Friction
Mat App Rate
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-01-31 12:00
2017-02-01 0:00
2017-02-01 12:00
2017-02-02 0:00
2017-02-02 12:00
2017-02-03 0:00
2017-02-03 12:00
2017-02-04 0:00
DATE

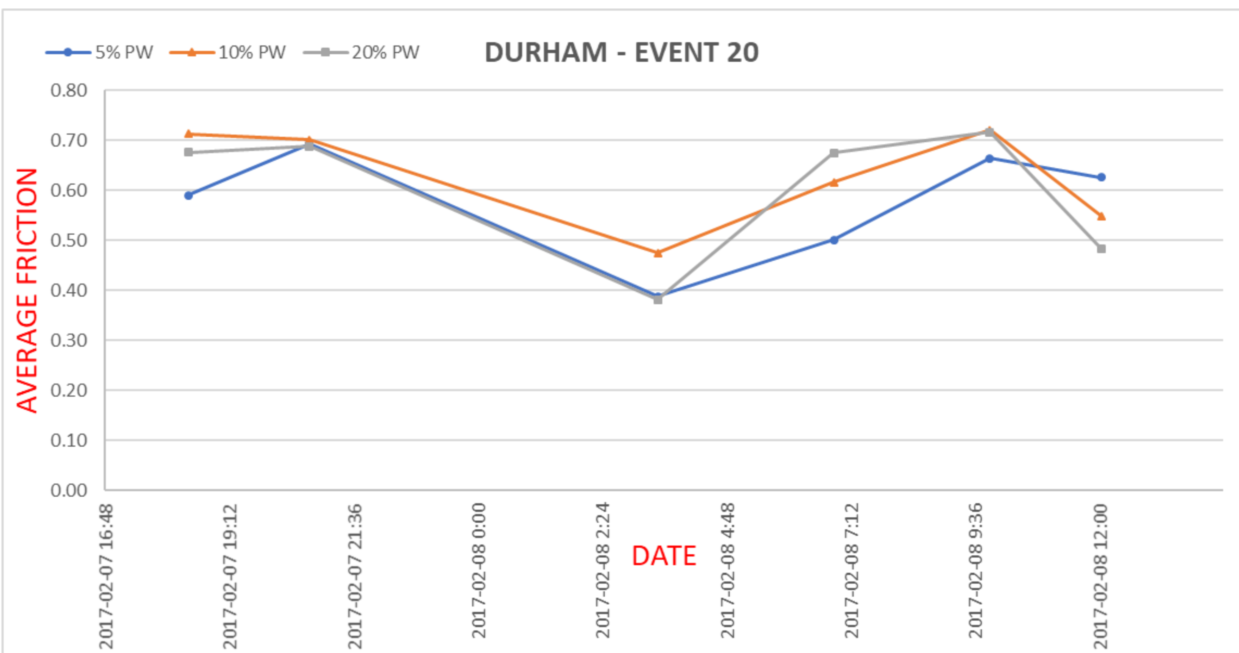

PW 5%
PW 10%
PW 20%
DURHAM - EVENT 19
AVERAGE FRICTION
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-01-31 0:00
2017-01-31 12:00
2017-02-01 0:00
2017-02-01 12:00
2017-02-02 0:00
2017-02-02 12:00
2017-02-03 0:00
2017-02-03 12:00
2017-02-04 0:00
DATE

EVENT – 20

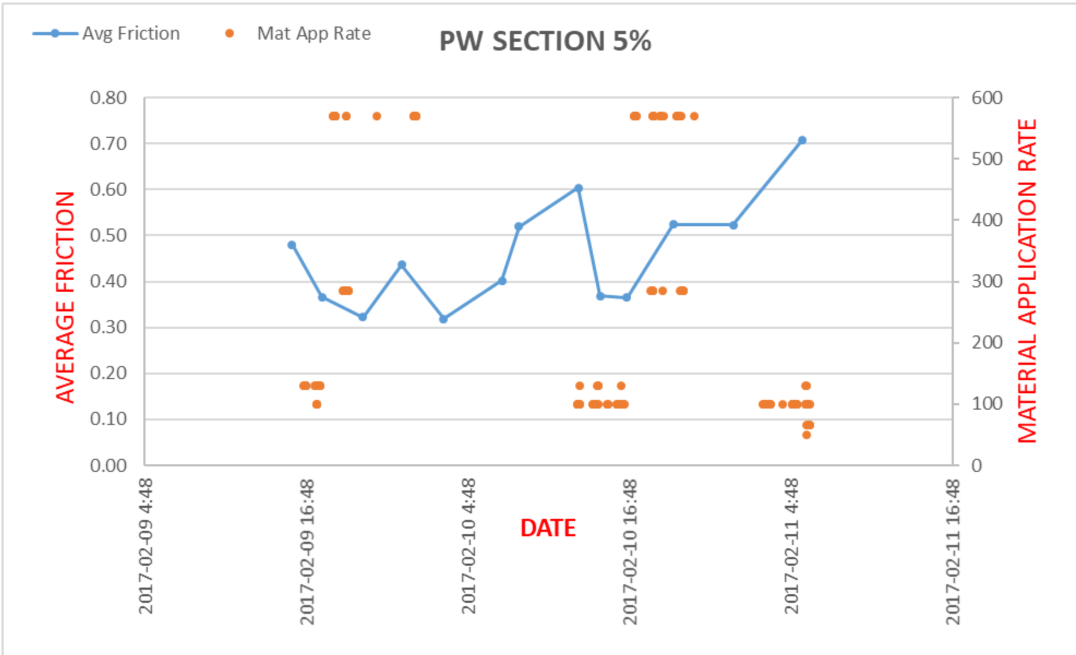

Avg Friction
Material App
PW SECTION 5%
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
AVERAGE FRICTION
140
120
100
80
60
40
20
0
MATERIAL APPLICATION RATE
2017-02-07 16:48
2017-02-07 19:12
2017-02-07 21:36
2017-02-08 0:00
2017-02-08 2:24
2017-02-08 4:48
2017-02-08 7:12
2017-02-08 9:36
2017-02-08 12:00
2017-02-08 14:24
2017-02-08 16:48
DATE

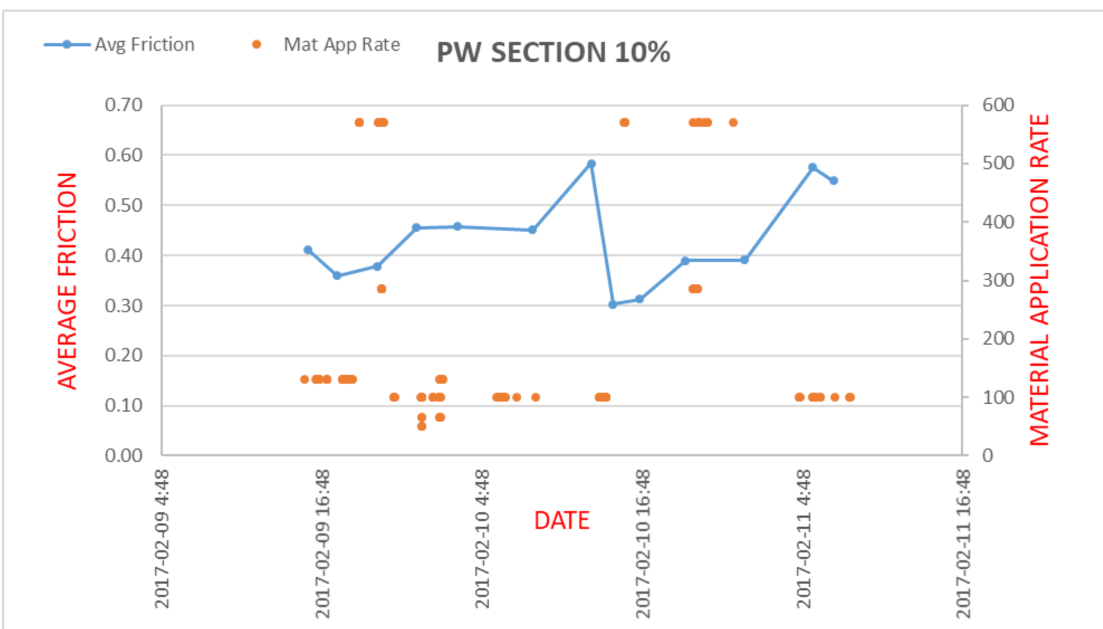

Avg Friction
MATERIAL APP
PW SECTION 10%
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
AVERAGE FRICTION
600
500
400
300
200
100
0
MATERIAL APPLICTION RATE
2017-02-07 14:24
2017-02-07 19:12
2017-02-08 0:00
2017-02-08 4:48
2017-02-08 9:36
2017-02-08 14:24
2017-02-08 19:12
DATE

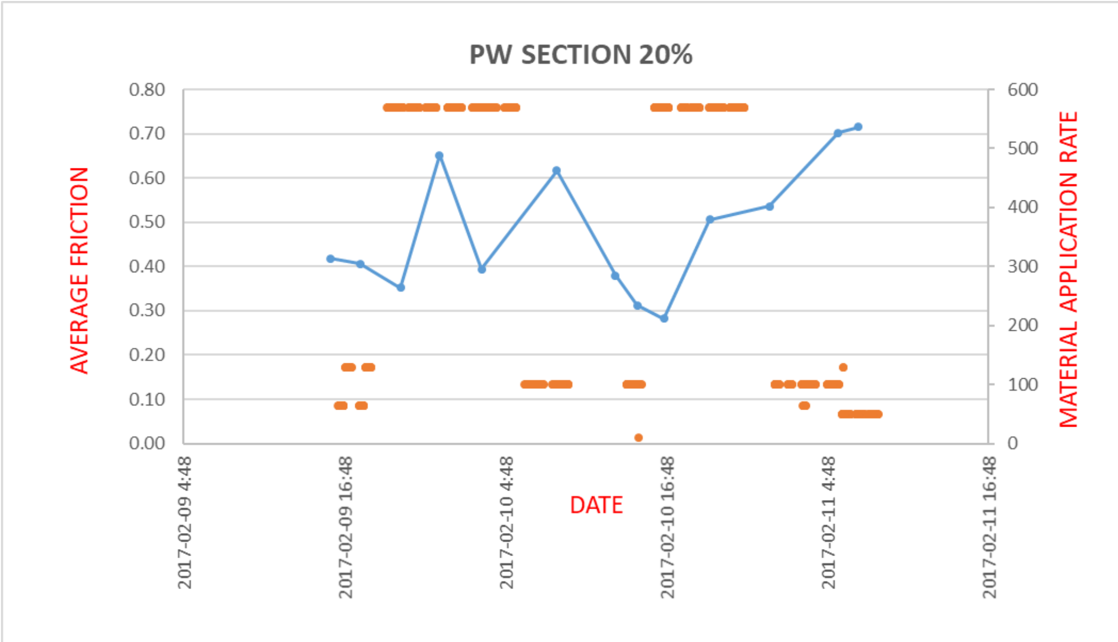

Avg Friction
Material App
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-02-07 16:48
2017-02-07 19:12
2017-02-07 21:36
2017-02-08 0:00
2017-02-08 2:24
2017-02-08 4:48
2017-02-08 7:12
2017-02-08 9:36
2017-02-08 12:00
2017-02-08 14:24
2017-02-08 16:48
2017-02-08 19:12

