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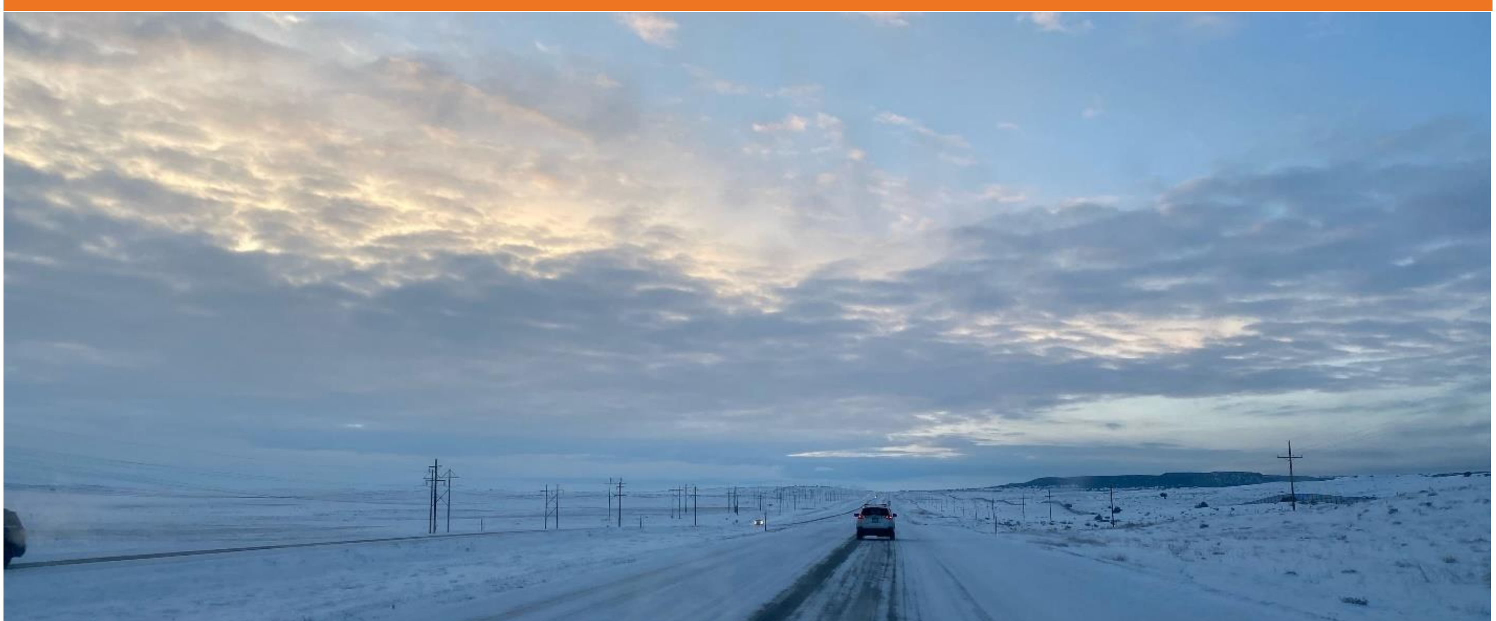
September 2022

Assessing the Effectiveness of Friction as a Performance Management Tool in Colorado



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16. Abstract

The objective of this project was to evaluate the feasibility of using roadway friction data as a key component of a winter maintenance performance management tool by the Colorado Department of Transportation (CDOT). Work accomplished to support these findings identified states and countries that are using roadway friction data in performance management tools to support WMO. Based on a review of the literature, sufficient work has been done on the use of roadway friction data in performance management tools by other agencies to ensure the feasibility of CDOT using roadway friction data in this capacity. RWIS based and mobile roadway friction data sources in Colorado were assessed to determine if friction data of sufficient resolution and quality was available to support a performance management tool. Test sections along I-25 and I-70 were identified for further analysis. Sufficient RWIS based roadwy friction data is present in the Greater Denver Area, Upper Front Range, and Intermountain Regions of Colorado to allow for analysis of use in the performance management tool. In the locations where mobile roadway friction data is collected, additional and more consistent data collection is recommended, and a mobile friction sensor data collection protocol guide is suggested to be developed to support this. The application of available roadway friction data in existing performance management tools was assessed. Based on topographical, weather, and climatic differences across the US, it is recommended that CDOT modify an existing performance management tool (Idaho Method) for application in Colorado. The following recommendations for implementation of friction data in a performance management tool were made - use a data driven step down approach to a less conservative roadway friction threshold value (starting at μ=0.6) in the application of ITD PI, CDOT should be careful to ensure the correct roadway friction data that meets the friction threshold is used. Training materials were developed to support the use of roadway friction data in CDOTs winter maintenance operations and in a performance management tool. Recommendations were made to support to use of friction data by CDOT.

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Assessing the Effectiveness of Friction as a Performance Management Tool in Colorado

Final Report

By

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EXECUTIVE SUMMARY

The objective of this research effort was to evaluate the feasibility of using roadway friction data as a key component of a winter maintenance performance management tool for the Colorado Department of Transportation (CDOT).

An investigation identified states and countries that are using roadway friction data in performance management tools to support winter maintenance operations (WMO). Based on a review of the literature, sufficient work has been done by other agencies on using roadway friction data in this capacity and existing performance management tools that incorporate roadway friction have been tested and operationally applied by other US state departments of transportation (DOTs). Both roadway friction data and performance management tools are sufficiently explored to ensure the feasibility of their use by CDOT.

This work then assessed roadway friction sources in Colorado to determine if data of sufficient resolution and quality are available to support a performance management tool. It was found that outside of the Greater Denver Area, Upper Front Range, and Intermountain Regions of Colorado, the friction sensor network is insufficient for the collection of friction values to assess road condition statewide and, therefore, insufficient for use in a statewide performance tool for winter maintenance operations. It is recommended that additional Road Weather Information System (RWIS) sites or mobile friction sensors be deployed to equally distribute data sources across the state and increase the data density in rural areas. Another option is to explore the use of modeling to extrapolate friction values.

In locations where mobile roadway friction data are collected, additional and more consistent data collection is recommended. Based on the data comparison between the RWIS stationary friction sensors and the mobile Teconer friction sensor data, the mobile friction data are not present in sufficient quantity to perform a comparative analysis. It is recommended that a mobile friction sensor data collection protocol guide be developed that considers, at a minimum:

calibration, cleaning, routes, frequency of use, and timing of data collection before, during, and after storm events.

To support CDOT, the application of available roadway friction data in existing performance management tools was assessed. Given topographical, weather, and climatic differences across the US, it is recommended that CDOT modify an existing performance management tool (Idaho Method) for application in Colorado. The following recommendations for implementation of friction data in a performance management tool were made:

- Use a data driven step-down approach to a less conservative roadway friction threshold value (starting at μ=0.6) in the application of Idaho Transportation Department (ITD) Performance Index (PI),
- CDOT should be careful to use the correct roadway friction data when meeting the friction threshold.

Training materials were developed to support the use of roadway friction data in CDOT winter maintenance operations and in a performance management tool. As such, presentation was developed that presents a high-level summary of what constitutes friction data, where the data come from, where they can be found, and how they can be used.

In addition to this effort, recommendations were made to support to use of friction data by CDOT.

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INTRODUCTION

The objective of this research effort was to evaluate the feasibility of using roadway friction data as a key component of a winter maintenance performance management tool for the Colorado Department of Transportation (CDOT).

To accomplish this the following tasks were used to support this effort:

- A literature review was used to identify domestic and international winter maintenance operations (WMO) agencies that have used friction data in operations and performance management tools.
- An analysis of available friction data sources, locations, data quality and quantity was conducted.
- An implementation plan with recommendations to support the application of friction data in a performance management tool was created.
- Training materials were developed to support the use of roadway friction data in CDOT winter maintenance operations.

A detailed description of each task can be found in the proceeding sections.

LITERATURE REVIEW SUMMARY

The following section provides a summary of identified literature relevant to this project. Additional resources can be found in APPENDICIES. Please note that the term grip and friction are used synonymously in this report.

Utilizing friction measurements is a quantitative way to inform and support winter maintenance operations. Past work for CDOT assessed the feasibility of using friction data to determine product performance, as well as performance of various application techniques (anti-icing versus deicing) (CDOT Study 314.03). Additionally, friction data was investigated for use in chain-up recommendations (Walsh, 2016). Work was identified by winter maintenance agencies that have used friction data as a part of performance measurements (such as Idaho, Finland, Norway, and Sweden).

Idaho Transportation Department (ITD) implemented a number of key performance indicators (KPIs) to evaluate the effectiveness of their winter maintenance program. Using data from their Road Weather Information System (RWIS) network, ITD evaluated patterns in "grip" and adopted a grip level parameter for their winter maintenance operations. When "grip" was measured by Vaisala's DSC211 sensors and determined to be 0.6 or lower, conditions were expected to have an impact on mobility. The threshold of 0.6 is used in ITD's winter mobility index, which is measured for each storm. The index ranges from 0 to 1 and represents the amount of time the road conditions did not impact mobility, or the percentage of time the grip value did not fall below 0.6 with precipitation present on a below-freezing roadway. Additional information on this can be in section Idaho Transportation Department Use of Roadway Friction Data in Performance Measurement.

Road friction measurements have been used to improve safety and set winter maintenance standards in three Scandinavian countries: Finland, Norway, and Sweden. Generally, these countries require that, should a road fall below a set friction threshold, it be returned to that threshold within a specified period of time.

Finland has set of quality standards which they use to determine the period of time allotted to bring roads back to the set friction threshold (typically 0.25). These standards are set depending on road classification, which is determined by traffic volume and road type (trunk road vs. local connector, etc.) and time of day (Table 1 through Figure 2).

Table 1. Friction Value and Driving Conditions for Finland (Recreated from (Zein, 2009))

Friction Value	0.00 – 0.14	0.15 – 0.19	0.20 – 0.24	0.25 – 0.29	0.30 – 0.44	0.45 – 1.00
Driving Condition	Very Slippery	Slippery	Satisfactory Winter Conditions	Good Winter Condition	Not Slippery	Not Slippery

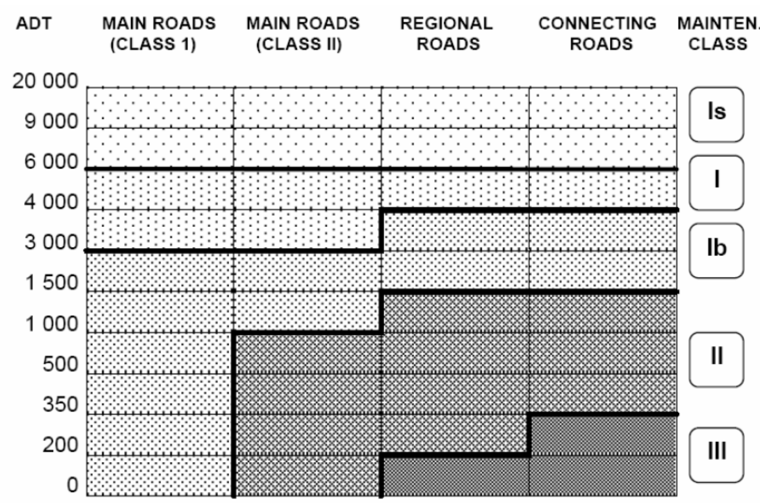

Figure 1. Finland, Road Maintenance Classes (Copied from (Zein, 2009))

QUALITY STANDARDS OF ANTI-SLIPPING PROCEDURES							
Winter maintenance class	Is	I	Ib and TIb	II	III	K1	K2
Friction requirement — Normal	0.30	0.28	0.25	according to traffic demands	according to traffic demands	according to traffic demands	
	road surface below -6 °C **0.25**	Road surface below -4 °C **0.25**	spot sanding **0.25** line treatment **0.20-0.22**				
At night	22 - 05 0.28	22 - 05 0.25	22 - 05 as needed	22 - 06 as needed	22 - 06 as needed	after 22 K1 by 05 K2 by 06	
Cycle time	2 h	2 h	salt **3 h** sand **4 h**	**6 h** line sanding	**10 h** line sanding	2 h	

Figure 2. Finland, Winter Maintenance Quality Standards (Copied from (Zein, 2009))

The Swedish Road Administration friction thresholds are determined by the road classification, precipitation type, and road surface temperature. Generally, desired friction thresholds range between 0.20 – 0.35 (Figure 3).

Standard classes 1–3

Cross-sectional elements	Requirements during precipitation/Action time after precipitation				
	Trigger value		Action time in hours		
	Snowfall	Rain	Standard class		
	Loose Snow depth cm	Friction μ	1	2	3
Traffic lane	1	0.30	2	3	4
Side shoulder	1	0.25	4	6	8
Roadside facility	1	0.25	4	6	8

Cross-sectional elements	Dry weather requirements when action time after precipitation has expired			
	Road surface temperature			Evenness cm
	Warmer than -6°C friction coefficient	-6°C to -12°C friction coefficient	colder than -12°C friction coefficient	
Traffic lane	Snow and ice-free	0.35	0.25	1.5
Side shoulder	0,25	0,25	0.25	1.5
Roadside facility	0.25	0.25	0.25	1.5

Standard classes 4–5

Cross-sectional element	Dry weather requirements when action time after precipitation has expired							
	Trigger value				Action Time			
	Loose Snow depth cm		Friction coeff. μ	Eveness cm	Snow depth/friction hours		Evenness hours	
	Standard class				Standard class		Standard class	
	4	5			4	5	4	5
Traffic lane	2	3	0.25	1.5	5	6	48	72
Roadside facility	2	3	0.25	1.5	8	8	48	72

Cross-sectional element	Requirements during precipitation/Action time after precipitation				
	Threshold value			Action time in hours	
	Snowfall		Rain		
	Loose Snow depth cm		Friction coeff. μ		
	Standard class			Standard class	
	4	5		4	5
Traffic lane	2	3	0.25	5	6
Roadside facility	2	4	0.25	8	8

Figure 3. Sweden, Friction Thresholds (Copied from (Zein, 2009))

Norway has set friction thresholds that depend on the traffic volume and annual average daily traffic volume (AADT) for each road. Generally, high-volume roads need to be brought back to a friction coefficient of 0.4, whereas low-volume roads need to be brought back to a friction coefficient of between 0.15 and 0.25 (Figure 4).

Tasks	Triggering criteria and maximum time for action in regard to different AADT		
	< 3000	3001 – 5000	> 5000
Preventive salting	If expected friction value < 0,4	If expected friction value < 0,4	If expected friction value < 0,4
After snowfall: Bare road before	6 hrs.	4 hrs.	2 hrs.

Class of road	AADT	Local sanding		Continuous sanding	
		Start at	Finished within	Start at	Finished within
Trunk Roads		μ < 0,30	1 hr.	μ < 0,20	2 hrs.
All other roads	> 1500	μ < 0,25	1 hr.	μ < 0,20	2 hrs.
	501 – 1500	μ < 0,25	2 hrs.	μ < 0,15	3 hrs.
	0 - 500	μ < 0,20	2 hrs	μ < 0,15	4hrs

Source: PIARC (2006).

Figure 4. Norway, Friction Thresholds (Copied from (Zein, 2009))

Performance metrics utilizing friction measurements in Idaho, Finland, Norway, and Sweden are unique to each transportation agency, depending on the goal of the performance metric (when to treat the roadway versus time to bring a road back to safe driving conditions, for example). Generally, the friction thresholds in the Scandinavian countries trend lower (approximately 0.2 – 0.4) than in Idaho (0.6). These thresholds provide a good starting point, but it is important for an agency to understand the unique characteristics in their region and the associated friction values when setting effective friction measurement thresholds.