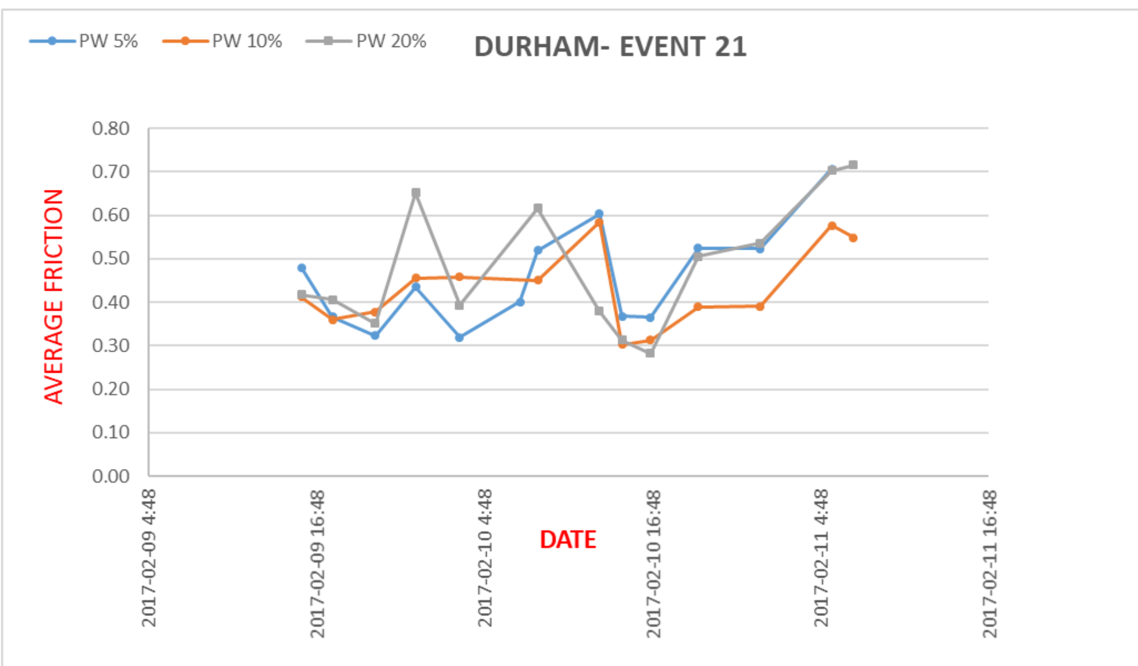

5% PW
10% PW
20% PW
DURHAM - EVENT 20
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-02-07 16:48
2017-02-07 19:12
2017-02-07 21:36
2017-02-08 0:00
2017-02-08 2:24
2017-02-08 4:48
2017-02-08 7:12
2017-02-08 9:36
2017-02-08 12:00

EVENT – 21

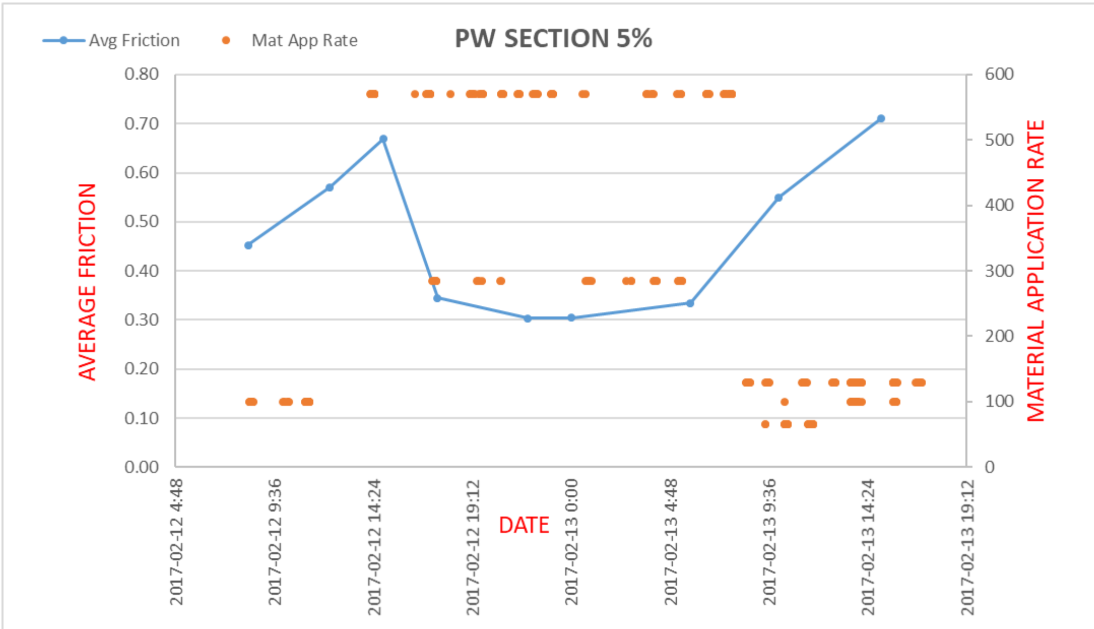

Avg Friction
Mat App Rate
PW SECTION 5%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
MATERIAL APPLICATION RATE
2017-02-09 4:48
2017-02-09 16:48
2017-02-10 4:48
2017-02-10 16:48
2017-02-11 4:48
2017-02-11 16:48
DATE


Avg Friction
Mat App Rate
PW SECTION 10%
AVERAGE FRICTION
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
MATERIAL APPLICATION RATE
2017-02-09 4:48
2017-02-09 16:48
2017-02-10 4:48
2017-02-10 16:48
2017-02-11 4:48
2017-02-11 16:48
DATE

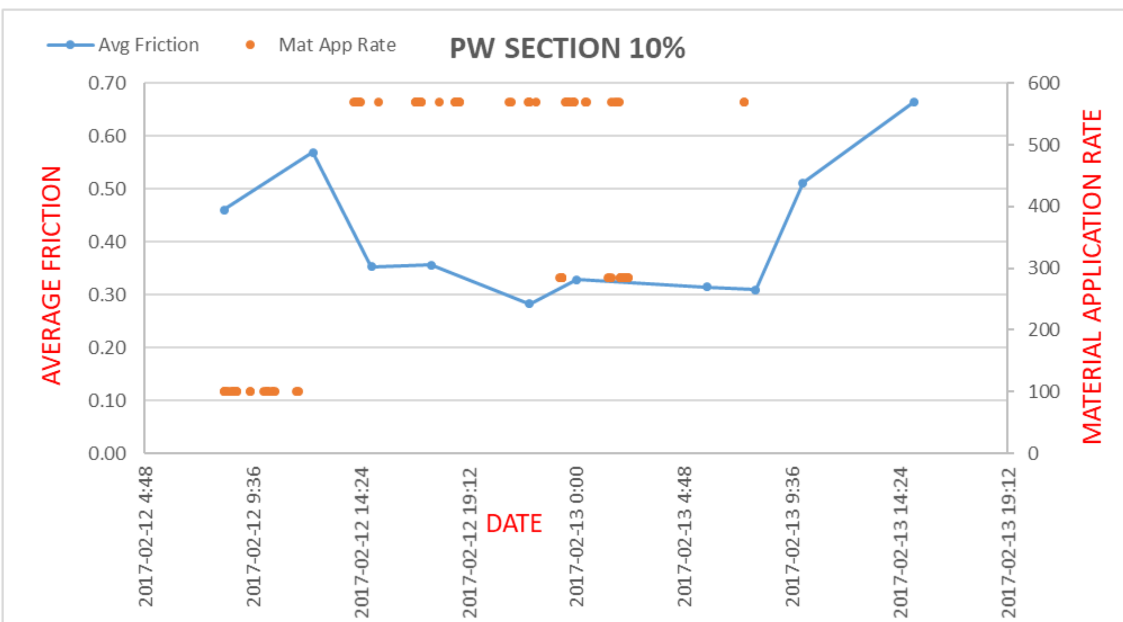

PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-02-09 4:48
2017-02-09 16:48
2017-02-10 4:48
2017-02-10 16:48
2017-02-11 4:48
2017-02-11 16:48


PW 5%
PW 10%
PW 20%
DURHAM- EVENT 21
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-02-09 4:48
2017-02-09 16:48
2017-02-10 4:48
2017-02-10 16:48
2017-02-11 4:48
2017-02-11 16:48

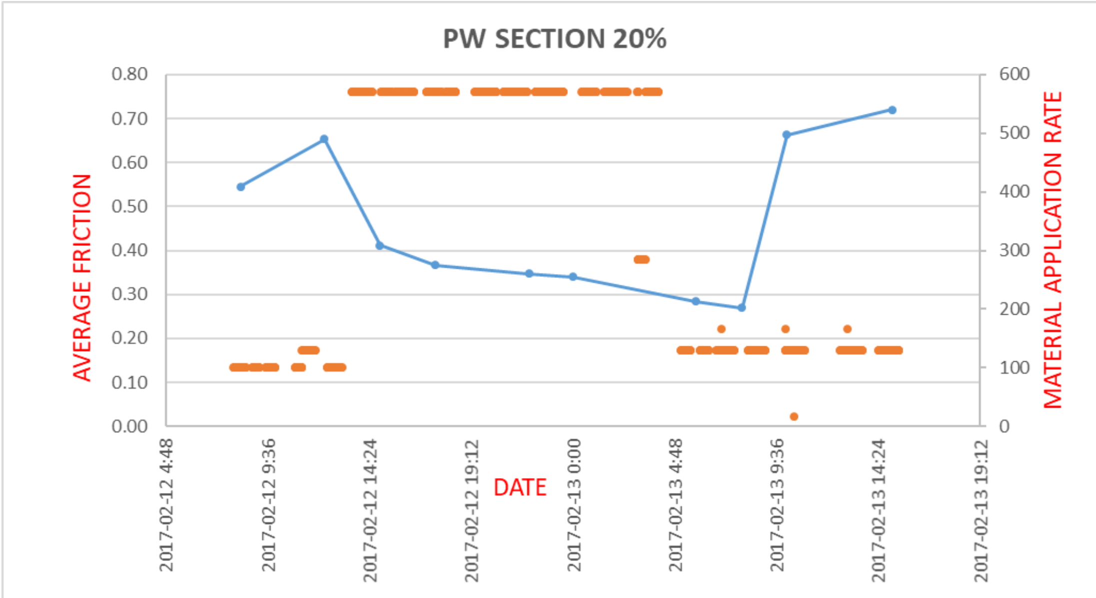
EVENT – 22

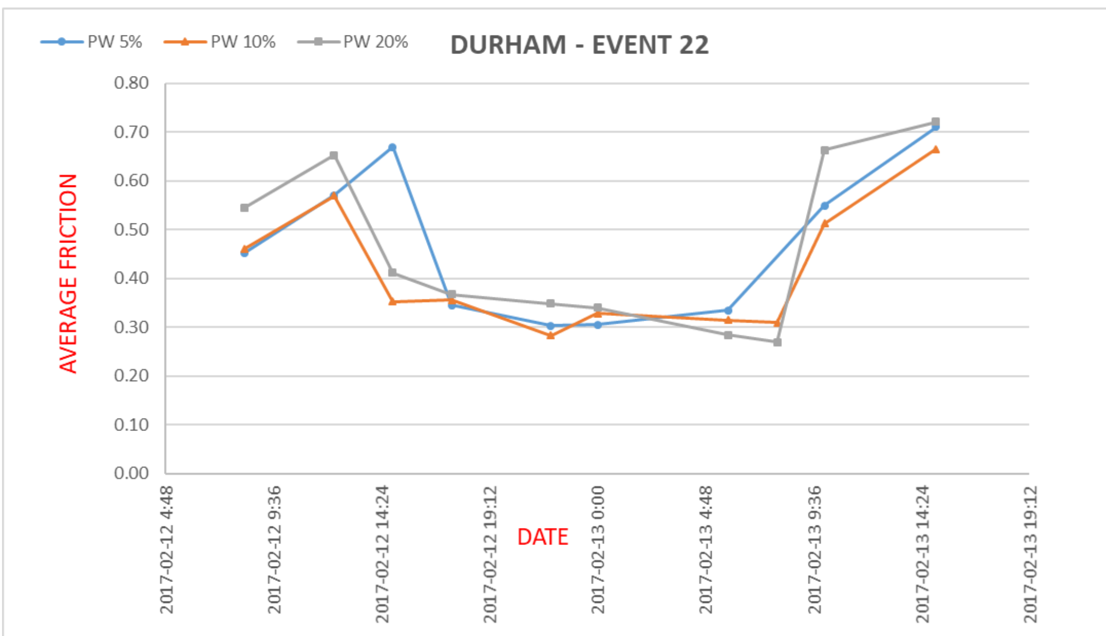


Avg Friction
Mat App Rate
PW SECTION 5%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-02-12 4:48
2017-02-12 9:36
2017-02-12 14:24
2017-02-12 19:12
2017-02-13 0:00
2017-02-13 4:48
2017-02-13 9:36
2017-02-13 14:24
2017-02-13 19:12



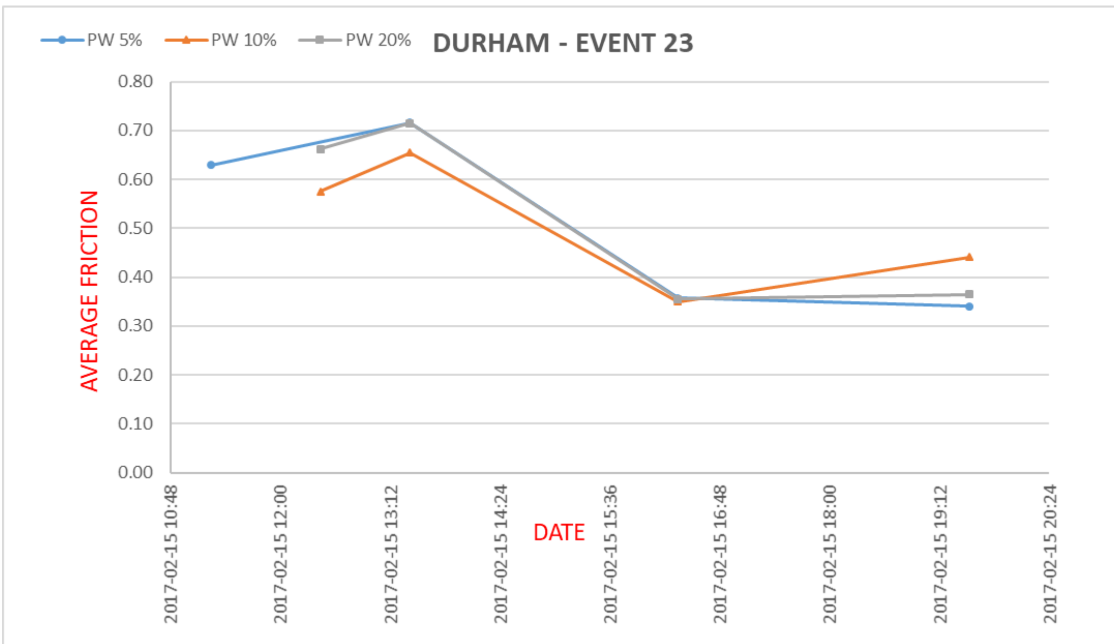
Avg Friction
Mat App Rate
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-02-12 4:48
2017-02-12 9:36
2017-02-12 14:24
2017-02-12 19:12
2017-02-13 0:00
2017-02-13 4:48
2017-02-13 9:36
2017-02-13 14:24
2017-02-13 19:12


PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-02-12 4:48
2017-02-12 9:36
2017-02-12 14:24
2017-02-12 19:12
2017-02-13 0:00
2017-02-13 4:48
2017-02-13 9:36
2017-02-13 14:24
2017-02-13 19:12

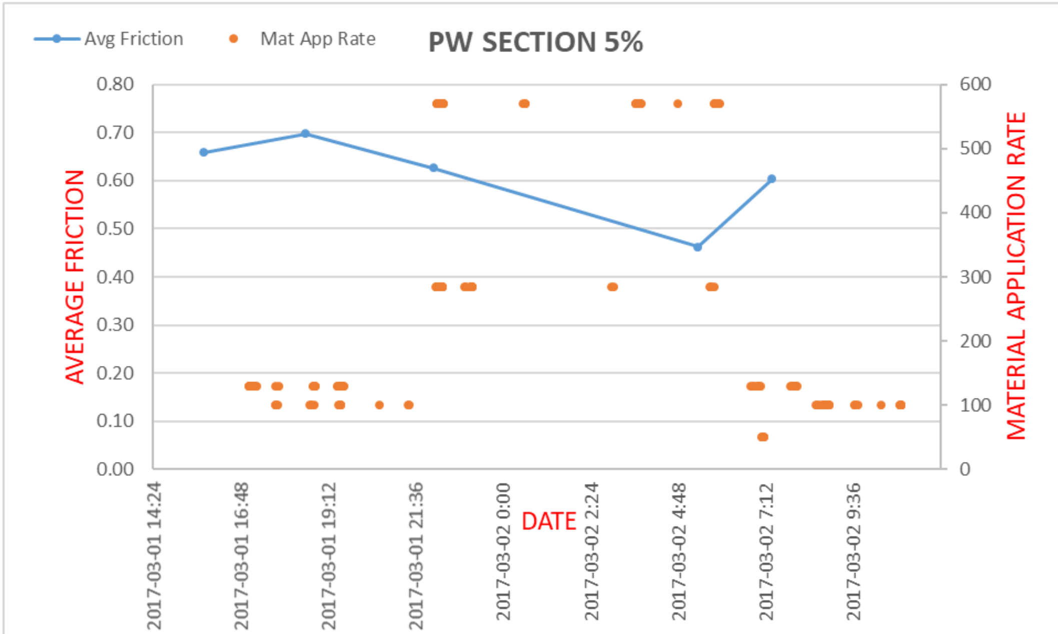

PW 5%
PW 10%
PW 20%
DURHAM - EVENT 22
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-02-12 4:48
2017-02-12 9:36
2017-02-12 14:24
2017-02-12 19:12
2017-02-13 0:00
2017-02-13 4:48
2017-02-13 9:36
2017-02-13 14:24
2017-02-13 19:12

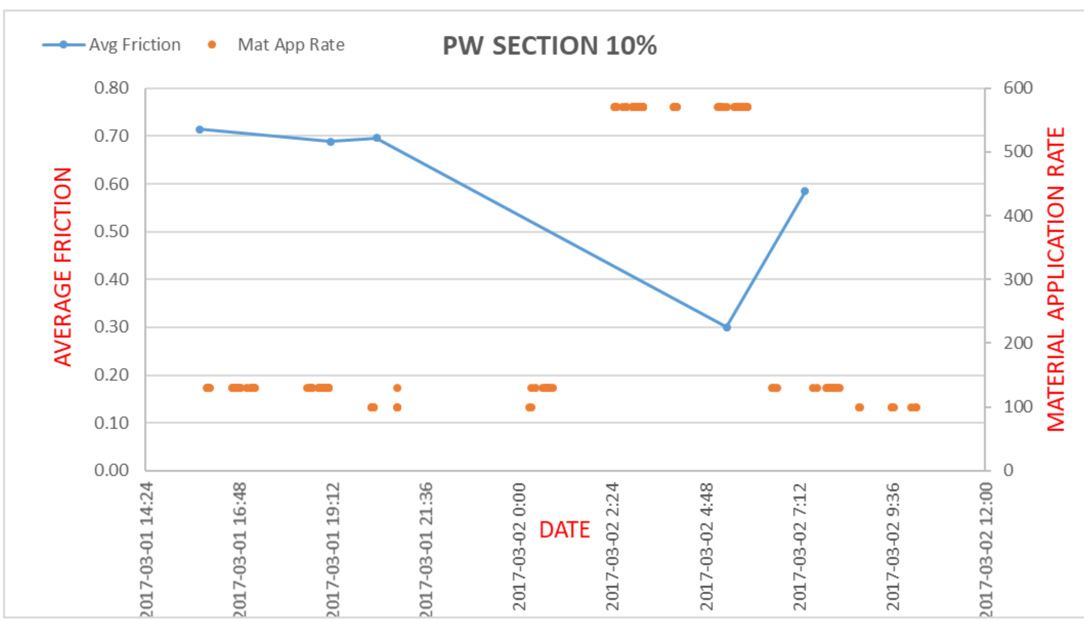
EVENT – 23

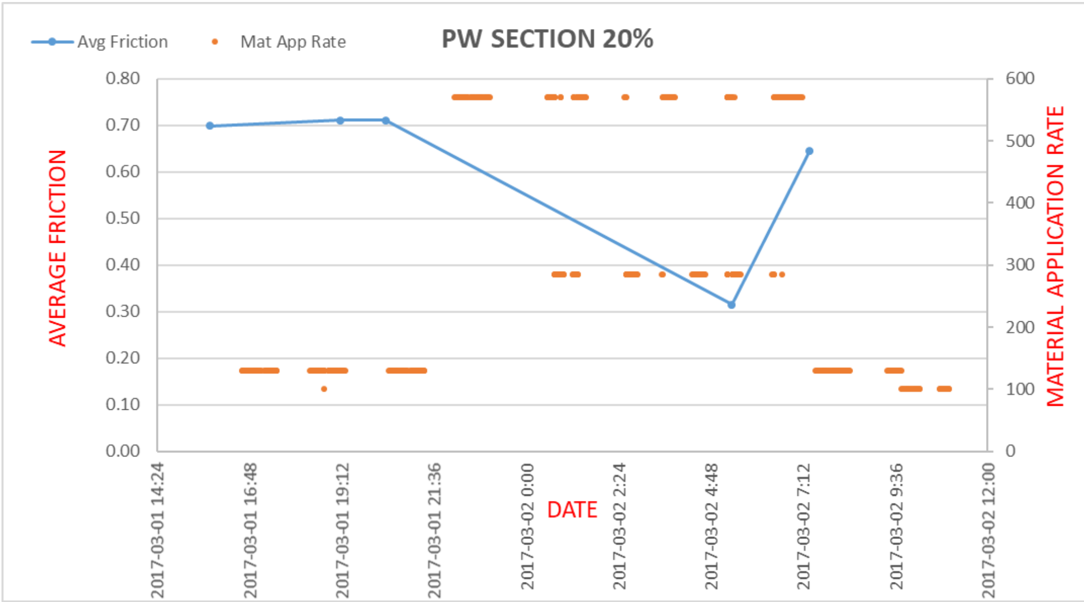
Material data was not available for Event 23