What do Roadway Friction Values Mean?

Roadway friction values report road surface slipperiness and typically range from 0.0 to 1.0[*], with 0.0 being very slippery and 1.0 being not slippery at all. In the context of this project, reduced roadway friction can be caused by wet, icy, and/or snowy roadway conditions as compared to dry pavement. The following table summarizes common friction values associated with winter conditions on roadways (Table 2).

[*] Reported friction values can be higher than 1.0 as seen in Table 2 due in part to the method used to collect the friction data.

Table 2. Summary table of friction values measured on roadways during various winter weather conditions.

Road Condition	Detailed	Friction Values Seen in Literature					Friction Range
		Fay et al, 2018 [2]	**Akin et al, 2013** [3]	**Wallman & Åström, 2001** [4]	**Finnish Winter Maintenance Policy, 2001** [5]	**Road Surface Condition Classification Used in Japan, 2002** [5]	
Bare/Dry	Bare pavement	0.80-0.82	0.8-1.1	0.8-1.0	0.45-1.0	0.45-1.0	0.45-1.1
Wet/Damp	Wet pavement		0.5-0.89	0.7-0.8	0.3-0.44	0.45-1.0	0.3-0.89
Icy	Icy pavement		0.2-0.52		0.15-0.19	0.15	0.15-0.52
	Black Ice			0.15-0.3			0.15-0.3
	Loose Snow on Black Ice			0.15-0.25		0.15-0.20	0.15-0.25
	Wet black Ice			0.05-0.1	0.0-0.14		0.0-0.14
Snowy	Snowy pavement	0.11-0.41	0.2-0.8				0.11-0.8
	Loose Snow/Slush			0.2-0.5		0.25-0.35	0.2-0.5
	Trafficked snowy pavement (packed snow)	0.11-0.36		0.2-0.3	0.2-0.29	0.2-0.3	0.11-0.36
Treated Pavement	Snow plowed off pavement	0.38-0.81					0.38-0.81
	Anti-iced pavement	0.74-0.82					0.74-0.82

How Roadway Friction Data can be Used in Winter Maintenance Operations

Friction data provide a quantitative means by which WMO can be informed and supported, and have been successfully used by state DOTs and international agencies. There are many ways friction data can used for performance measurements:

Planning

- When to go out to do maintenance.

Real-time Decision Making

- When the roads are no longer safe or when you are losing the road.
- When the roads are safe.
- When WMO are complete.

Post Storm Review

- Length of time roadway friction was below a defined friction value.
- Friction recovery time.

How Friction Data Has Been Utilized by Other Agencies

To better evaluate winter maintenance programs, transportation agencies have incorporated roadway friction (and other quantitative measurements) into decision-making tools. This incorporation of roadway friction has helped determine when and where winter maintenance activities need to take place.

Idaho Transportation Department Use of Roadway Friction Data in Performance Measurement

Idaho Transportation Department (ITD) has implemented a number of key performance indicators to evaluate the effectiveness of their WMO program. Using data from their RWIS network, ITD utilizes an index to measure the performance of their WMO (Jensen and Koeberlein, 2015). The performance index is measured using:

- A coefficient of friction threshold of 0.6.
- A severity index which utilizes RWIS data - wind speed, precipitation layer thickness, and surface temperature.

The performance index (PI) is calculated as follows:

$$Peformance\ Index\ (PI) = \frac{Grip < 0.6Duration(hours)}{SeverityIndex}$$

Where the severity index is:

$$SeverityIndex = MaxWindSpeed(mph) + MaxLayerThickness(mm) + \frac{300}{MinSurfaceTemp(°F)}$$

And max layer thickness is:

$$MaxLayerThickness(mm) = \max\,(IceLayer, SnowLayer, WaterLayer)$$

WMO response efforts are then categorized as shown in Table 3.

Table 3. ITDs WMO response effort based on friction values.

0.00	Successfully Treated
0.00 – 0.30	Significantly Accelerated Grip Recovery
0.31 – 0.49	Some Success at Grip Recovery
0.50 – 0.69	Very Little Success at Deicing
0.70 and Greater	Limited Maintenance or No Deicer Success

Previous CDOT work by Walsh (2016) for CDOT determined that the winter performance index (PI) developed by Idaho can be applied in Colorado, based on testing of the PI in Region 4 during the 2015-2016 winter season. Walsh recommended statewide implementation following the 2015-2016 winter season if CDOT determined the PI to be a valuable tool (Walsh, 2016).

International Examples of Roadway Friction Use in Performance Measurement

The following international roadway friction values are used to improve safety and set WMO standards. Generally, these standards suggest that if a roadway's coefficient of friction falls below a set threshold, it must be returned to that threshold within a specified period of time.

Based on work presented at the 2021 Transportation Research Board (TRB) Annual Meeting to the Winter Maintenance Committee, Sweden is currently using a friction threshold of 0.4 (Table 4) (Ericksson, 2021).

Table 4. Swedish friction threshold used in WMO.

Friction Coefficient	WMO Needed?
Greater than 0.4	No
Less than 0.4	Yes

Norway uses the following friction threshold values (Zein, 2009):

Table 5. Norwegian friction thresholds used in WMO.

Friction Coefficient	Road Condition
Greater than 0.25	Satisfactory Friction
Less than 0.25	Slippery
Less than 0.15	Seriously Slippery

Note that the roadway friction threshold values used by Sweden and Norway are significantly lower than the 0.6 friction value currently used in the ITD PI method.

FRICTION AND ROAD WEATHER INFORMATION SOURCES IN COLORADO

The state of Colorado and CDOT have many roadside weather and atmospheric information sources (Figure 5). A more detailed look at road surface and weather data in the state identified 145 RWIS stations: 75 friction data recorders, 53 streaming video locations, and 816 still camera locations, which can be viewed through COTrip, https://www.cotrip.org/map.htm#/roadConditions) and WebMDSS. In addition to the RWIS data, streaming video, and still camera images, CDOT collects road condition information from mobile friction devices (Teconer, https://www.teconer.fi/en/surface-condition-friction-measurements/). CDOT currently has 54 Teconer units in service, with many more being deployed annually. The Teconer sensor data can be viewed here: https://roadweather.online/. CDOT also has one High Sierra IceSight, three Lufft MARWIS, and three Vaisala DSP310 mobile sensors, which report road condition information.

While the RWIS stations collect data from a fixed location, the Teconer units are typically mounted on a maintenance supervisors' vehicles; data are collected as the vehicle is driven, through space and time.

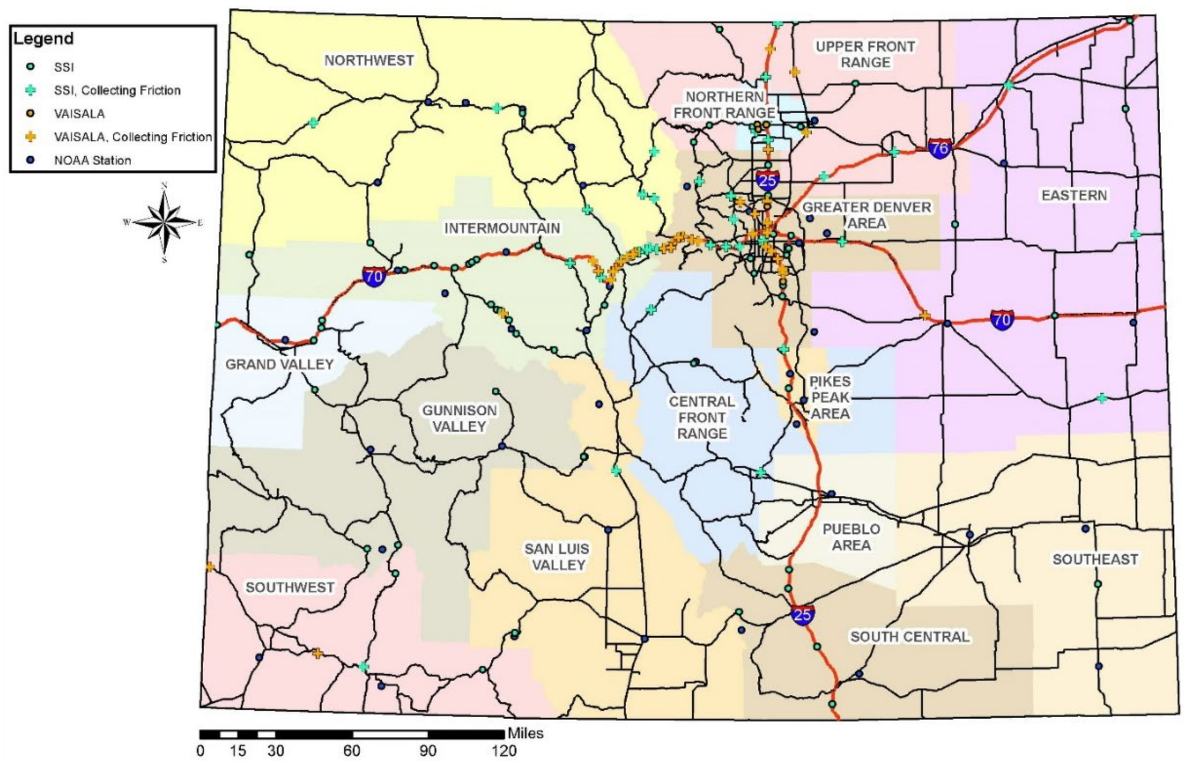

Figure 5. Map of Colorado showing DOT maintenance districts, interstate and state highways, RWIS sites from both SSI and Vaisala, and National Oceanic and Atmospheric Administration (NOAA) weather station sites.

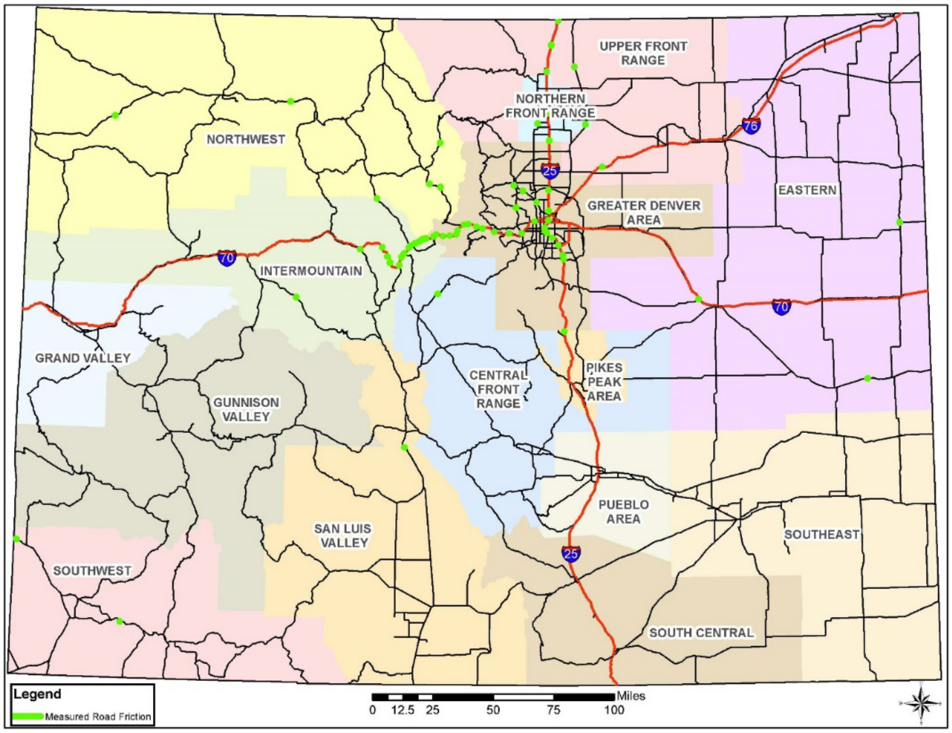

Figure 6. Map of Colorado showing the interstate and state highway systems, counties, and locations in the state where friction is measured (green dots).

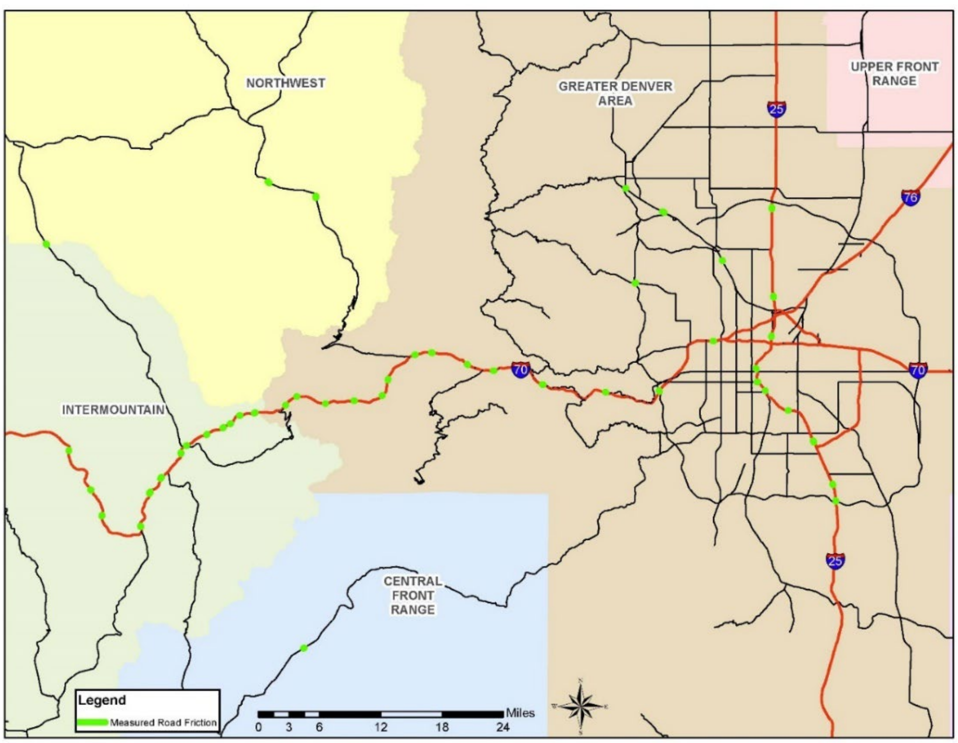

Figure 7. Map of Colorado showing the densest network of friction sensors along I-25 and I-70.

Figure 6 and Figure 7 show the locations of friction sensors in Colorado (as of 2020 and those used in the analysis for this effort). From Figure 6 one can observe that the friction sensor network is densest in the Greater Denver Area, Upper Front Range, and Intermountain Counties. Outside of these areas the resolution of friction sensors decreases significantly. Figure 7 provides a close-up view of the friction sensor network in the Greater Denver Area and Intermountain Counties along the I-25 and I-70 corridors. Due to the increased density of friction sensors in the Greater Denver Area and Intermountain Counties of Colorado, test sections along the I-25 and I-70 corridors were identified for data collection and a feasibility assessment of friction data as a key component of a performance management tool in winter maintenance operations.

FRICTION VALUES MEASURED ON COLORADO'S ROADWAYS

Roadway friction data collected from RWIS sites along sections of Colorado's I-25 and I-70 corridor were analyzed to determine roadway friction values. The analysis identified that the following friction ranges occurred in the winter seasons between 2017 and 2020 (October through March, when only considering friction values less than 0.6[†]) (Table 6). The roadway friction values that were below 0.6 during the 2017 – 2020 winter seasons typically ranged between 0.15 and 0.50.

Table 6. Summary roadway friction values below 0.6 along sections of Colorado's I-25 and I-70 corridors during winter seasons (October through March).

Winter Seasons Considered	I-25 Friction values ranges below 0.6	I-70 Friction values ranges below 0.6
2017-2018	0.23 to 0.54	0.15 to 0.48
2018-2019	0.16 to 0.53	0.15 to 0.52
2019-2020	0.18 to 0.52	0.13 to 0.53
2017-2020	**0.17 to 0.52**	**0.15 to 0.48**

Additional information on the analysis used to produce the information reported in Table 6 can be found in RWIS Friction Data Thresholds.

[†] When considering all roadway friction values, significantly more data occur in the 0.6 – 1.0 value range because Colorado's highways often have good roadway friction. The purpose of this project was to investigate roadway friction before, during, and after winter storm events. Friction values above 0.6 are typically considered good and safe, whereas friction values below 0.6 are typically consider of concern or dangerous (depending on how low the friction value is) when looking at data specific to the winter season.

How CDOT Roadway Friction Data can be Applied to the ITD PI Method

The analysis of the CDOT roadway friction data found that the currently used roadway friction threshold of 0.6 defined in the ITD performance metric may be too conservative for CDOT. Instead, the researchers would recommend using a friction threshold value of 0.5 (based on the 0.48 – 0.52 friction value range shown in Table 6) for winter maintenance performance measurement.

In addition to this research effort, several other projects related to the use of roadway friction data and WMO are ongoing within Colorado. These may help inform this effort and aid in determining a useful roadway friction threshold value.

CDOT Variable Speed Limit Project

An ongoing CDOT project by DiExSys is working to identify variable speed limit (VSL) threshold values based, in part, on roadway friction values. Preliminary friction data ranges associated with changes in speed limit are provided in Table 7 and are summarized as:

- 0.6 > Safe, no change in speed limit recommended.
- 0.59 – 0.42 reduced safety, moderate reduction in speed limit suggested.
- <0.41 increased reduction in safety, significant reduction in speed limit suggested.

Table 7. Summary of VSL recommendations based on roadway friction values ranges (DiExSys, 2021).

	Speeds		
Coefficient of Frictionand Grade	Car	Truck 55	Truck 45
0.70 or greater	65	55	45
0.60 to 0.69	60	55	45
0.50 to 0.59	55	55	45
0.42 to 0.49	50	50	45
0.34 to 0.41	45	45	45
0.27 to 0.33	40	40	40
0.20 to 0.26	35	35	35
0.19 or less	30	30	30

Note that this project also found that the RWIS based friction sensors proved to be the best possible data source for their effort. See Appendix B. Analysis of RWIS-based versus Mobile Friction Data for our supporting results.

NCAR Analysis of CDOT Roadway Friction Data Applied in a Friction Forecasting Model

The National Center for Atmospheric Research (NCAR) and Western Transportation Institute (WTI) are currently working on an active Aurora project, sponsored by the Institute for Transportation at Iowa State University, looking at Roadway Friction Modeling. As a part of this effort, CDOT provided roadway friction data and NCAR applied an existing model developed to forecast friction values based on additional RWIS data - road temperature and precipitation type and amount.

Designed for airports, the model uses airport runway friction data from a friction wheel. The preliminary analysis, based on CDOT roadway friction data, is summarized in Table 8. The model would possibly alert CDOT that unsafe roadway friction conditions could be present at friction values of 0.33 – 0.29, would likely be alerted at roadway friction values of 0.28 – 0.24, and would most likely would be alerted at roadway friction values equal to or less than 0.23. Note that much lower friction values are associated with slick/slippery conditions when using the airport forecast model. The ongoing Aurora effort will work to better apply this model to the roadway environment.

Table 8. Friction thresholds identified by NCAR airport friction forecasting model using CDOT roadway friction data.

Friction Values	Alert
0.34	No Alert
0.33 – 0.29	Roadway Traction Alert Possible
0.28 – 0.24	Roadway Traction Alert Likely
0.23	Roadway Traction Alert Most Likely
0.22	

ANALYSIS OF RWIS-BASED VERSUS MOBILE FRICTION DATA

A detailed analysis of two friction data sources, the RWIS-based friction sensors and the mobile Teconer sensors, was conducted to determine if friction data can be used as a key component of a performance management tool and can be found in Appendix B. Analysis of RWIS-based versus Mobile Friction Data .

The analysis includes an assessment of data resolution across the state and investigates if the data sets can be combined by evaluating the identified test sections along the I-25 and I-70 corridors in Colorado (see Identified Test Sections for Analysis). Based on this analysis, it was determined that the RWIS-based friction sensors should be used for this effort due to quantity and spatial resolution of the data (see Friction Data Discussion).

Additionally, the friction data were analyzed to determine threshold values common in Colorado (Table 6) (see RWIS Friction Data Thresholds). It was found that if sufficient data from each data source are collected, the threshold values could apply to both friction data sets with error rates of approximately 20%.

Finally, a preliminary Kriging analysis of RWIS-based roadway friction data from the I-25 test section was conducted (Regression-Kriging Analysis of RWIS Friction Data). Based on this analysis, it was found that if similar road conditions are present between RWIS station locations, then roadway friction along the I-25 should be at or similar to the nearest RWIS station locations. Due to more complex road environment along the I-70 test section, it was determined this Kriging analysis method could not be applied.

The information gained from the analysis of roadway friction data available to CDOT was used to support the findings in the following IMPLEMENTATION PLAN, TRAINING MATERIALS, and CONCLUSIONS sections.

IMPLEMENTATION PLAN

The following three recommendations are discussed for successful integration of friction data into a performance management tool for Colorado DOT:

1. Use a less conservative roadway friction threshold value than the one currently selected.
2. Modify the existing performance management tool.
3. Develop quality assurance (QA) and quality control (QC) practices to support the use of the roadway friction values in WMO.

How to Apply Roadway Friction as a Performance Management Tool

This research effort recommends that CDOT modify and apply an existing performance management (PM) tool developed by Idaho Transportation Department (ITD).

Why is this Recommended?

- Previous work completed by Walsh (2016) for CDOT.
- Success of the ITD PI in Idaho (Jensen and Koeberlein, 2015) from which they able to:
    - Reduce the amount of time roads have mobility impeded in 2010-2015 by 45%, reaching and surpassing their original goal in just two years.
    - Improve consistency of operations and customer service statewide.

Reducing the Roadway Friction Threshold

The results of this research effort support the use of a less conservative friction value than 0.6 (used in the ITD PI method) for CDOT. The research team recommends considering a friction threshold somewhere between 0.48 - 0.52.

Why is this Recommended?

- Results from our analysis (see
- FRICTION VALUES MEASURED ON COLORADO'S ROADWAYS, Table 6)
- VSL analysis (see CDOT Variable Speed Limit Project)

Implementing Reduced Roadway Friction Threshold Values

To rollout this change, consider initially applying the 0.6 roadway friction threshold value in the application of the ITD PI in Colorado, while simultaneously looking at the feasibility of using a slow step-down approach toward a lower friction threshold value. For example, implement a lower friction threshold of 0.58 and, after a period of time (e.g., a winter season), look at the data and how the lower friction threshold affected achieving your defined level of service (LOS). Did WMO change significantly? Were there changes in roadway safety? If lowering the friction threshold makes sense, consider formally changing the threshold to 0.58. If this change is easy, consider another step down, say, to a friction threshold of 0.56. This approach will allow CDOT to make incremental changes to the friction threshold over time, and support decision making with data. If the data do not support the newest change in the roadway friction threshold, CDOT can return to a higher roadway friction threshold at any point in the step-down approach. The step-down process for systematically reducing the friction threshold is shown in Figure 8 and an example of the step-down approach in practice is provided in (Figure 9).

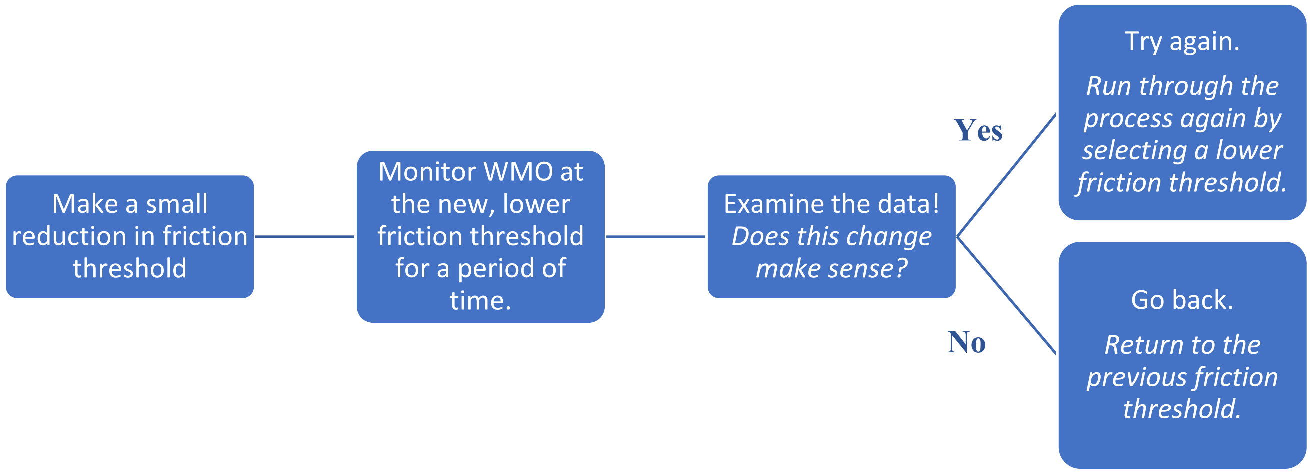

Figure 8. Flow chart approach for step-down in friction threshold values overtime based on data.

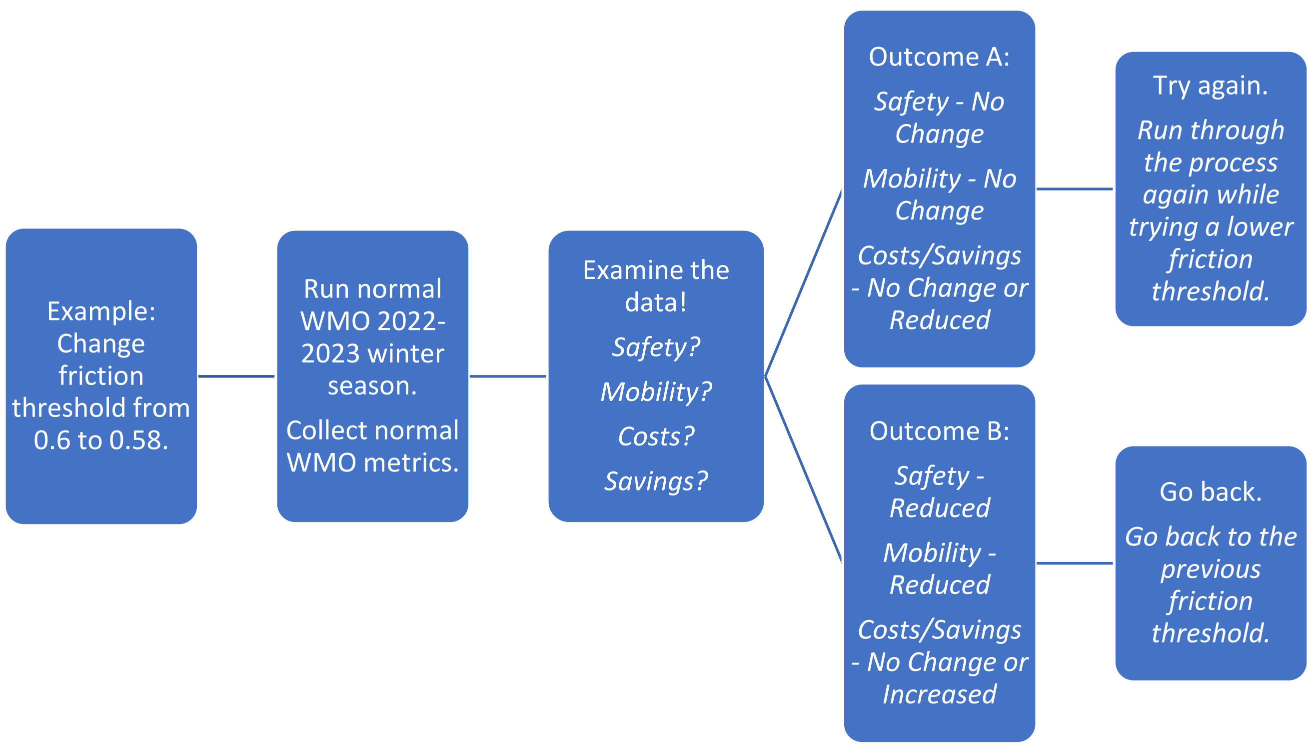

Figure 9. Example application of the flow chart approach for step down in friction threshold values overtime based on data.

When modifying the roadway friction threshold for WMO, choose a friction threshold value that achieves safety and mobility while balancing maintenance effort, cost, and sustainability!

The Importance of Accurate Storm Time Frame when Applying the ITD PI Analysis

The research team suggests that CDOT use the most accurate time frame during which storms occurred when applying the ITD PI tool, which has an input for the number of hours roadway friction values were below 0.6. Currently, storm summaries developed by CDOT include the dates of storm events but do not report specific time frames within those dates when areas within the state were impacted by winter weather. When using the ITD PI, CDOT should be sure to use roadway friction data that meet the friction threshold.

Ensuring Quality Data - Calibration and Maintenance

The importance of routine maintenance and calibration of all sensors, including friction sensors, cannot be overstated. Calibration and maintenance of both mobile and stationary sensors will ensure that data collected are as error free as possible.

Why is this Recommended?

During the research effort, it was determined that data collected at Colorado RWIS stations prior to 2017 were poor quality due to a lack of maintenance and calibration of the sensors. This has resulted in a huge loss of data and limits CDOT's ability to conduct long term analyses. CDOT has invested in the RWIS network; now the goal is to maintain the stream of quality data for use in operations, safety, and performance management.

Where to Start

Key recommendations:

1. Create a statewide maintenance plan for all mobile friction sensors and RWIS sites. This maintenance plan may include periodic cleaning or wiping of the surface of the sensor to ensure accurate readings. Additionally, mobile friction sensors should have their mounting, cables, and fittings checked periodically to ensure that the sensors are securely mounted to a vehicle as these fittings can come loose over time.
2. Ensure that all sensors are calibrated to the manufacturer’s specifications at the recommended frequency.
3. Designate a point person to identify and/or receive notification when a sensor is down or provides anomalous readings. This may be a person within the agency or from the RWIS vendor or data provider.

Stationary RWIS Non-Contact Friction Sensors

RWIS-based non-contact friction sensors were determined to provide the most consistent and robust data set for this effort. This was in part due to the passive nature of data collection sensors, which are always on, and due to their density and placement across the state. The densest networks are along the I-25 and I-70 corridors, and in CDOT Region 1 in the Denver Metro area. Outside of these areas, the presence of RWIS-based non-contact friction sensors is limited to nonexistent.