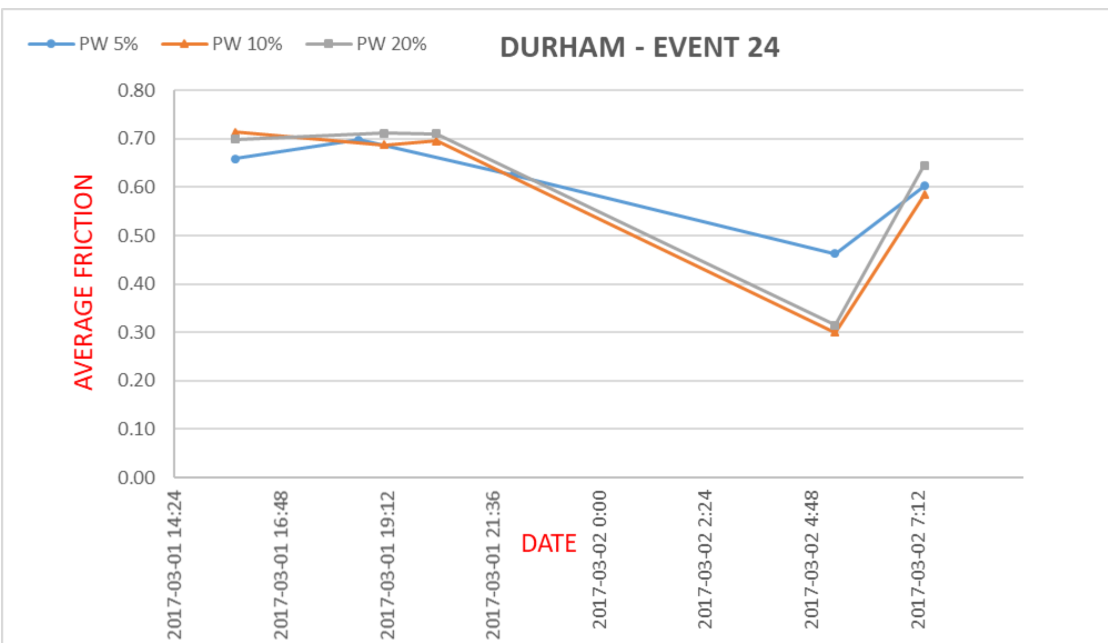
EVENT – 24


Avg Friction
Mat App Rate
PW SECTION 5%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
MATERIAL APPLICATION RATE
2017-03-01 14:24
2017-03-01 16:48
2017-03-01 19:12
2017-03-01 21:36
2017-03-02 0:00
2017-03-02 2:24
2017-03-02 4:48
2017-03-02 7:12
2017-03-02 9:36
DATE


Avg Friction
Mat App Rate
PW SECTION 10%
AVERAGE FRICTION
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
MATERIAL APPLICATION RATE
2017-03-01 14:24
2017-03-01 16:48
2017-03-01 19:12
2017-03-01 21:36
2017-03-02 0:00
2017-03-02 2:24
2017-03-02 4:48
2017-03-02 7:12
2017-03-02 9:36
2017-03-02 12:00
DATE

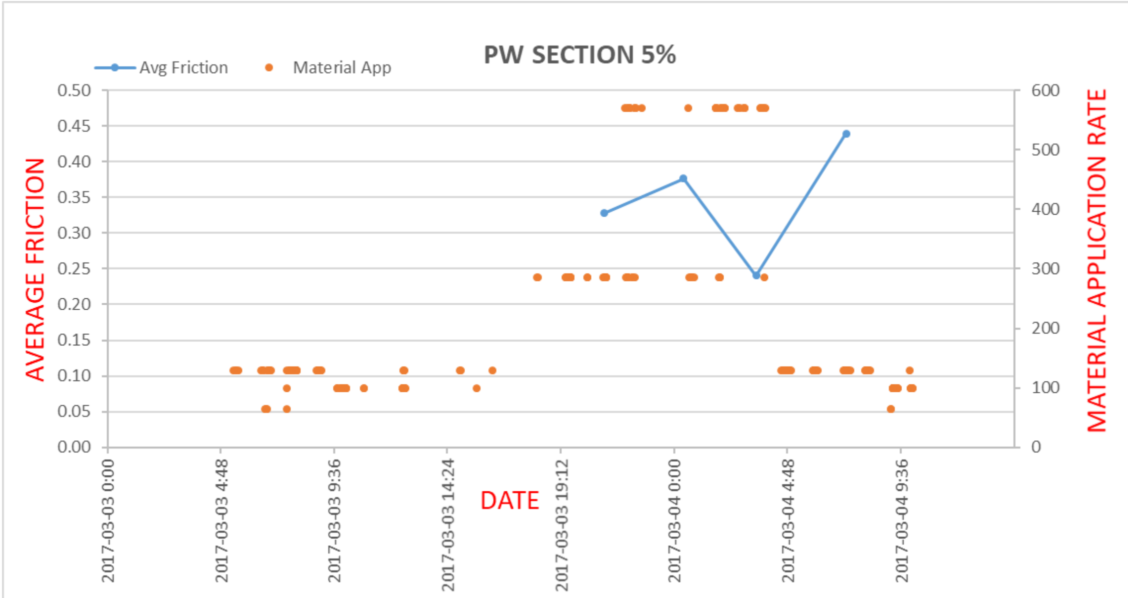


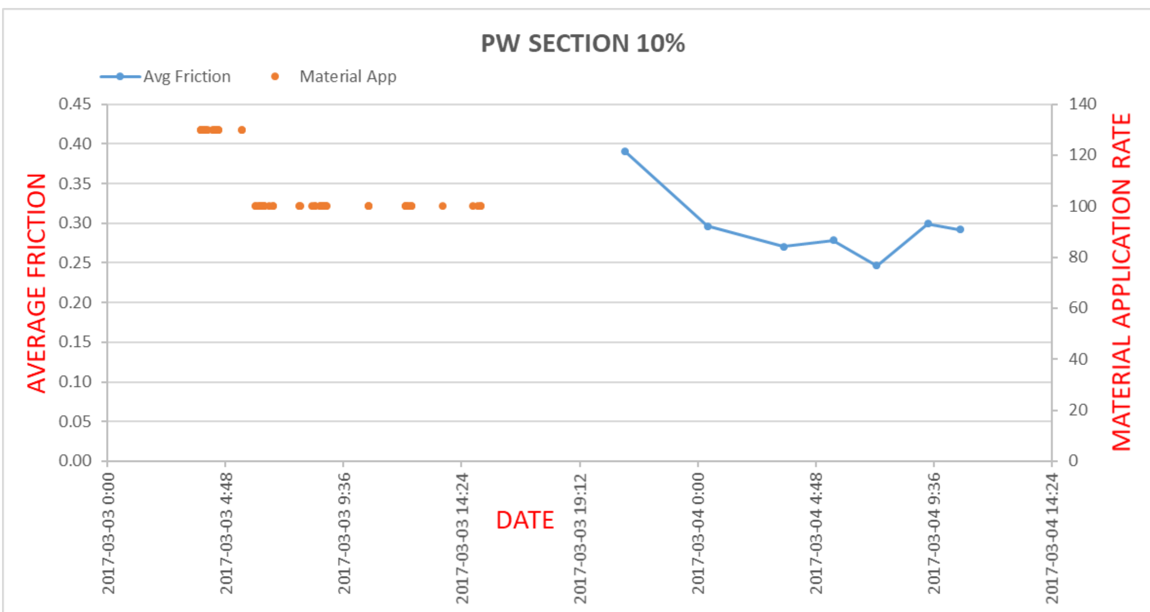
Avg Friction
Mat App Rate
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-01 14:24
2017-03-01 16:48
2017-03-01 19:12
2017-03-01 21:36
2017-03-02 0:00
2017-03-02 2:24
2017-03-02 4:48
2017-03-02 7:12
2017-03-02 9:36
2017-03-02 12:00