Key recommendations:

1. Ensure all RWIS sensors are maintained and calibrated on a routine schedule. Typically, this is done annually.

2. Ensure the friction data being collected are accurate and precise; QC and QA will need to be run on all RWIS data. This is often done by the RWIS sensor vendor and/or data provider and CDOT can work with them directly to learn more. Routine QA/QC will help to identify sensor issues as they occur, indicating a need for maintenance and/or calibration, while also ensuring the captured data are useable.
3. RWIS sites are often placed in trouble spots. For future RWIS locations, consider placing RWIS sites in areas with typical weather patterns for the region. The goal is to collect data that represent a large area, instead of a point location.
4. Create a list of future RWIS site locations so when funding is available you can act quickly.

Mobile Friction Sensors

Mobile friction sensors are a valid and useful data source. However, this project found that insufficient data was collected using the mobile devices for them to be a viable data source statewide in Colorado. While there are insufficient data to use in a CDOT performance measurement tool at this time, future mobile friction data could provide a robust enough data set. As is, mobile sensors can be used to "fill in the gaps" between RWIS locations and in areas lacking in sensors.

Key recommendations:

1. Make sure the mobile sensor is mounted on a vehicle that routinely runs the WMO routes.
2. Make sure the sensor the is calibrated each time it is turned on (see manufacturers guidelines for calibration methods).
3. Verify that the sensor is clean and securely mounted prior to operating the vehicle.
4. Turn the sensor on every time the vehicle is out.

5. Utilize the friction sensors online dashboard to quickly view the routes' roadway friction values and rating (dry, wet, icy, snowy, etc.) - https://roadweather.online/

TRAINING MATERIALS

Training materials titled Using Roadway Friction in Winter Maintenance Operations were developed in Power Point [Road Friction_Training.ppt] along with speaker notes for each slide. The training slides are provided in Appendix C. Training . The high-level presentation provides a summary of what friction data are, where they come from, where they can be found, and how they can be used. This was designed so that it could be incorporated in the annual snowplow operator training program and used by CDOT trainers when doing site visits/trainings.

CONCLUSIONS

The following conclusions can be made based on this research effort:

- Sufficient work has been done on the use of roadway friction data in performance measurement tools for other agencies to ensure the feasibility of using roadway friction data at CDOT.
- The Greater Denver Area, Upper Front Range, and Intermountain Regions of Colorado have sufficient friction sensor networks to use friction data in a performance management tool. Outside of these areas there is insufficient coverage at this time and, therefore, the limited available friction data should not be incorporated into a performance management tools for these parts of Colorado. It is recommended that additional RWIS sites with friction sensors, standalone friction sensors, or mobile friction sensors be deployed in these locations to increase data density. Another option is to explore the use of modeling to extrapolate friction values.
- The RWIS-based network of friction data sources (i.e., stationary non-contact friction sensors) provides the most robust data set for use by CDOT in this capacity.
- The ITD PI can be feasibly applied in Colorado but would benefit from the application of a data-driven step-down approach to a less conservative roadway friction threshold value and verification that the roadway friction data used meet the friction threshold.
- Additional and more consistent data collection is recommended where mobile roadway friction data are collected because the mobile friction data are not present in sufficient quantity to perform a comparative analysis. To support CDOT in this effort, it is recommended that a mobile friction sensor data collection protocol guide be developed that considers, at a minimum: calibration, cleaning, routes, frequency of use, and timing of data collection before, during, and after storm events.
- CDOT should maintain a data dictionary that retains RWIS station numbers, locations, data collected, etc. to improve their understanding of the data collection and support data analysis from season to season.
- CDOT should consider moving toward a consistent and uniform sensor system across the entire state. Side-by-side testing of various stationary friction sensors is currently

underway (https://aurora-program.org/research/in-progress/invasive-and-non-invasive-sensing-assessing-agreement-between-measurement-systems/) but it cannot be assumed that every sensor provides the same data.

- Regular maintenance and calibration of sensors will ensure data quality over time.

FUTURE WORK

The following research needs and knowledge gaps were identified throughout this research effort:

- CDOT has a wealth of RWIS and mobile roadway data currently provided by vendors. It is recommended that CDOT consider a long-term data storage/retention plan to ensure they have access to these data indefinitely.
- Consider working in cooperation with "connected vehicle" and crowdsourcing efforts at CDOT to connect mobile roadway friction data with RWIS station data so that each time a mobile friction sensor passes an RWIS station it leaves a note, or pings, information about when and what unit passed. This will significantly aid future data comparison efforts. (Note that some vendors already provide this information.)
- Future work using kriging, regression-kriging (RK), or other spatial analysis methods could be used to extrapolate roadway friction values beyond where data are collected and used to make informed decisions about spatial resolution and locations for future RWIS sites. The kriging output of roadway friction values between RWIS stations could be compared to mobile friction data. Additionally, RK could determine if proxy variables such as pavement temperature, precipitation, and road condition could be used in place of friction data in certain locations.
- CDOT can continue to leverage past and current efforts, such as the chain-up recommendations (Walsh, 2016) and VSL analysis (DiExSys, 2021), to inform future use of friction data.
- CDOT should consider assessing the quality of precipitation data being recorded.

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APPENDICIES

Appendix A. Summary of Identified Literature

Document Title, Date	Summary of Document	Notes
Feasibility of Using Friction Indicators to Improve Winter Maintenance Operations and Mobility (2002)	This is a good article that gives an update on how road friction data is collected and used until 2002. It contains the history of measuring road friction and how to use it as a road maintenance indicator (e.g. friction measuring tools, deicing methods, maintenance operations, etc.). It also gives examples of winter road condition and maintenance performance evaluations in different countries. The article indicates that we can advance these winter maintenance techniques with better friction data collection technology and predictive models.	Possible parameters for predictive model include traffic volume, ambient temperature, pavement type.
Using Friction Measurements to Gauge Winter Maintenance Performance (2007)	This article identifies several U.S. and foreign highway agencies that use or investigate friction for winter maintenance operations and performance measurements. The Real Time Traction Tool (RT3) is used by many states for automation of winter road conditions using real-time friction and pavement temperature measurements. They also use friction standards to evaluate performance of friction improvement methods.	Agencies are using RT3s experimentally and as guidance tools for drivers. Possible parameters for models include location, time, temperature, and traction.

Experiences of Mobile Road Condition Monitoring (2012)	The Teconer RCM411 sensor has been developed and tested for use in surface condition monitoring. Using optical detection of surface conditions with infrared spectroscopy, a model estimates the coefficient of friction starting from the measured surface condition. It then compares results to an accelerometer-based friction meter.	
Idaho Transportation Department Winter Maintenance Best Practices (2015)	Idaho uses RWIS and non-invasive pavement sensors to measure surface grip and atmospheric parameters. Since implementation, IDT has increased the mobility index during winter storms.	This article does not include any information about modeling friction, although the authors were able to use RWIS to establish consistency for operations and customer service statewide.

Document Title, Date	Summary of Document	Notes
Idaho's Winter Operations Systems (2018)	IDT uses RWIS, snowplow Mobile Data Collection (MDC), the Winter Automated Reporting System (WARS), and Agile Assets' Transportation Asset Management System (TAMS).	No references to using friction as a performance indicator.
Pavement Friction and Skid Resistance Measurement Methods: A Literature Review (2016)	This article provides an overview of different friction measuring devices: pros and cons.	
Utah Department of Transportation (UDOT) Weather Operations: Road Weather Index and Performance Metric (2015)	Utah Road Weather Index is a real-time index to evaluate weather, road conditions, and maintenance performance. Snowfall rates and road temperatures have the greatest impacts on roads.	UDOT Winter Road Weather Index quantifies atmospheric conditions and road conditions into one value; it accounts for snowfall rate, road temperature, blowing snow, freezing rain, and road grip/conditions. Reportable variables also include winter maintenance performance, storm intensity (winter weather index), number of storms, storm duration, normal climate comparison, and budget comparison.

Snow Removal Performance Metrics (2017)	The research team conducted a comprehensive literature review on the use of performance measures by transportation agencies for winter highway maintenance activities. To identify the effective performance metrics for snow and ice maintenance operations, all possible states with snow and ice were surveyed on their use of performance measures. The survey results identify commonalities and differences between agencies and were used to develop a matrix of performance measures. Relative costs associated with different metrics were also presented.	Wisconsin, Iowa, and Idaho DOTs share their winter maintenance performance with the public via website interface. Data collected from surveys indicate time to bare pavement, time to recovery speed, friction, system related outcomes (incidents, closures, chain laws), storm severity, material usage, equipment, cost of operations, and customer satisfaction are important metrics.

Document Title, Date	Summary of Document	Notes
Winter Maintenance Performance Measurement Using Friction Testing (2009)	Winter road surface friction measurements have been used by three Scandinavian countries (Finland, Norway, and Sweden) as a quality standard and been found by the respective road administrations to be a useful tool to safeguard traffic safety. These road agencies have indicated that measuring friction can be difficult and challenging, and there are plans to improve the quality standards with further research and development.	This paper has compiled journal articles on how agencies use friction to assess road conditions, and how they should treat the road relative to traffic volumes.
Surface Texture for Asphalt and Concrete Pavements (2005)	This Technical Advisory includes information on state-of-the-practice for providing surface texture/friction on pavements, and issues guidance for selecting techniques that will provide adequate wet pavement friction and low-tire/surface noise characteristics.	Things to take into account when considering surface friction and texture: climate, traffic volume and composition, speed limit, roadway geometry, potential conflicting movements and maneuvers, material quality and costs.

Evaluation of Temperature Influence on Friction Measurements (2011)	The results of this paper show it is possible to define a reference temperature to adjust friction measured at any other temperature value. If the air temperature is greater than the reference temperature, the friction reading is biased by a positive quantity and the adjustment factor reduces the measured friction. For measurements performed at temperatures lower than the reference temperature, the adjustment factor increases the measured friction.	By adjusting friction values to a standard temperature, friction levels measured any time of the year and at any temperature will provide agencies the tool to improve the comparison of pavement sections and a more objective assessment of pavement conditions in relation to safety. It will also improve uniformity in the interpretation of friction characterizing the entire pavement network.

Appendix B. Analysis of RWIS-based versus Mobile Friction Data Sources

Methodology

Test sections were identified along I-25 and I-70 with the help of the CDOT project panel members (Tom Aguilar, Tyler Weldon, and Jamie Yount). The RWIS station locations and Teconer sensors that are present in these test sections were also identified. Friction and road weather data from the RWIS stations in the test sections were provided by CDOT for October through March from 2017 – 2020. Data were provided by Teconer for the units that are present in each test section between 2017 and 2020. Details on the data processing, data QA/QC, and analysis methods can be found in the next section.

Friction Data Assessment

Friction Data Sources

To determine if friction data can be used as a key component of a performance management tool, an analysis of the available friction data sets in Colorado, including CDOT's RWIS network (stationary sensors) and the Teconer snsors (mobile mounted sensors), was conducted to determine if the data sets can be combined and if there is sufficient resolution over time and space to make informed decisions regarding their use in performance management. The following sub-sections provide details on the test sections, data locations, data elements, QA/QC, analysis periods, and analysis results.

Identified Test Sections for Analysis

The I-25 test section runs from mile post 247 to 298 and contains six RWIS stations (with friction sensors) over approximately 51 miles (Figure 10). It is oriented North-South with consistent elevation and topography (high plains along the front range) and remains a 4-lane interstate across the 51 mile section.

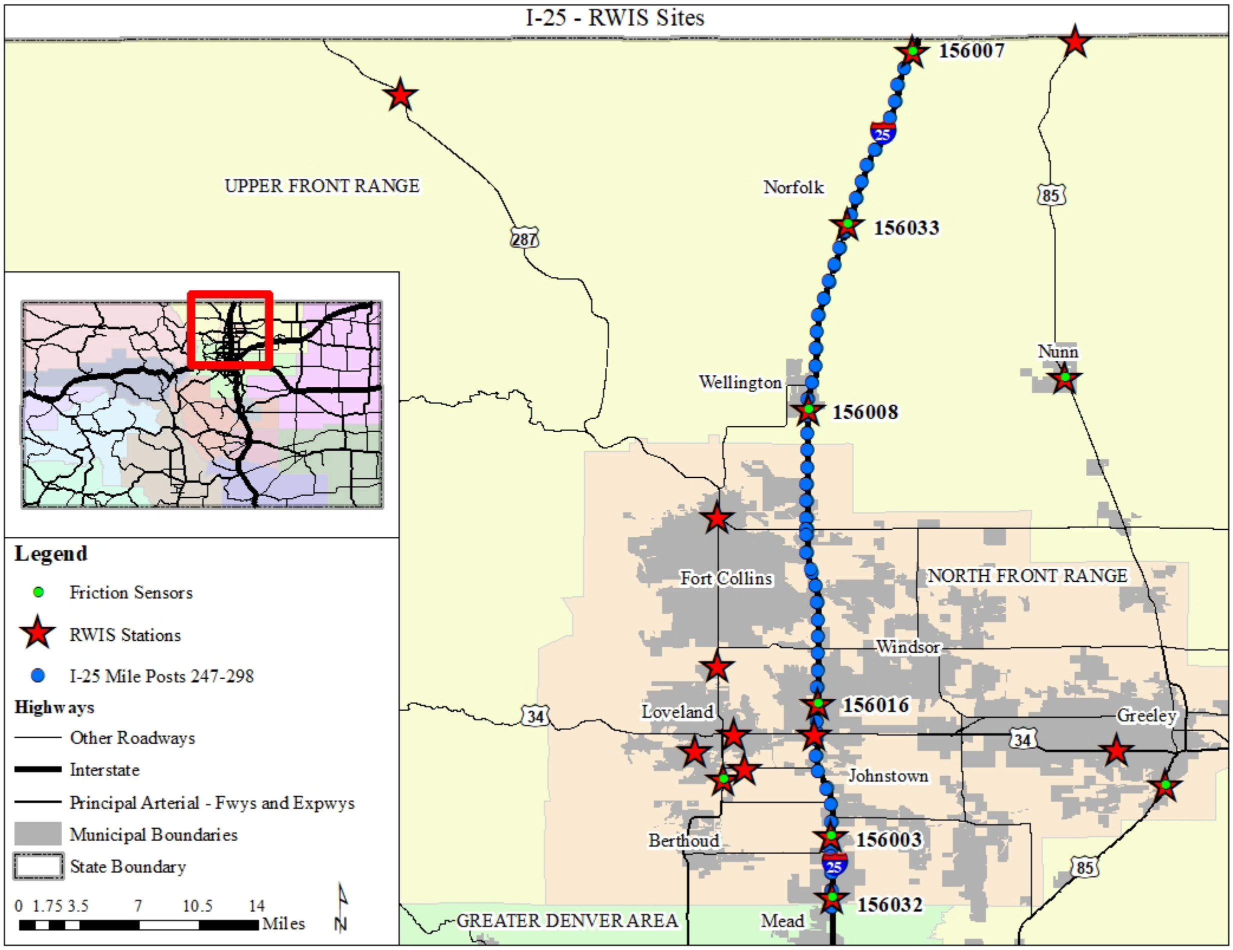


Figure 10. Map of the I-25 test section with mileposts, RWIS stations, and RWIS locations with friction sensors (ID numbers are shown for those RWIS sites of interest on I-25).

RWIS Stations on I-25 (north to south) with identifying numbers:

- 025S298 NATURAL FORT (RWIS) #156007
- 025S288 @ CR-82 BUCKEYE RD #156033
- 025N277 WELLINGTON (RWIS) #156008
- 025N259 CROSSROADS BLVD (RWIS) #156016
- 025S251 BERTHOUD (RWIS) #156003
- 025N248 2.4 MI N OF WCR-34 #156032

The I-70 test section runs from mile post 200 to 239 and contains 18 RWIS stations over approximately 39 miles (Figure 11). It is generally oriented East-West through the Rocky Mountains but varies from 4-lane to 2-lane, is highly variable in elevation, topography, and shading, and can be described as a curvy mountain highway. RWIS station ID numbers are shown in Figure 11.

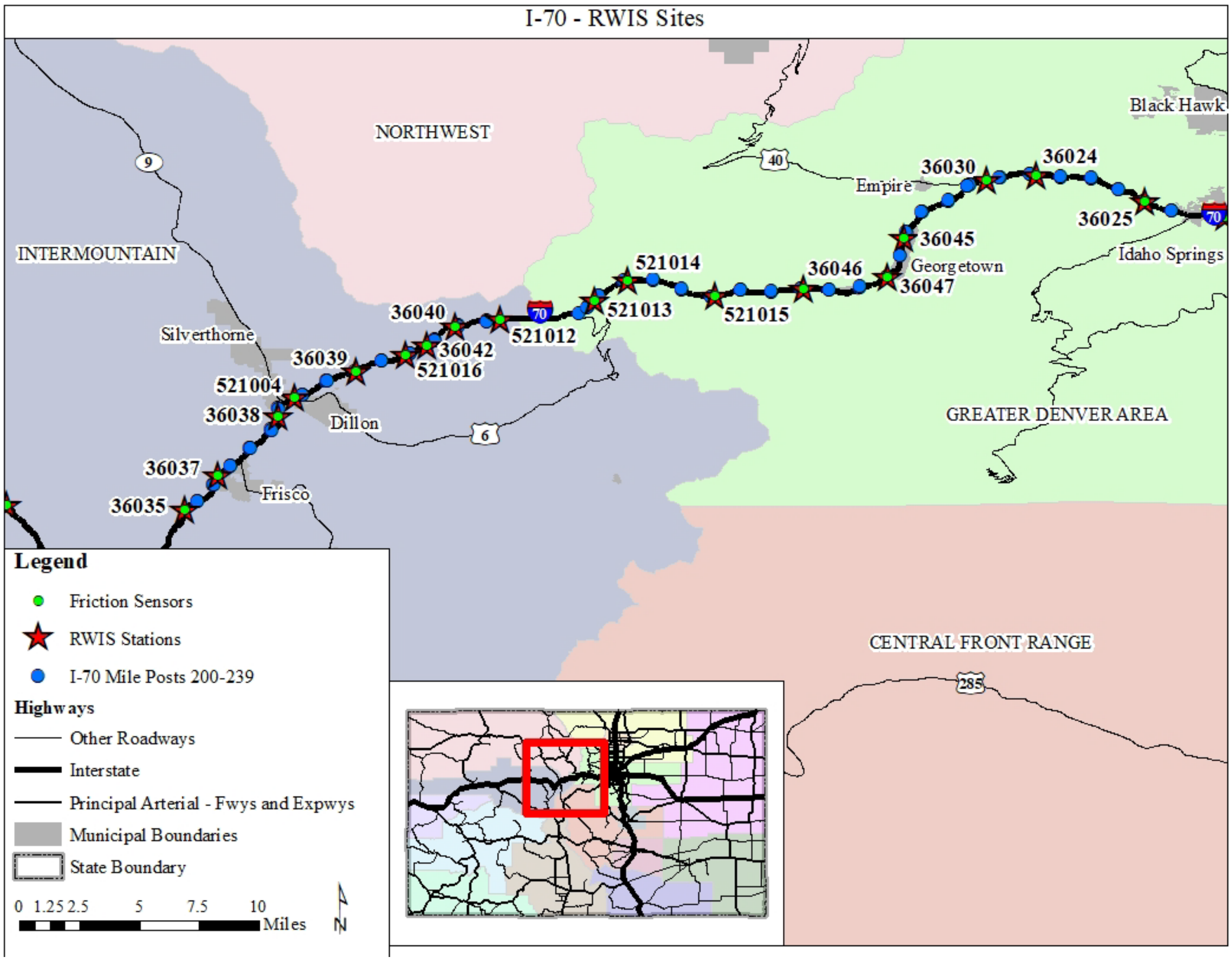


Figure 11. Map of the I-70 test section with mileposts, RWIS stations, and RWIS locations with friction sensor locations shown (ID numbers are shown for those RWIS sites of interest on I-70).

RWIS Station locations on I-70 (west to east) and identifying numbers:

- 070W200 1.3 MI W OF FRISCO (RWS200) #36035
- 070E201 0.9 MI W OF CO-9 FRISCO (RWS200) #36037
- 070E205 0.7 MI W OF CO-9 SILVERTHORNE (RWS200) #36038
- 070W205 SILVERTHORNE (RWIS) #521004
- 070W208 2.4 MI E OF SILVERTHORNE (RWS200) #36039
- 070E210 I-70 @ E OF LOWER TRUCK RAMP (RWIS) #521016
- 070E211 2.9 MI W OF EJMT - THE BOX (RWS200) #36042
- 070W212 1.7 MI W OF EJMT - UPPER RTR (RWS200) #36040
- 070E214 EJT WEST PORTAL (RWIS) #521012
- 070E217 US 6 LOVELAND PASS (RWIS) #521013
- 070W218 HERMANS GULCH (RWIS) #521014
- 070W221 BAKERVILLE (RWIS) #521015
- 070W224 1.6 MI W OF WOODWARD ST. GEORGETOWN (RWS200) #36046
- 070E227 0.9 MI W OF 15TH ST. GEORGETOWN (RWS200) #36047
- 070W229 0.85 MI E OF 15TH ST GEORGETOWN (RWS200) #36045
- 070E233 0.7 MI E OF US-40 (RWS200) #36030
- 070E234 DOWNIEVILLE INT - (RWS200) #36024
- 070E238 0.3 MI E OF FALL RIVER RD. (RWS-200) #36025

RWIS Data Elements

The following data are collected by RWIS stations in Colorado:

RWIS Atmospheric Data

- Air Temperature
- Minimum Air Temperature
- Maximum Air Temperature
- Wet Bulb Temperature

- Relative Humidity
- Dew Point
- Visibility
- Wind Direction
- Wind Speed
- Wind Gust Direction
- Wind Gust Speed
- Precipitation Rate
- Precipitation 1hr
- Precipitation 3hr
- Precipitation 6hr
- Precipitation 12hr
- Precipitation 24hr

Variables selected for use in this project:

- Friction Coefficient
- Pavement Temperature
- Surface Status

RWIS Road Surface Data

- Friction Coefficient
- Pavement Temperature
- Surface Status

Friction coefficient, pavement temperature, and surface status/state were determined to be key variables to support this effort and CDOT provided data from October through March from 2017-2020. Note that there were concerns that the RWIS friction data collected prior to 2017 was not of good quality due to maintenance and calibration issues so it was not used in this effort.

Teconer Data Elements

The following Teconer sensors were identified along the I-25 and I-70 test sections (Table 9):

Table 9. List of Teconer units deployed along the I-25 and I-70 test corridors.

I-25	I-70
RCMG94, RCMG96, RCMG27, RCMH66, RCMH78, RCMH81, RCMI10, RCMI11, RCMI12, RCMI13, RCMI14, RCMI18, RCMI21, RCMI25, RTDV04	RCMG95, RCMH70, RCMH71, RCMH73, RCMH74, RCMH75, RCMH78, RCMH79, RCMH81, RCMI03, RCMI04, RCMI06, RCMI08, RCMI11, RCMI16, RCMI17, RCMI18, RCMI20, RCMI21, RCMI24, RCMI25, RCMI29, RTDU59, RTDU61

The Teconer units provide the following data: friction coefficient, surface condition, water layer thickness, and GPS tracking information reported as latitude and longitude coordinates for each data point. Teconer provided access to the data from October through March of 2017-2020 for identified units (Table 9) along the I-25 and I-70 test sections. There were 768 data files for I-25 and there were 3,061 data files for I-70.

Note that Teconer applies a smoothing algorithm to the friction data, which modifies the raw friction data from the road surface to report a rolling average friction value every 1 to 3 seconds. This provides a general picture of road friction values, reducing potentially high and low friction values from being reported. For this reason, it is likely that friction data reported by the Teconer sensor will differ from other mobile friction sensors and stationary friction sensors in close proximity.

Friction Data Analysis Period

The RWIS and Teconer data were analyzed from October through March of 2017-2020 to focus on data from winter weather events. Because the quantity of data for the Teconer and RWIS sites was extensive (more than 3,800 files with many rows), it was important to focus on winter storm events. Therefore, starting in 2019-2020, CDOT began to create storm summaries for the winter season. Using this information, the following storms were identified by month:

- 6 storms occurred in October 2019
- 3 storms occurred in November 2019
- 5 storms occurred in December 2019
- 5 storms occurred in January 2020
- 5 storms occurred in February 2020
- 5 storms occurred in March 2020

The CDOT defined 2019-2020 storm events, provided above, were used to define the analysis periods between the RWIS and Teconer data sets. RWIS data analysis was conducted using all the data from sites in both the I-25 and I-70 corridors, and for specific identified storm events in the 2019-2020 winter season. In contrast, the Teconer data were not always collected during the defined storms or near RWIS stations and were therefore only analyzed for specific identified storm events in the 2019-2020 winter season. While originally thought to be extensive, digging further into the data revealed that there were imbalances regarding when and where the data was collected.

I-25 Summary of Data Analysis

Data were selected from the six RWIS sites that collected friction data during the 2017-2020 winter seasons (Figure 10, see Identified Test Sections for Analysis for a list of locations). While friction data are available prior to 2017, the data quality came into question and was therefore not used.

Available Teconer data along the I-25 corridor are provided in Table 10. It can be observed from Table 10 that the number of available observations of Teconer data has increased since the 2017-2018 winter seasons. It is recommended that CDOT establish a Teconer data collection plan for storm events and routes. Additional recommendations are provided in the CONCLUSIONS section of this report.

Establish a Teconer data collection plan for storm events and routes.

Table 10. Total of data files collected by Teconer units along the I-25 test section by winter season.

Winter Season	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	TOTAL
2017-2018	0	4	14	2	9	19	0	1	0	49
2018-2019	7	51	61	37	36	60	81	41	9	383
2019-2020	25	79	70	12	4	58	37	36	0	321

An important point to make regarding the data is that even though there may be Teconer files for time periods of interest, that does not mean that the maintenance vehicles traveled past the RWIS sites along the I-25 and I-70 test sections. Also, there were times that maintenance vehicles collected data when there was not a storm. To further filter the data, data files for the following storm dates were pulled for analysis due to presence to significant Teconer files (see grey boxes in Table 10):

- October 9-11, 2019
- October 28-30, 2019
- November 25-26, 2019

These storm dates were chosen because they represented storms that impacted both the I-25 and I-70 test sections (notes for the storms stated “Light/moderate snow N/C Mtns” (northern / central mountains) and “Light/moderate snow mtns”) and took place during the months with the two largest numbers of Teconer data files available, highlighted in grey in Table 10 (i.e. 79 and 70 Teconer files from October and November, respectively.). For these dates, 65 Teconer files were analyzed to determine whether the Teconer sensors passed by an RWIS site on the I-25 test section during the specified storm events. (Note: This is less than the numbers identified in Table 10 because not every file was associated with the selected storm dates (e.g. October 9, 10, 11, 28, 29, 30 and November 25, 26).

The Teconer data files were analyzed, and records were pulled when the Teconer sensor was near one of the stationary RWIS identified on the I-25 test section. The Teconer sensor was considered “near” a stationary RWIS site when the latitude and longitude of the Teconer record was within four decimal places of the RWIS site’s location (or within 36.4 feet (Fox, 2017)). Since the Teconer unit records data for each second, in the case where multiple records fell within the threshold of “near” an RWIS site, the closest record was pulled for each minute that the unit was nearby an RWIS station in I-25 test sections.

Figure 12 shows the total number of Teconer records from the selected storm dates pulled for each RWIS station (blue numbers next to each red star with a green dot). Table 11 presents the total Teconer records pulled for each RWIS station on the I-25 test section and the average percent difference and standard deviation between the RWIS-based and the Teconer friction values. The average difference in friction values range from 5% to 38%, with standard deviation ranging from 16 to 55 (Figure 10 provides a map of the I-25 test section with RWIS site locations and ID numbers). The coefficient of friction value that the Teconer recorded for each record was than compared to the coefficient of friction recorded at the nearby RWIS site for that time. The coefficient of friction from the Teconer and the RWIS were plotted to compare the two sources for the three chosen storm dates (Figure 13, Figure 14, and Figure 15). All Teconer data records pulled for each RWIS station and comparable RWIS data records are included in the Supplemental Document – Additional Figures & Teconer Data.

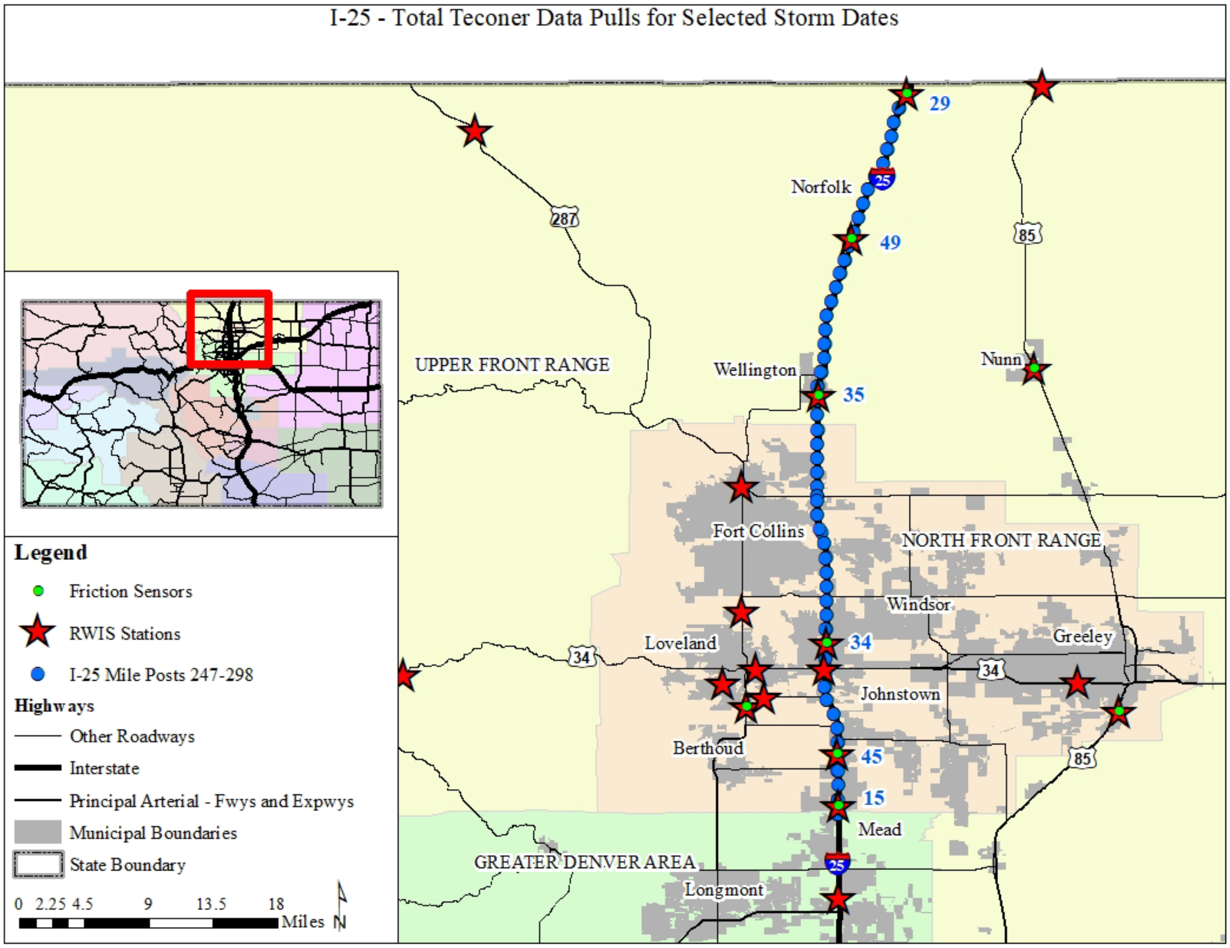
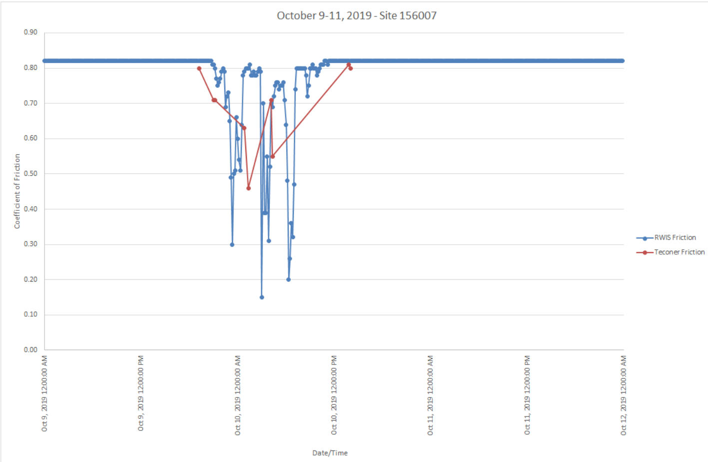


Figure 12. Total Teconer data records per location on the I-25 test section.