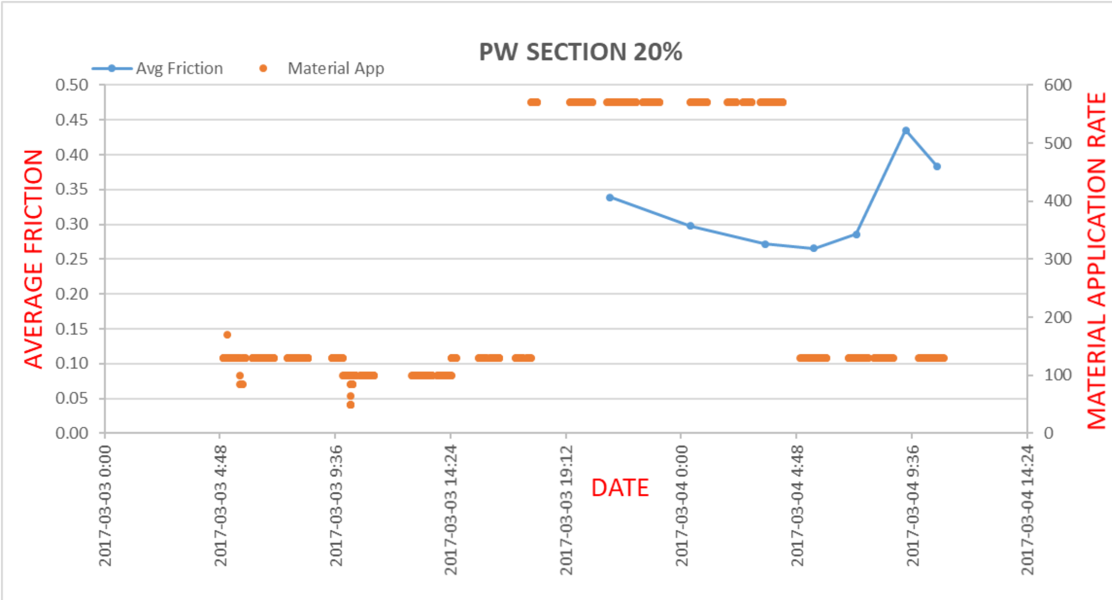


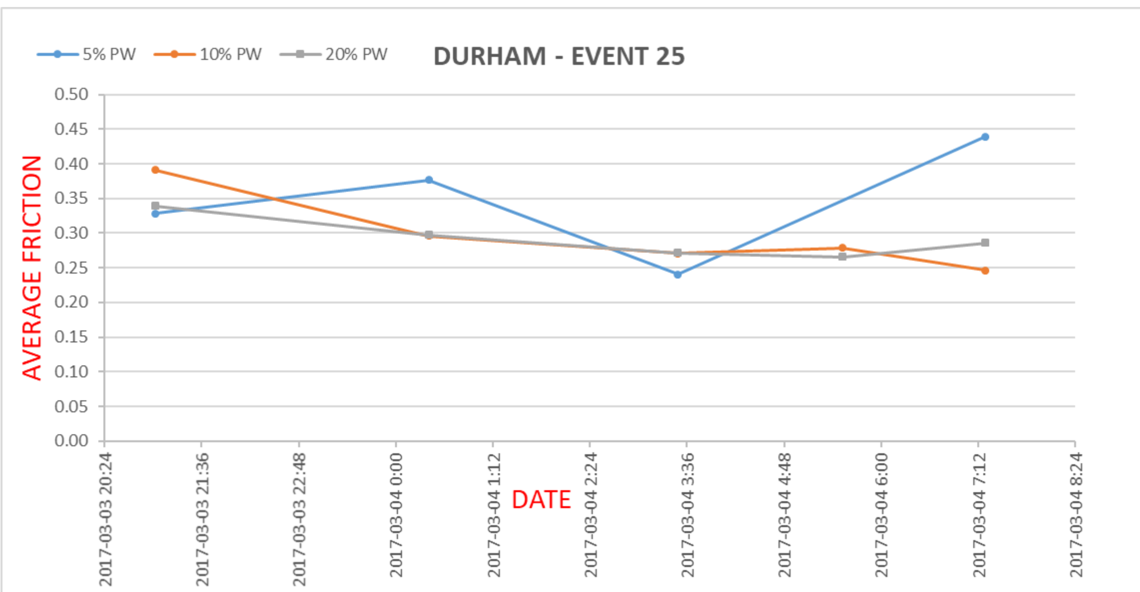
PW 5%
PW 10%
PW 20%
DURHAM - EVENT 24
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-03-01 14:24
2017-03-01 16:48
2017-03-01 19:12
2017-03-01 21:36
2017-03-02 0:00
2017-03-02 2:24
2017-03-02 4:48
2017-03-02 7:12

EVENT – 25

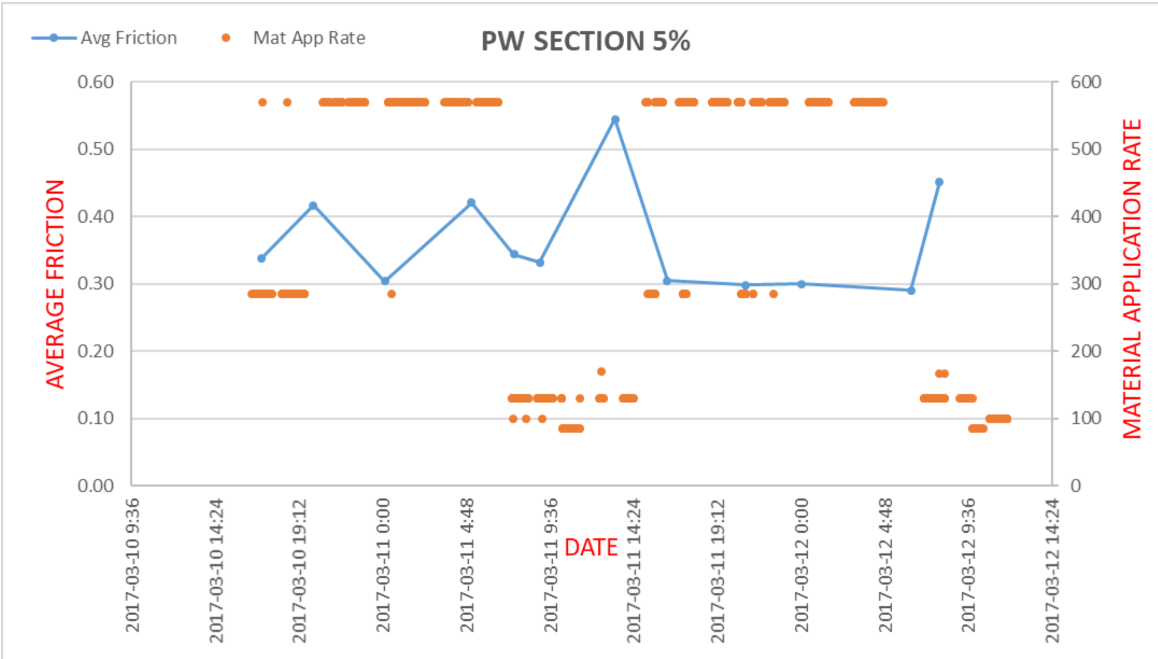

PW SECTION 5%
Avg Friction
Material App
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
600
500
400
300
200
100
0
2017-03-03 0:00
2017-03-03 4:48
2017-03-03 9:36
2017-03-03 14:24
2017-03-03 19:12
2017-03-04 0:00
2017-03-04 4:48
2017-03-04 9:36

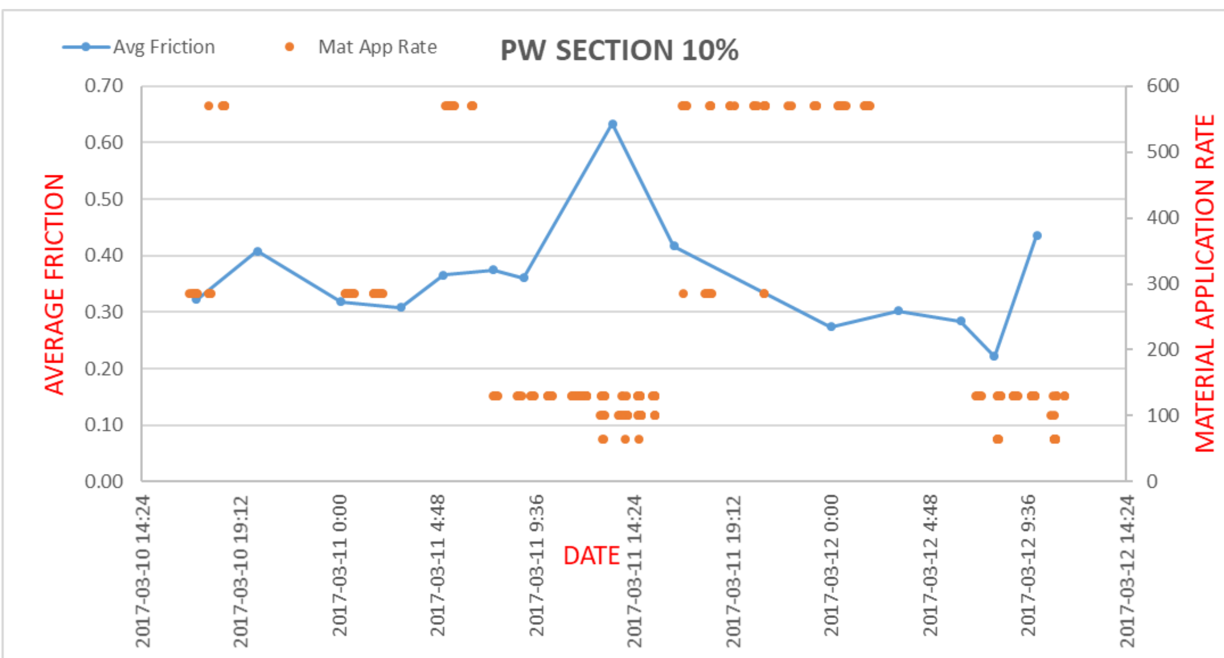

PW SECTION 10%
Avg Friction
Material App
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
140
120
100
80
60
40
20
0
2017-03-03 0:00
2017-03-03 4:48
2017-03-03 9:36
2017-03-03 14:24
2017-03-03 19:12
2017-03-04 0:00
2017-03-04 4:48
2017-03-04 9:36
2017-03-04 14:24

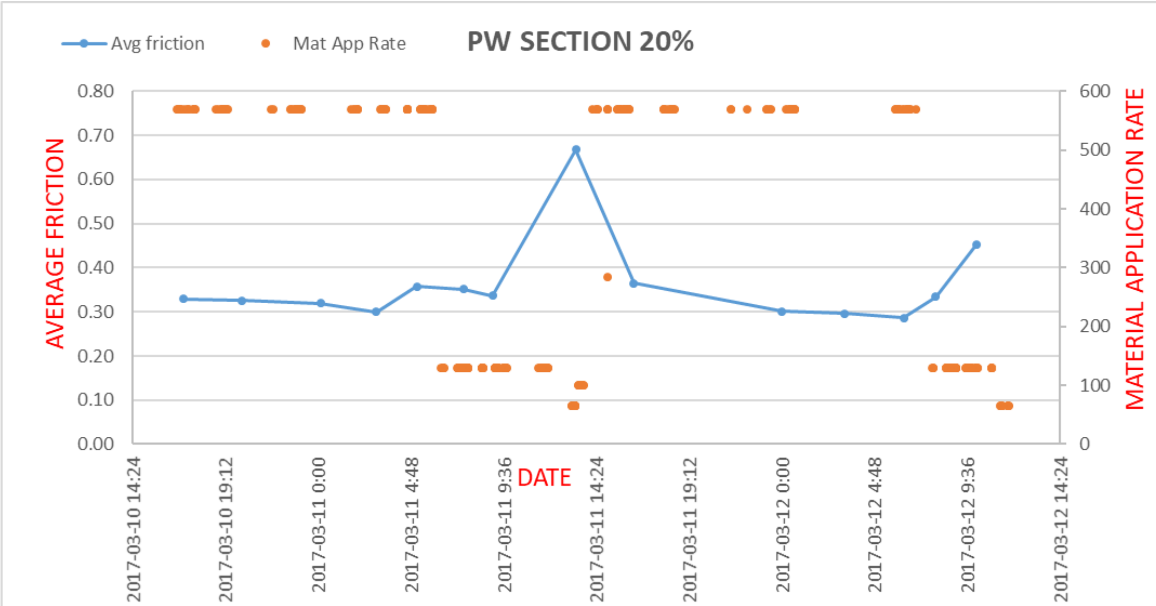

PW SECTION 20%
Avg Friction
Material App
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
600
500
400
300
200
100
0
2017-03-03 0:00
2017-03-03 4:48
2017-03-03 9:36
2017-03-03 14:24
2017-03-03 19:12
2017-03-04 0:00
2017-03-04 4:48
2017-03-04 9:36
2017-03-04 14:24