Table 11. Total Teconer records pulled per RWIS location per storm date for I-25

Nearby RWIS Site ID (N to S)	Total Teconer Data Records				Average Percent Difference Between RWIS and Teconer Coefficient of Friction	Standard Deviation
	October 9-11, 2019	October 28-30, 2019	November 25-26, 2019	Total Records		
156007	10	10	9	29	5.0%	47.6
156033	8	13	9	30	38.3%	55.0
156008	11	15	9	35	14.5%	30.8
156016	5	17	12	34	10.2%	43.4
156003	7	32	10	49	27.2%	16.6
156032	1	10	4	15	10.0%	28.0

A)



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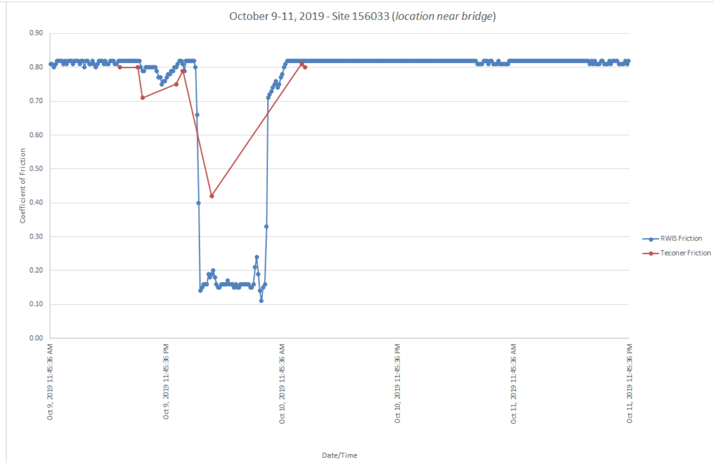

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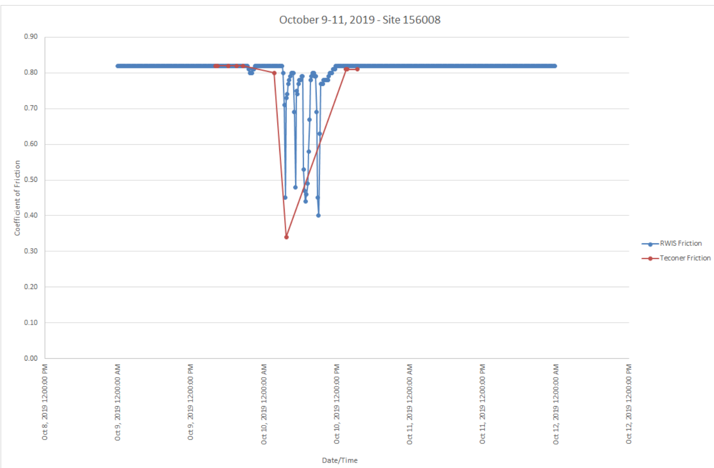

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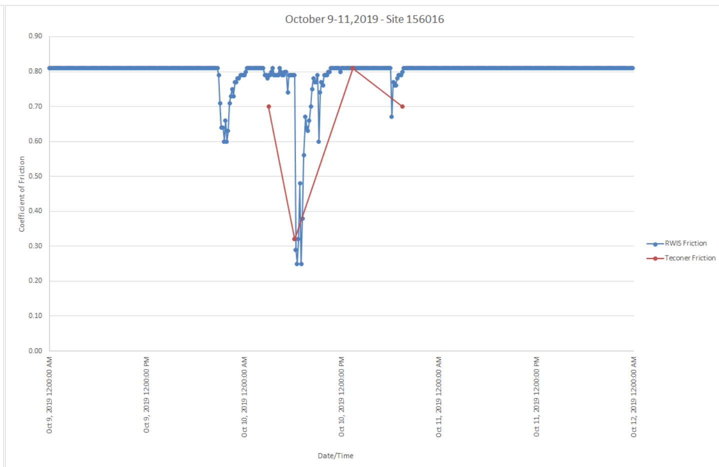

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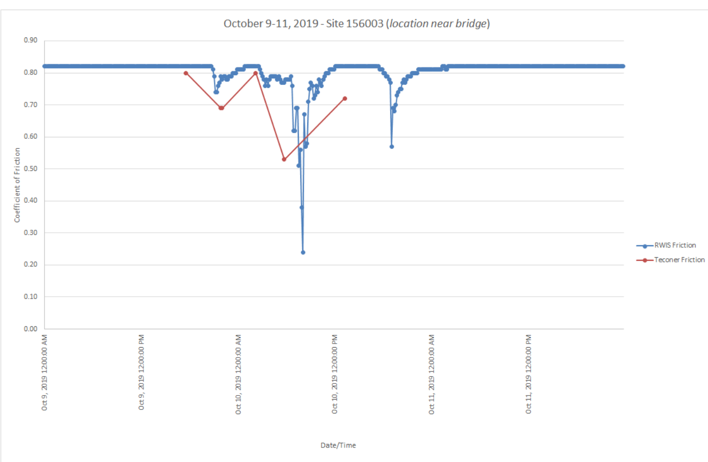

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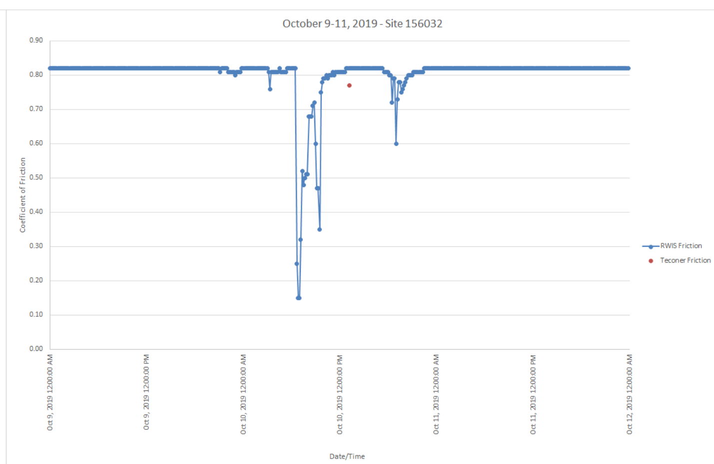
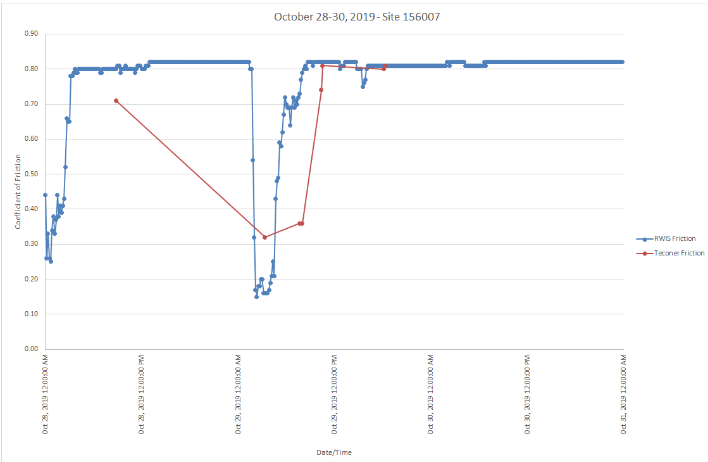


Figure 13. A-F shows RWIS and Teconer friction data from RWIS locations along I-25 during the Oct.9-11, 2019 storm event.

A)



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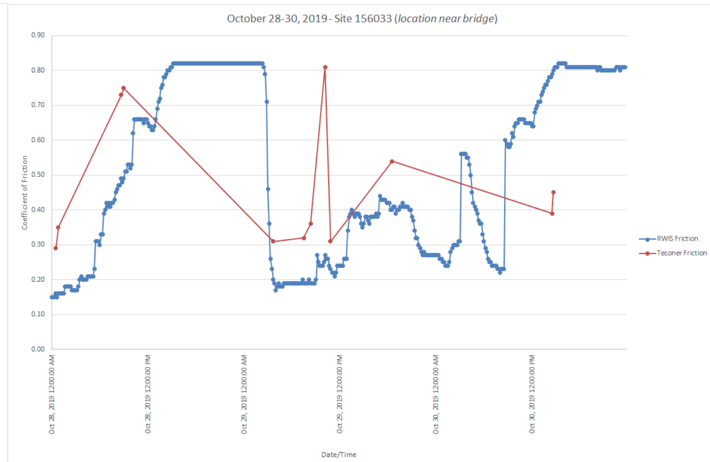

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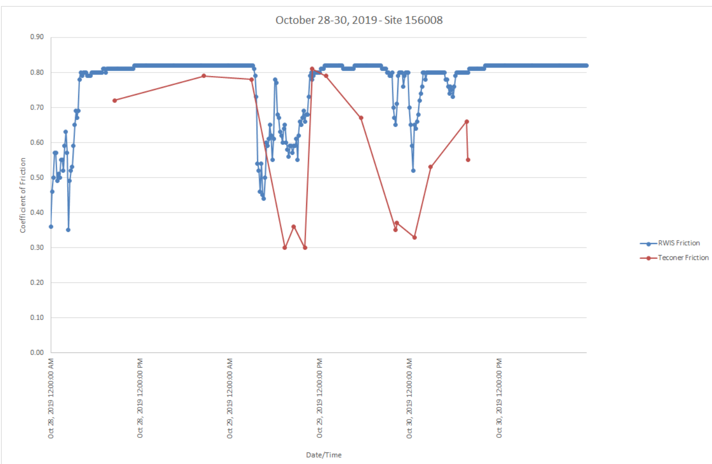

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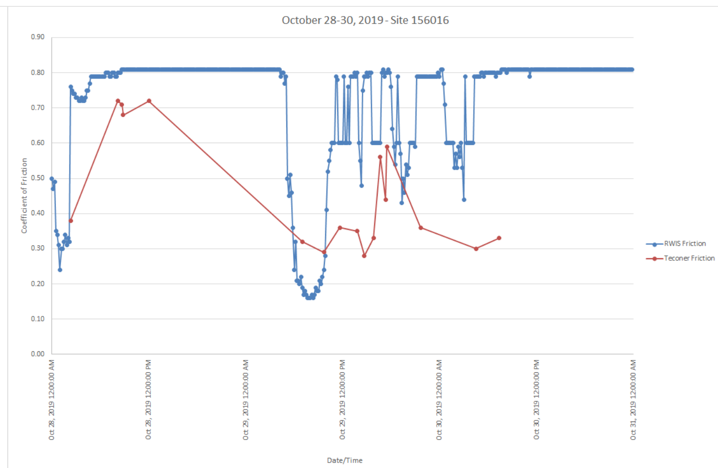

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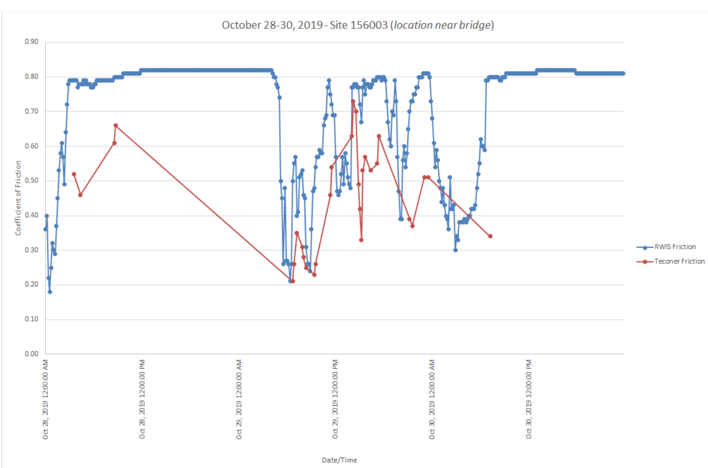

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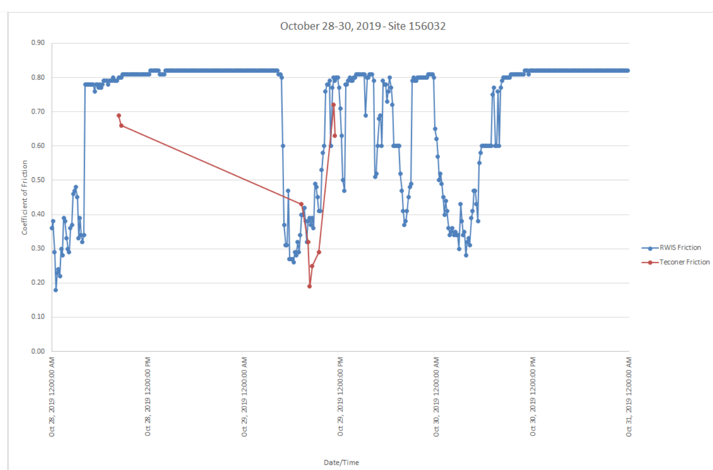
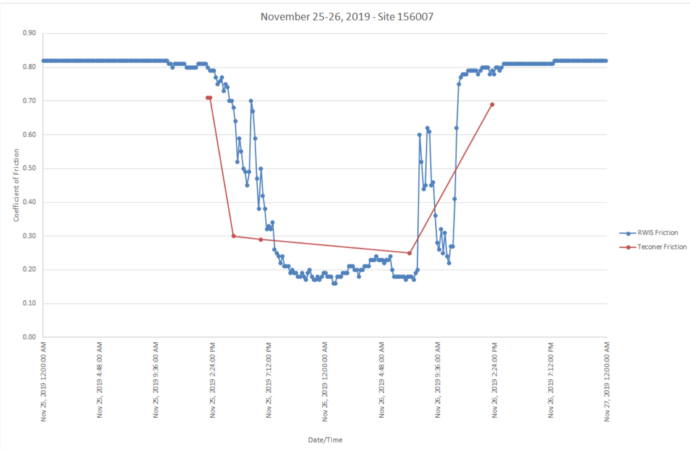


Figure 14. A-F shows RWIS and Teconer friction data from RWIS locations along I-25 during the Oct.28-30, 2019 storm event.