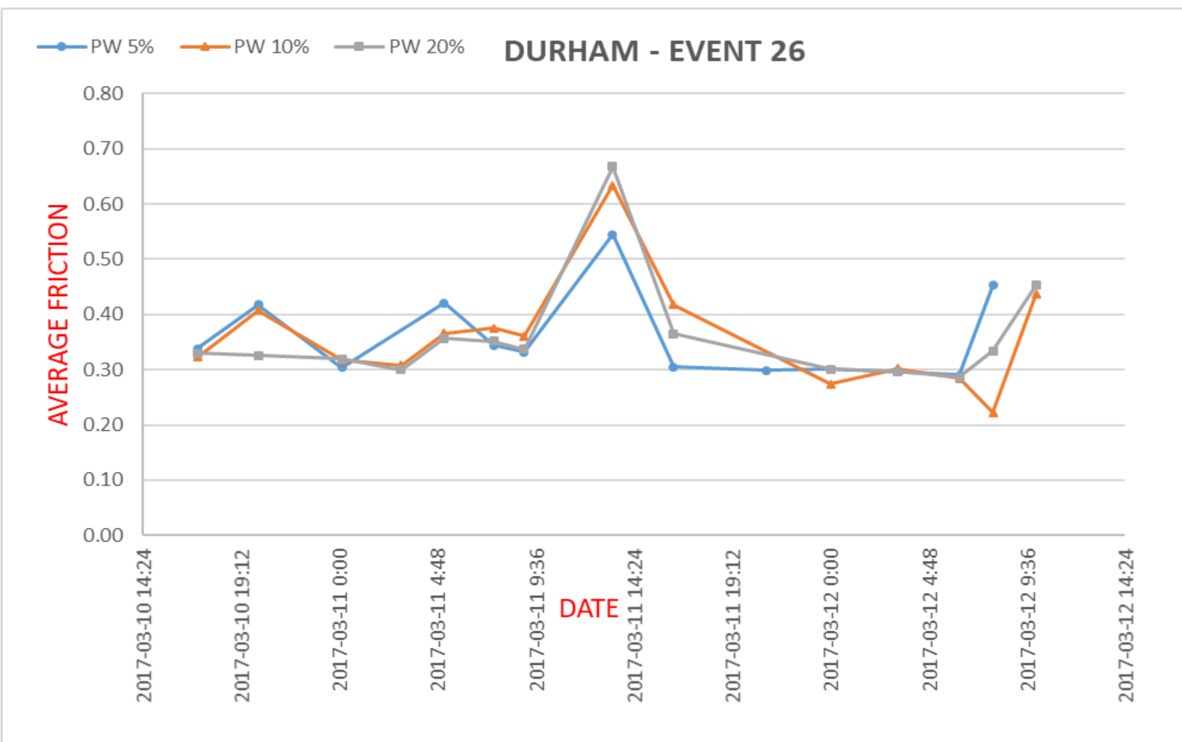

5% PW
10% PW
20% PW
DURHAM - EVENT 25
AVERAGE FRICTION
DATE
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2017-03-03 20:24
2017-03-03 21:36
2017-03-03 22:48
2017-03-04 0:00
2017-03-04 1:12
2017-03-04 2:24
2017-03-04 3:36
2017-03-04 4:48
2017-03-04 6:00
2017-03-04 7:12
2017-03-04 8:24

EVENT – 26


PW SECTION 5%
Avg Friction
Mat App Rate
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-10 9:36
2017-03-10 14:24
2017-03-10 19:12
2017-03-11 0:00
2017-03-11 4:48
2017-03-11 9:36
2017-03-11 14:24
2017-03-11 19:12
2017-03-12 0:00
2017-03-12 4:48
2017-03-12 9:36
2017-03-12 14:24


PW SECTION 10%
Avg Friction
Mat App Rate
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-10 14:24
2017-03-10 19:12
2017-03-11 0:00
2017-03-11 4:48
2017-03-11 9:36
2017-03-11 14:24
2017-03-11 19:12
2017-03-12 0:00
2017-03-12 4:48
2017-03-12 9:36
2017-03-12 14:24

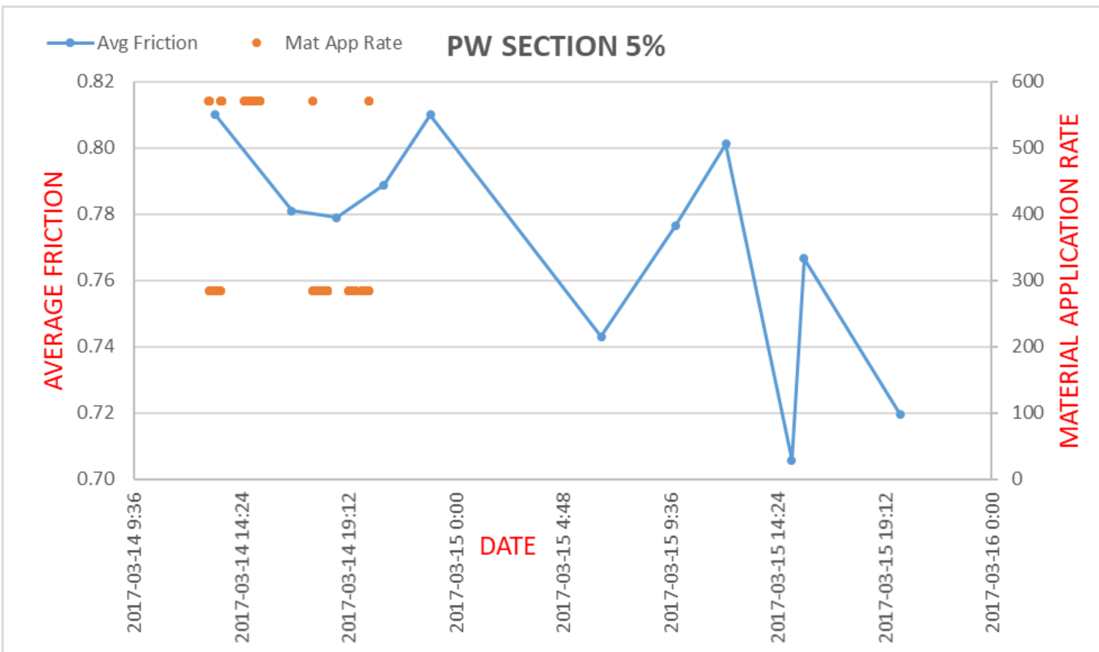

PW SECTION 20%
Avg friction
Mat App Rate
AVERAGE FRICTION
MATERIAL APPLICATION RATE
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-10 14:24
2017-03-10 19:12
2017-03-11 0:00
2017-03-11 4:48
2017-03-11 9:36
2017-03-11 14:24
2017-03-11 19:12
2017-03-12 0:00
2017-03-12 4:48
2017-03-12 9:36
2017-03-12 14:24

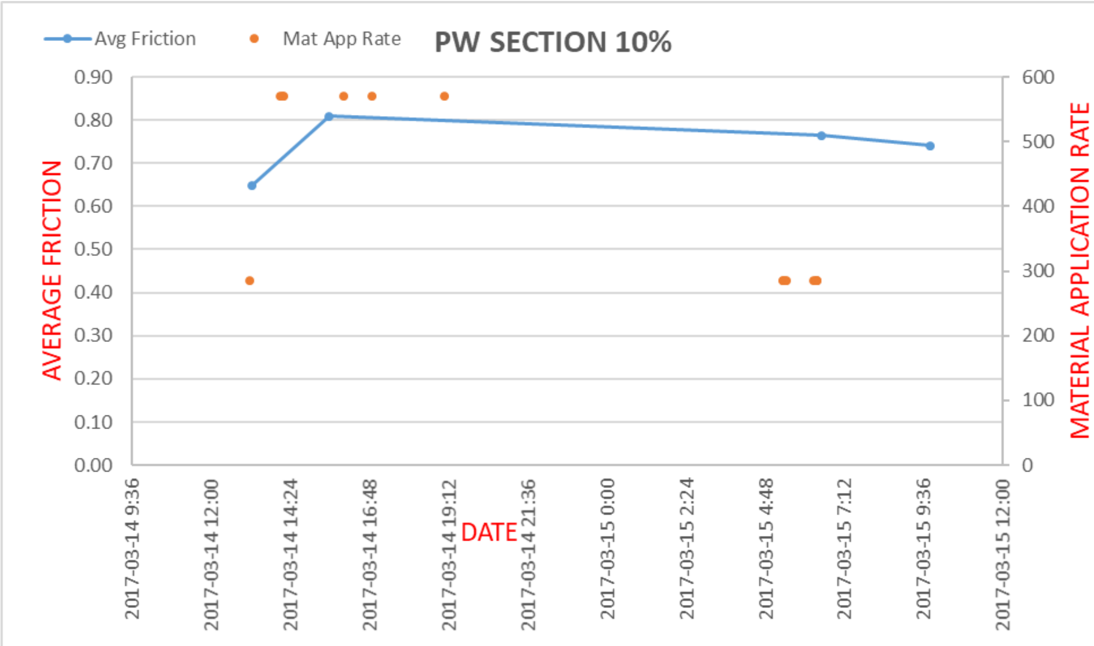

DURHAM - EVENT 26
PW 5%
PW 10%
PW 20%
AVERAGE FRICTION
DATE
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
2017-03-10 14:24
2017-03-10 19:12
2017-03-11 0:00
2017-03-11 4:48
2017-03-11 9:36
2017-03-11 14:24
2017-03-11 19:12
2017-03-12 0:00
2017-03-12 4:48
2017-03-12 9:36
2017-03-12 14:24