A)



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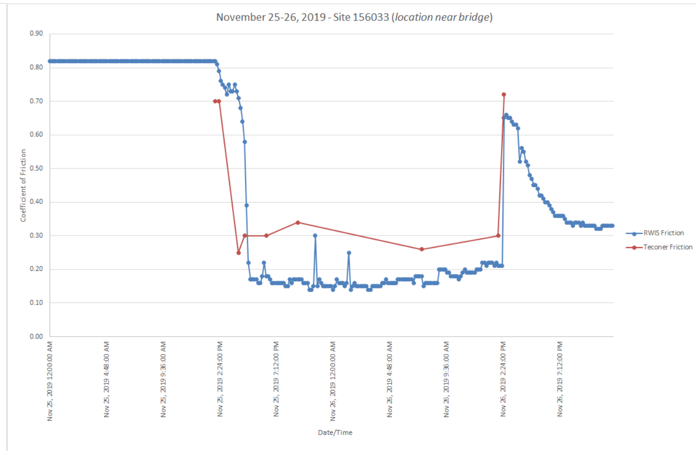

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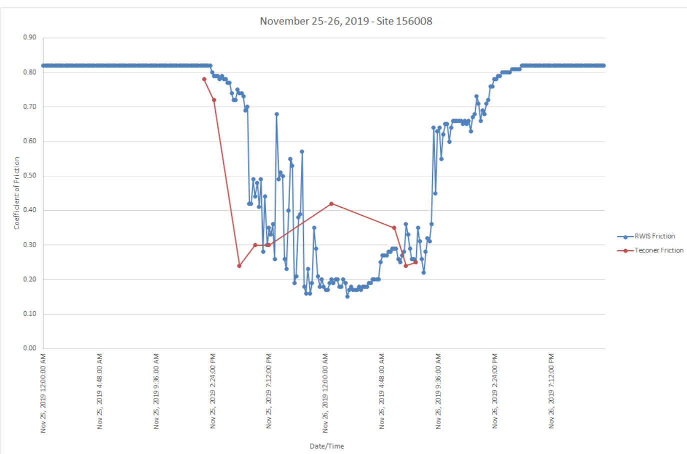

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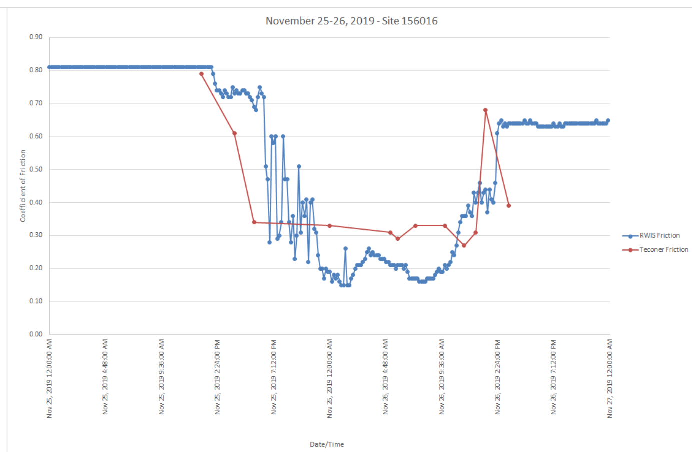

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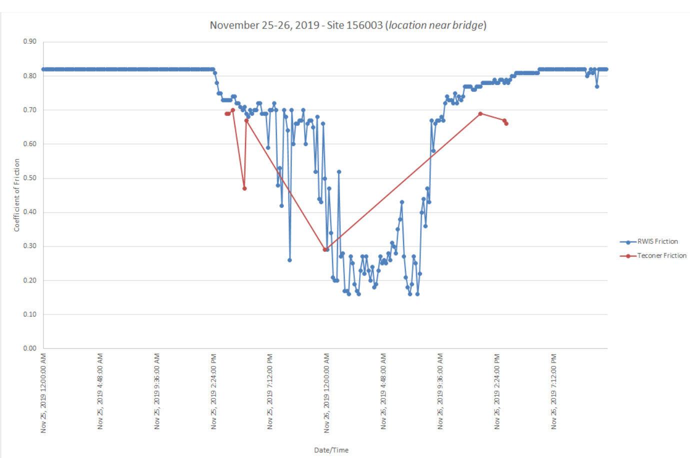

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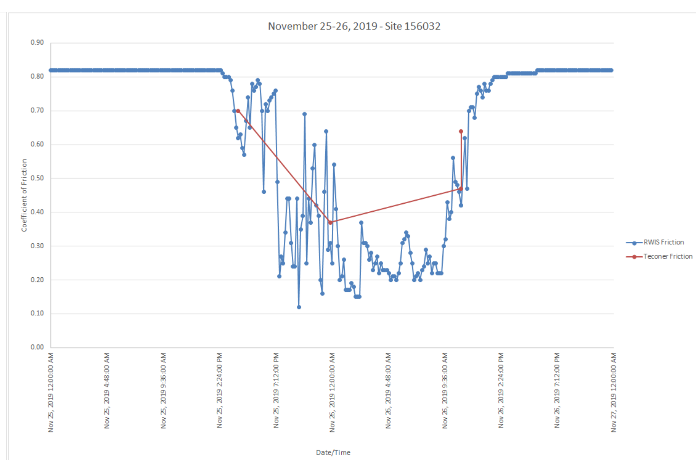


Figure 15. A-F shows RWIS and Teconer friction data from RWIS locations along I-25 during the Nov. 25-26, 2019, storm event.

Considering Figure 13, Figure 14, and Figure 15 and the average percent difference and standard deviation between the RWIS-based friction values and the Teconer friction values for each RWIS site along the I-25 test section from Table 11 the following conclusions can be made:

- There is a similar overall trend in friction values between RWIS and Teconer friction data.
- Significantly more friction data were collected through the RWIS stations than Teconer units and the points at which the graphs do not follow similar trends is often an artifact of limited Teconer data.
- The friction values from the RWIS-based sensor and the Teconer generally match trends where more Teconer data were collected (Figure 14a) – particularly when considering typical friction thresholds for winter maintenance activities (0.4 and above is drivable, anything below 0.4 is of concern/needs treatment).
- The average difference in friction values between the stationary and mobile sensors is highly variable and can be large. This may be due to data collection occurring at different locations on the roads surface, the smoothing algorithm Teconer uses, and/or limited Teconer data when compared to the RWIS friction data set.

I-70 Summary of Data Analysis

RWIS-based friction data was selected from 18 RWIS sites along the I-70 test section during the 2017-2020 winter seasons (Figure 11, see Identified Test Sections for Analysis for a list of locations). While friction data were available prior to 2017, their quality came into question and they were not used.

Available Teconer data along the I-70 corridor is provided in Table 12 and shows that the number of available Teconer observations has increased significantly over time but that number is not consistent. As mentioned previously, one recommendation to CDOT is to establish a Teconer data collection plan for each storm event, route, etc.

Table 12. Total number of data files collected by Teconer units along the I-70 test section by winter season.

Winter Season	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	TOTAL
2017-2018	0	0	2	97	70	0	0	0	0	169
2018-2019	0	0	0	218	262	208	361	235	132	416
2019-2020	65	204	205	201	225	250	157	106	33	1446

To remain consistent with the analysis of the I-25 corridor, data files for the following storm dates were pulled for analysis:

- October 9-11, 2019
- October 28-30, 2019
- November 25-26, 2019

These storm dates were chosen because they were expected to represent storms that impacted both the I-25 and I-70 test sections and were within a time frame where there was an abundance of Teconer data. 85 Teconer files, which were created during the above dates, were analyzed to determine whether the Teconer units passed by a stationary RWIS site along the I-70 test section during the identified storm events (e.g. was the latitude/longitude within the aforementioned 36.4 feet).

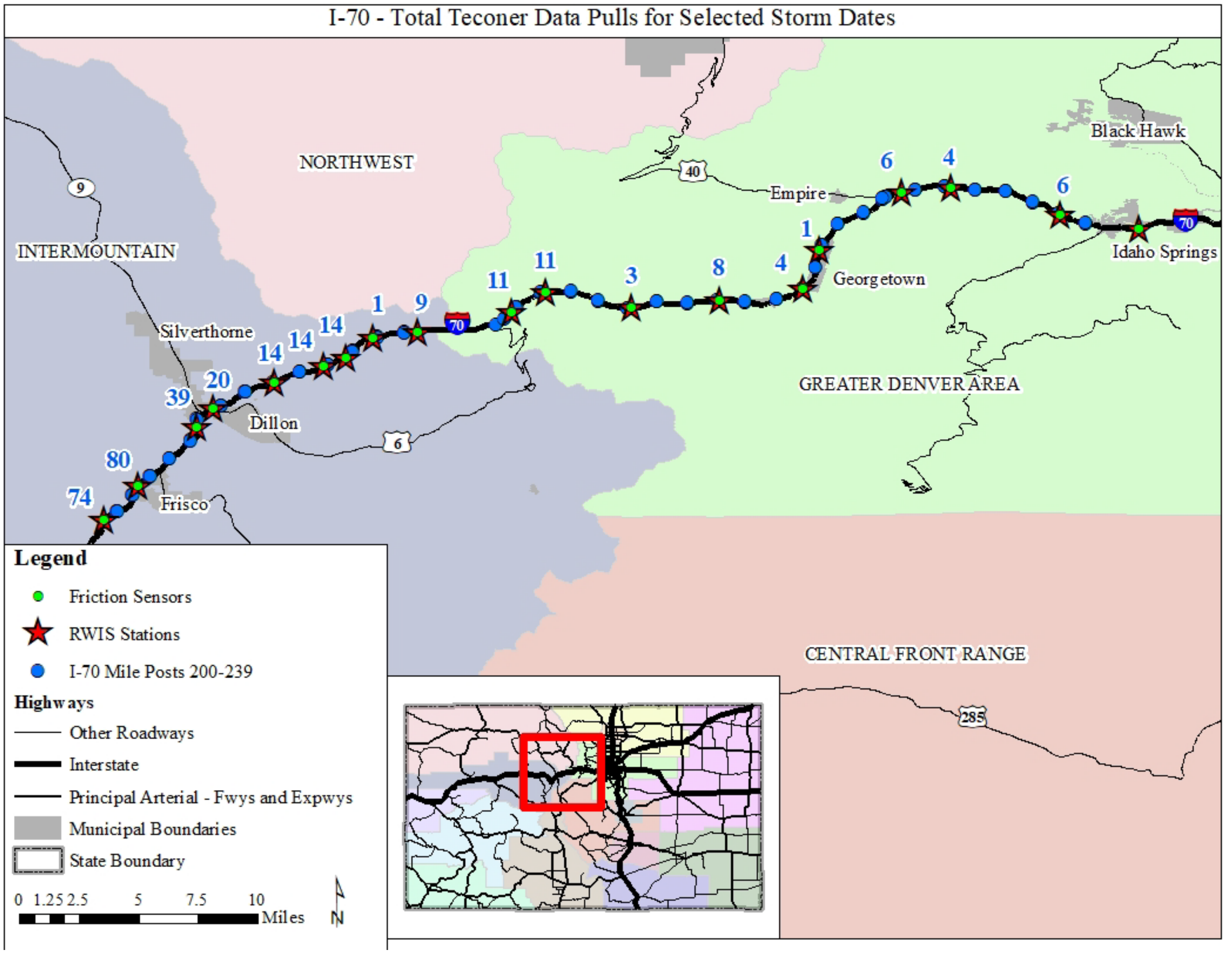


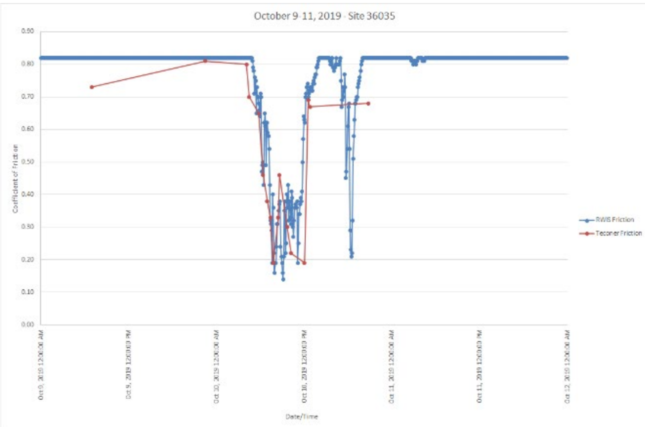
Figure 16. Total Teconer data records per RWIS location on the I-70 test section.

Figure 16 shows the total number of Teconer records from the selected storm dates pulled for each RWIS stations (blue numbers next to each red star with a green dot) and Figure 11 provides a map of the I-70 test section with RWIS site locations and ID numbers. Table 13 presents the total Teconer records pulled for each RWIS station on the I-70 test section and the average percent difference and standard deviation between the RWIs stationary friction values and the Teconer mobile friction values. The average difference in friction values range from 3% to 186%, with standard deviation ranging from 23 to 125. The coefficient of friction value that the Teconer recorded for each record was then compared to the coefficient of friction recorded at the nearby RWIS site for that time. The coefficient of friction from the Teconer and the RWIS were plotted to compare the two sources for the three chosen storm dates, (Figure 17, Figure 18, and Figure 19). Additional figures and Teconer data are provided in Supplemental Document – Additional Figures & Teconer Data.

Table 13. Total Teconer record pulls per RWIS location per storm date for I-70.