EVENT – 27

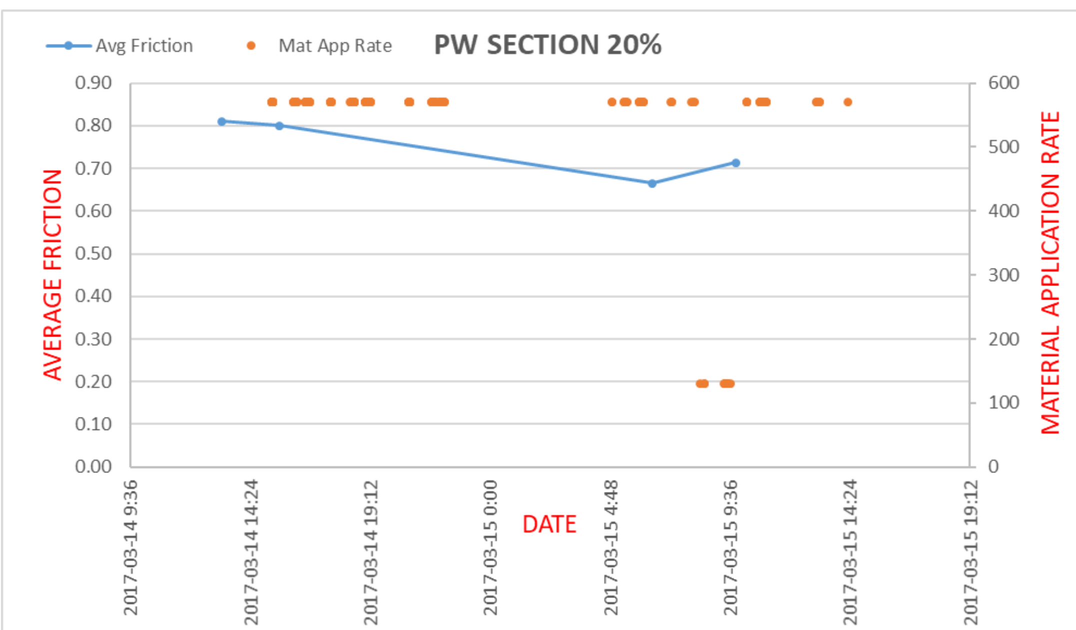
Material data was not available for Event 27. Moreover, only one run was recorded and hence, none of plots is shown for Event 27.

EVENT – 28

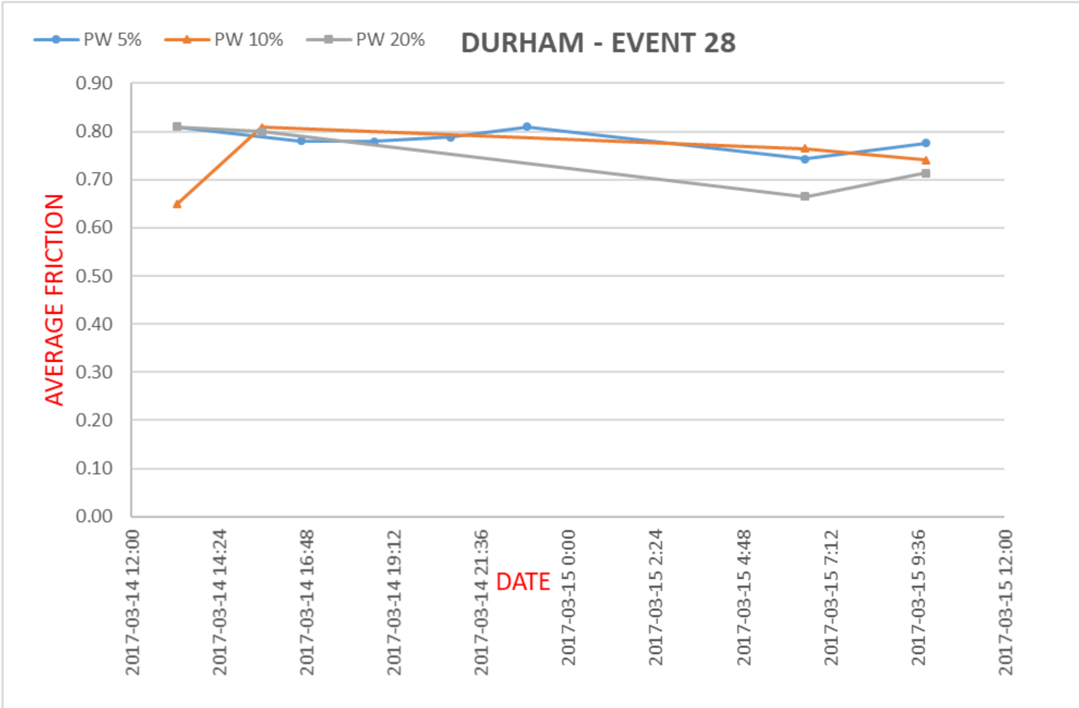




Avg Friction
Mat App Rate
PW SECTION 10%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-14 9:36
2017-03-14 12:00
2017-03-14 14:24
2017-03-14 16:48
2017-03-14 19:12
2017-03-14 21:36
2017-03-15 0:00
2017-03-15 2:24
2017-03-15 4:48
2017-03-15 7:12
2017-03-15 9:36
2017-03-15 12:00
DATE

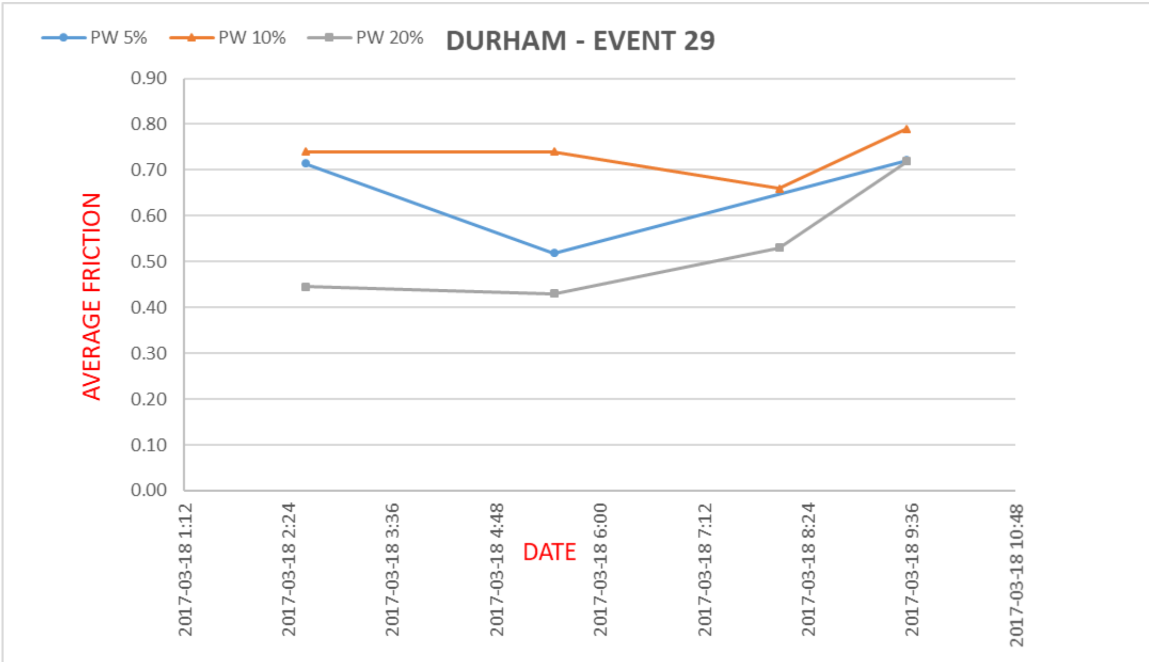


Avg Friction
Mat App Rate
PW SECTION 20%
AVERAGE FRICTION
MATERIAL APPLICATION RATE
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
600
500
400
300
200
100
0
2017-03-14 9:36
2017-03-14 14:24
2017-03-14 19:12
2017-03-15 0:00
2017-03-15 4:48
2017-03-15 9:36
2017-03-15 14:24
2017-03-15 19:12
DATE



EVENT – 29

Material data was not available for Event 29


PW 5%
PW 10%
PW 20%
DURHAM - EVENT 29
AVERAGE FRICTION
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
DATE
2017-03-18 1:12
2017-03-18 2:24
2017-03-18 3:36
2017-03-18 4:48
2017-03-18 6:00
2017-03-18 7:12
2017-03-18 8:24
2017-03-18 9:36
2017-03-18 10:48

Appendix C

Data Samples used in the Analysis

Table C. 1: RWIS Sample Data

Time EST	Air Temp (°C)	Dew Point (°C)	Relative Humidity (%)	Wind Speed (km/h)	Wind Gusts (km/h)
2016-12-31 22:19	-2	-3.1	92	28	33
2016-12-31 22:34	-1.9	-3.2	91	31	36
2016-12-31 22:49	-2	-3.4	90	30	36
2016-12-31 23:04	-2.1	-3.7	88	32	38
2016-12-31 23:19	-2.2	-3.8	89	31	37
2016-12-31 23:34	-2.3	-3.8	89	34	40
2016-12-31 23:49	-2.3	-4	89	31	36
2016-12-31 0:04	-5.4	-7.9	82	10	13
2016-12-31 0:19	-5.5	-7.8	84	10	13
2016-12-31 0:34	-5.5	-7.9	84	8	9
2016-12-31 0:49	-5.8	-7.6	87	8	10
2016-12-31 1:04	-5.7	-7.4	88	9	12
2016-12-31 1:19	-5.7	-7.1	90	7	10
2016-12-31 1:34	-5.7	-6.8	92	7	10
2016-12-31 1:49	-5.7	-6.7	92	7	9
2016-12-31 2:04	-5.7	-6.6	93	9	14
2016-12-31 2:19	-5.7	-6.4	95	13	15
2016-12-31 2:34	-5.7	-6.1	97	13	18
2016-12-31 2:49	-5.8	-5.9	99	9	13
2016-12-31 3:04	-5.9	-5.9	100	9	13
2016-12-31 3:19	-5.9	-5.9	100	8	14
2016-12-31 3:34	-5.8	-5.8	100	10	19

Table C. 2: Traffic Sample Data

DATE & TIME	Date	Timing	North Bound	South Bound	Total Counts
2017-01-12 8:00	2017-01-12	8:00	98	80	178
2017-01-12 9:00	2017-01-12	9:00	106	98	204
2017-01-12 10:00	2017-01-12	10:00	102	97	199
2017-01-12 11:00	2017-01-12	11:00	92	101	193
2017-01-12 12:00	2017-01-12	12:00	86	96	182
2017-01-12 13:00	2017-01-12	13:00	86	116	202
2017-01-12 14:00	2017-01-12	14:00	108	116	224
2017-01-12 15:00	2017-01-12	15:00	126	128	254
2017-01-12 16:00	2017-01-12	16:00	114	130	244
2017-01-12 17:00	2017-01-12	17:00	75	63	138
2017-01-12 18:00	2017-01-12	18:00	57	34	91
2017-01-12 19:00	2017-01-12	19:00	40	30	70
2017-01-12 20:00	2017-01-12	20:00	23	15	38
2017-01-12 21:00	2017-01-12	21:00	24	19	43
2017-01-12 22:00	2017-01-12	22:00	20	11	31
2017-01-12 23:00	2017-01-12	23:00	12	8	20
2017-01-13 0:00	2017-01-13	0:00	3	5	8
2017-01-13 1:00	2017-01-13	1:00	9	3	12
2017-01-13 2:00	2017-01-13	2:00	5	4	9
2017-01-13 3:00	2017-01-13	3:00	6	9	15

Table C. 3: Material Sample Data

Start_Date	Distance km	Rate Dry	Amount Dry kg	Kg Used	Material Dry	Latitude	Longitude	Counter	Section
2017-02-09 16:35	119654.1	130	3504789	132	1	44.15691	-80.816	26	5%PW-Sec
2017-02-09 16:37	119655.1	130	3504921	132	1	44.1481	-80.8135	27	5%PW-Sec
2017-02-09 16:38	119656.1	130	3505052	131	1	44.1392	-80.811	28	5%PW-Sec
2017-02-09 16:40	119657.1	130	3505182	130	1	44.13049	-80.8085	29	5%PW-Sec
2017-02-09 16:42	119658.1	130	3505312	130	1	44.12188	-80.8061	30	5%PW-Sec
2017-02-09 16:43	119659.1	130	3505444	132	1	44.11304	-80.8036	31	5%PW-Sec
2017-02-09 16:45	119660.1	130	3505575	131	1	44.10438	-80.8048	32	5%PW-Sec
2017-02-09 16:46	119661.1	130	3505704	129	1	44.09567	-80.803	33	5%PW-Sec
2017-02-09 16:48	119662.1	130	3505834	130	1	44.087	-80.8004	34	5%PW-Sec
2017-02-09 17:26	119689.5	130	3508235	2	1	44.08663	-80.8002	93	5%PW-Sec
2017-02-09 17:27	0	0	3508277	42	1	44.08965	-80.801	94	5%PW-Sec
2017-02-09 17:28	0	0	3508277	0	1	44.09845	-80.8037	95	5%PW-Sec
2017-02-09 17:29	0	0	3508277	0	1	44.10706	-80.8036	96	5%PW-Sec
2017-02-09 17:29	0	0	3508277	0	1	44.11585	-80.8042	97	5%PW-Sec
2017-02-09 17:29	119692.9	130	3508277	0	1	44.11635	-80.8043	98	5%PW-Sec
2017-02-09 17:30	119692.9	130	3508280	3	1	44.11651	-80.8044	99	5%PW-Sec
2017-02-09 17:30	0	0	3508321	41	1	44.1193	-80.8052	100	5%PW-Sec
2017-02-09 17:32	119694.3	100	3508323	2	1	44.12178	-80.8061	101	5%PW-Sec
2017-02-09 17:32	119694.4	100	3508339	16	1	44.12032	-80.8057	102	5%PW-Sec
2017-02-09 17:32	119694.5	100	3508346	7	1	44.11972	-80.8055	103	5%PW-Sec
2017-02-09 17:34	0	0	3508439	93	1	44.11164	-80.8032	104	5%PW-Sec
2017-02-09 17:34	0	0	3508439	0	1	44.11152	-80.8032	105	5%PW-Sec
2017-02-09 17:34	119695.6	100	3508441	2	1	44.10989	-80.8029	106	5%PW-Sec
2017-02-09 17:34	0	0	3508489	48	1	44.10567	-80.8042	107	5%PW-Sec
2017-02-09 17:36	119696.9	100	3508490	1	1	44.10089	-80.8044	108	5%PW-Sec
2017-02-09 17:36	119697	130	3508494	4	1	44.10098	-80.8044	109	5%PW-Sec
2017-02-09 17:38	119698	130	3508625	131	1	44.1096	-80.8028	110	5%PW-Sec
2017-02-09 17:39	119699	130	3508754	129	1	44.11846	-80.8049	111	5%PW-Sec
2017-02-09 17:39	0	0	3508786	32	1	44.12072	-80.8056	112	5%PW-Sec

Table C. 4: Friction Sample Data

Date	Friction	State	Ta	Tsurf	Water	Latitude	Longitude	Section
2016-12-15 12:28	0.18	5	-10.5	-10.07	0	44.378268	-80.871478	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.23	0	44.378391	-80.871513	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.2	0	44.378515	-80.871562	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.1	0	44.37864	-80.871598	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.42	0	44.378765	-80.871632	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.52	0	44.378877	-80.871677	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.5	-10.27	0	44.378993	-80.871708	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.3	0	44.379227	-80.871765	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.11	0	44.379324	-80.87179	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.16	0	44.379413	-80.871813	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.24	0	44.379498	-80.871829	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.21	0	44.37957	-80.871846	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.42	0	44.379629	-80.871851	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.5	0	44.379679	-80.871864	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.74	0	44.37972	-80.871875	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.91	0	44.379789	-80.871885	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-11.1	0	44.379832	-80.871887	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.98	0	44.379848	-80.871901	5%PW-Sec
2016-12-15 12:28	0.18	5	-10.6	-10.84	0	44.379862	-80.871905	5%PW-Sec
2016-12-15 12:28	0.19	5	-10.6	-10.95	0	44.379865	-80.871906	5%PW-Sec

Table C. 5: BP Records Sample Data

Hwy #	Event Beginning (1) Date YYYY/MM/DD	Event Beginning (1) Time HH:MM	Bare Pavement Lost (2) Date YYYY/MM/DD	Bare Pavement Lost (2) Time HH:MM	Event Ending (3) Date YYYY/MM/DD	Event Ending (3) Time HH:MM	Bare Pavement Regained (4) Date YYYY/MM/DD	Bare Pavement Regained (4) Time HH:MM	Event Type (5)	BP Regained Time N/A	Continuous Entry	COMMENTS	MMIS Event Number (6)	Name (7) *please print*
6	2016-12-17	16:30	2016-12-17	16:30	2016-12-19	18:00	2016-12-19	18:30	S		Y	Continued from last reporting period		Garrett Dier
10	2016-12-17	16:30	2016-12-17	16:30	2016-12-19	18:00	2016-12-19	18:30	S		Y	**Continued from last reporting period**		Garrett Dier
26	2016-12-17	17:30	2016-12-17	17:30	2016-12-21	7:00	2016-12-21	8:30	S		Y	**Continued from last reporting period**		Garrett Dier
10	2016-12-20	6:00	2016-12-20	6:00	2016-12-21	7:00	2016-12-21	8:30	S		Y	Drifting		Bob Kirk
6	2016-12-20	7:30	2016-12-20	7:30	2016-12-21	7:00	2016-12-21	8:30	S		Y	Drifting		Bob Kirk
26	2016-12-21	21:00	2016-12-21	21:00	2016-12-22	8:00	2016-12-22	9:00	B		Y			Bob Kirk
10	2016-12-21	21:30	2016-12-21	21:30	2016-12-22	7:30	2016-12-22	8:30	B		Y			Bob Kirk
6	2016-12-21	21:30	2016-12-21	21:30	2016-12-22	7:30	2016-12-22	8:30	B		Y			Bob Kirk
6	2016-12-23	5:00	2016-12-23	5:00	2016-12-23	6:30	2016-12-23	7:00	FR		Y	Frost		Tim Lewis
10	2016-12-23	5:30	2016-12-23	5:30	2016-12-23	8:30	2016-12-23	9:00	FR		Y	Frost		Tim Lewis
26	2016-12-23	5:00	2016-12-23	5:00	2016-12-23	6:30	2016-12-23	7:00	FR		Y	**Frost**		Tim Lewis
6	2016-12-24	0:30	2016-12-24	0:30	2016-12-24	9:30	2016-12-24	10:00	B		Y			Garrett Dier
10	2016-12-24	0:30	2016-12-24	0:30	2016-12-24	9:30	2016-12-24	10:00	B		Y			Garrett Dier
26	2016-12-24	0:30	2016-12-24	0:30	2016-12-24	9:00	20-16/12/24	9:30	B		Y			Garrett Dier

Appendix D

Questionnaire and Responses from Field Staff

a) Following Questionnaire was prepared for field staff regarding the performance of different pre-wetting ratios:

1. Which pre-wet rate was easy to use?
2. How was the road surface condition after first application (or first few applications) of different PW ratios?
3. Any effects on bare pavement recovery time? E.g. early recovery, similar trends etc.
4. Any slipperiness observed due to high PW ratio?
5. Any difference in the snow melting performance?
6. Any other comment?

b) The six responses were received and are summarized as below:

1. The melting action was accelerated by higher pre-wetting ratios.
2. The higher pre-wetting ratios caused slipperiness.
3. The higher pre-wetting ratios clogged the chute and hence, pre-wetting 5% is easy to use.

4. They didn’t observe any change in bare pavement recovery time due to higher pre-wetting ratios.
5. They would prefer to use either PW 5% or PW 20% salt

Appendix E

Paired t-test

Table E. 1: Comparison of overall average friction between PW 5% and PW 10% salt

t-Test: Paired Two Sample for Means		
	PW 5%	PW 10%
Mean	0.473206565	0.523175453
Variance	0.014279454	0.017338319
Observations	25	25
Pearson Correlation	0.878123156	
Hypothesized Mean Difference	0	
df	24	
t Stat	-3.79227344	
P(T<=t) one-tail	0.00044456	
t Critical one-tail	1.71088208	
P(T<=t) two-tail	0.00088912	
t Critical two-tail	2.063898562	
Significant Difference exist b/w overall average friction values using PW 5% an PW 10% treatments		

Table E. 2: Comparison of overall average friction between PW 5% and PW 20% salt

t-Test: Paired Two Sample for Means		
	PW 5%	PW 20%
Mean	0.473206565	0.536454001
Variance	0.014279454	0.013320796
Observations	25	25
Pearson Correlation	0.792523116	
Hypothesized Mean Difference	0	
df	24	
t Stat	-3.026064618	
P(T<=t) one-tail	0.0029163	
t Critical one-tail	1.71088208	
P(T<=t) two-tail	0.005832599	
t Critical two-tail	2.063898562	
Significant Differnce exist b/w overall average friction values using PW 5% an PW 20% treatments		

Table E. 3: Comparison of overall average friction between PW 10% and PW 20% salt

t-Test: Paired Two Sample for Means		
	PW 10%	PW 20%
Mean	0.523175453	0.536454001
Variance	0.017338319	0.013320796
Observations	25	25
Pearson Correlation	0.915382845	
Hypothesized Mean Difference	0	
df	24	
t Stat	0.189651802	
P(T<=t) one-tail	0.425588423	
t Critical one-tail	1.71088208	
P(T<=t) two-tail	0.851176847	
t Critical two-tail	2.063898562	
Significant Difference doesn't exist b/w overall average friction values using PW 10% an PW 20% treatments		