Nearby RWIS Site ID (W to E)	Total Teconer Data Records				Average Percent Difference Between RWIS and Teconer Coefficient of Friction	Standard Deviation
	October 9-11, 2019	October 28-30, 2019	November 25-26, 2019	Total Records		
36035	18	32	24	74	3.4%	60.1
36037	20	37	23	80	31.3%	75.4
36038	11	14	14	39	88.9%	125.3
521004	9	6	5	20	6.9%	48.0
36039	6	6	2	14	5.3%	48.6
521016	6	6	2	14	3.5%	34.1
36042	6	6	2	14	18.6%	23.6
36040	1	0	0	1	17.1%	N/A
521012	1	6	2	9	3.5%	65.8
521013	1	8	2	11	15.9%	39.6
521014	1	8	2	11	63.7%	89.9
521015	0	3	0	3	35.1%	62.7
36046	0	6	2	8	71.3%	64.7
36047	0	3	1	4	24.3%	67.5
36045	0	1	0	1	11.7%	N/A
36030	0	4	2	6	183.0%	93.4
36024	0	2	2	4	47.6%	25.2
36025	0	4	2	6	169.7%	106.0
TOTAL	80	152	87	319		

A)



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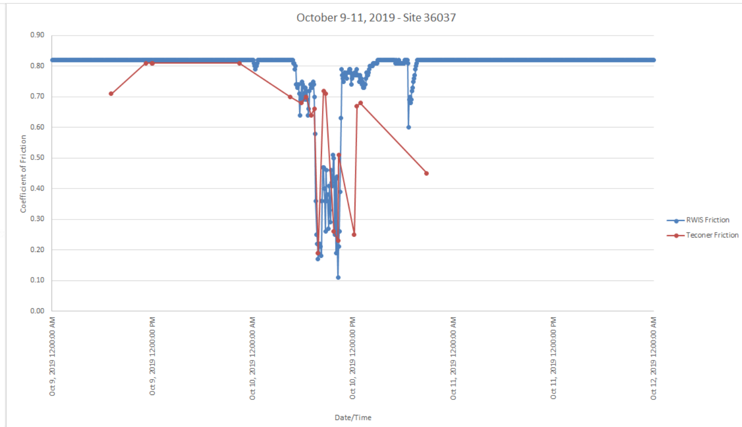

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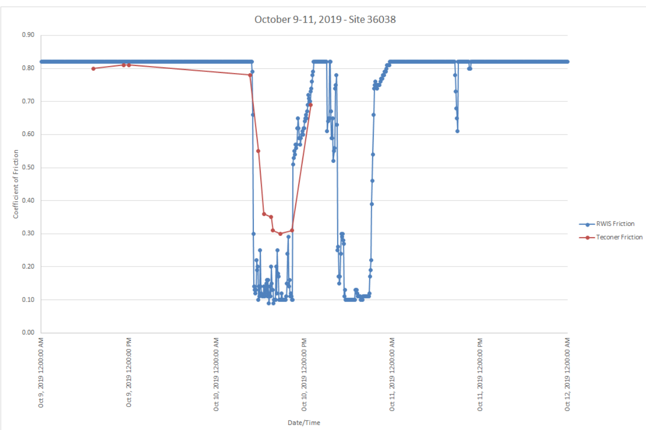

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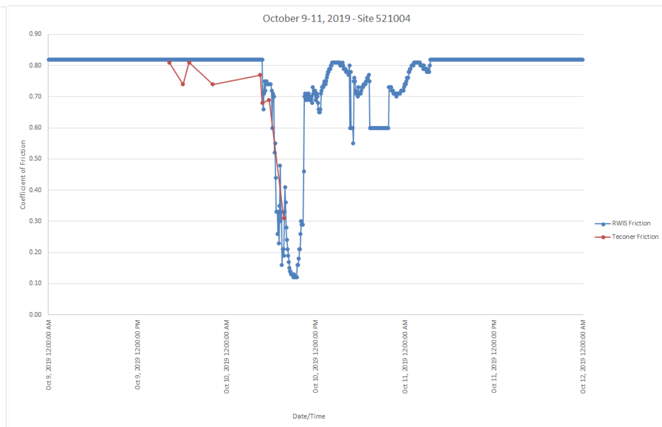

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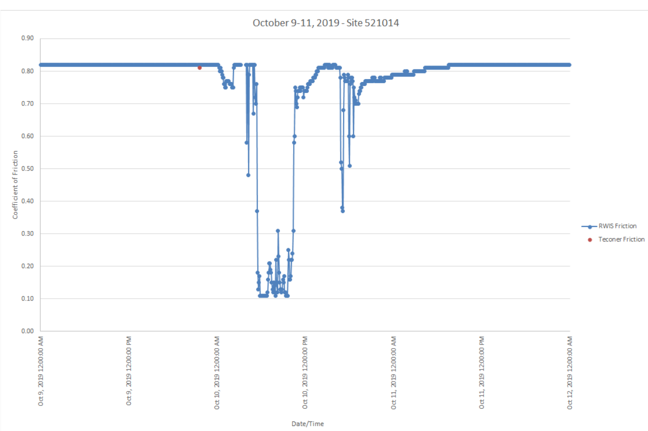

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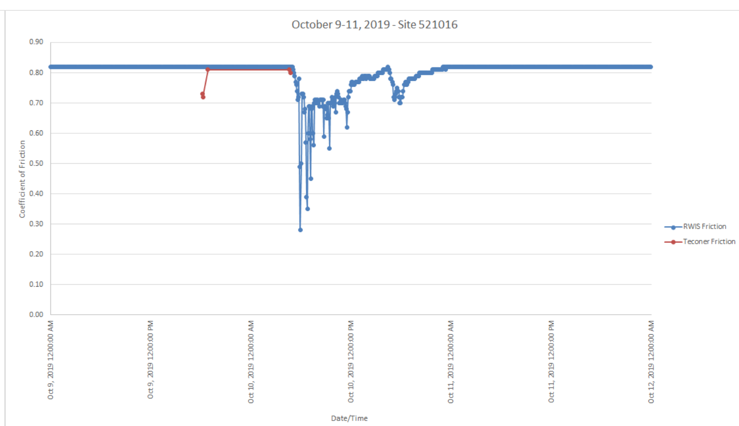
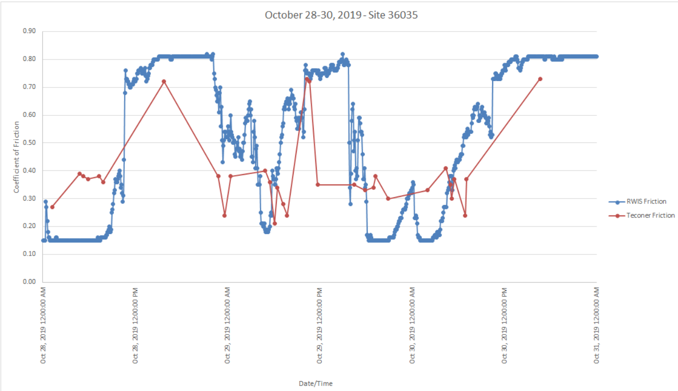


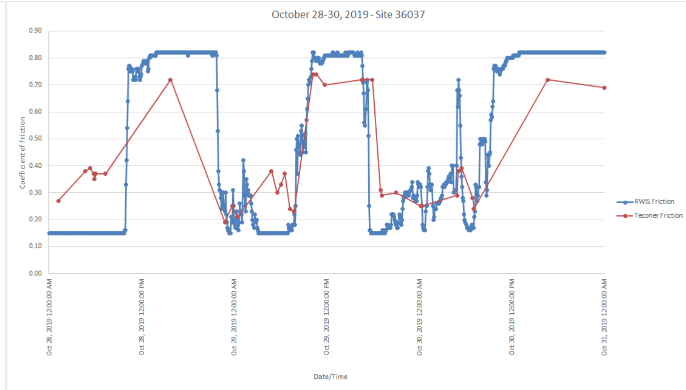
Figure 17. A-F shows RWIS and Teconer friction data from RWIS locations along I-70 during the Oct.9-11, 2019 storm event. Additional graphs are provided in Appendix A. Summary of Identified Literature Extra graphs from I-70 RWIS and Teconer friction data comparison.

A)



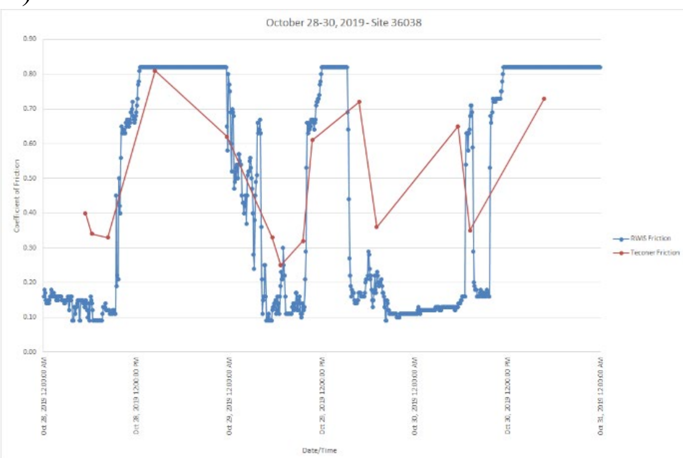
October 28-30, 2019 - Site 36035
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

B)



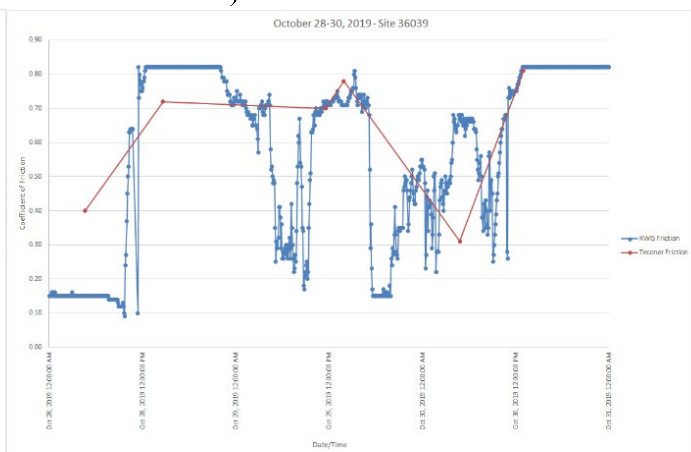
October 28-30, 2019 - Site 36037
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

C)



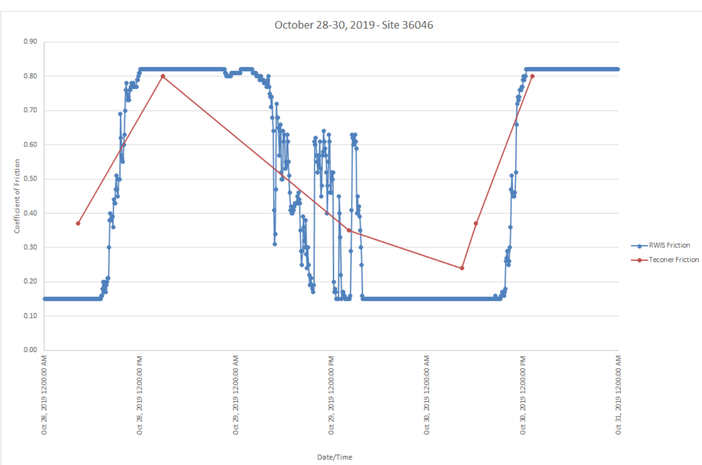
October 28-30, 2019 - Site 36038
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

D)



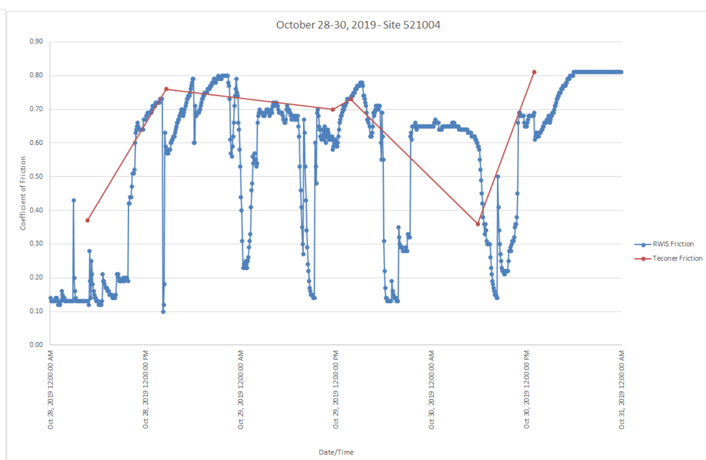
October 28-30, 2019 - Site 36039
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

E)



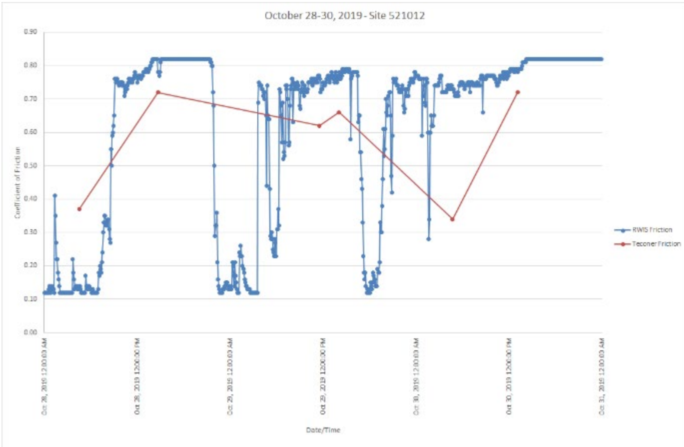
October 28-30, 2019 - Site 36046
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

F)



October 28-30, 2019 - Site 521004
Coefficient of Friction
Date/Time
RWIS Friction
Teconer Friction

G)



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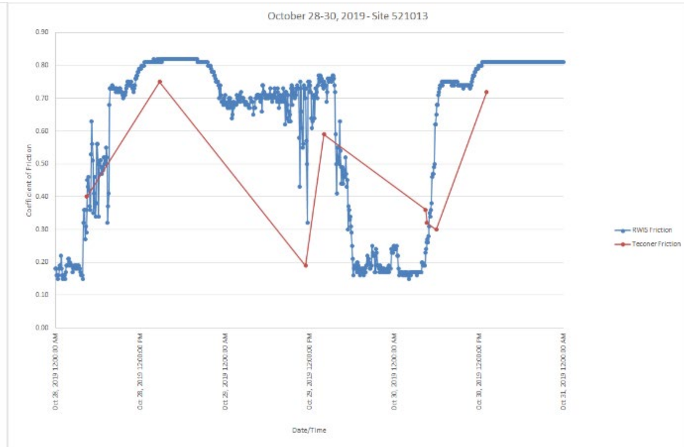
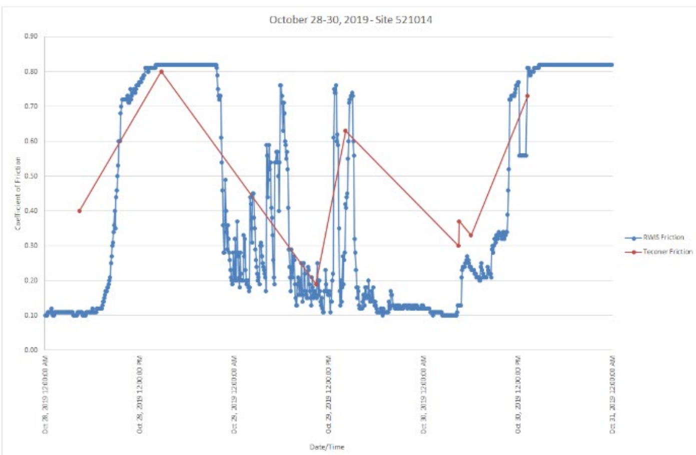


I)



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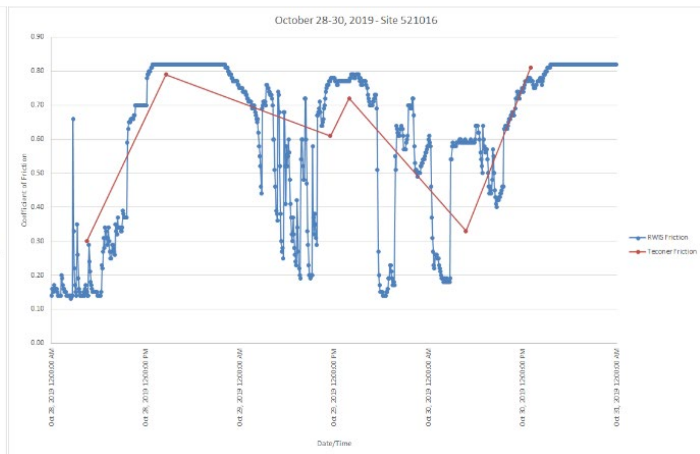
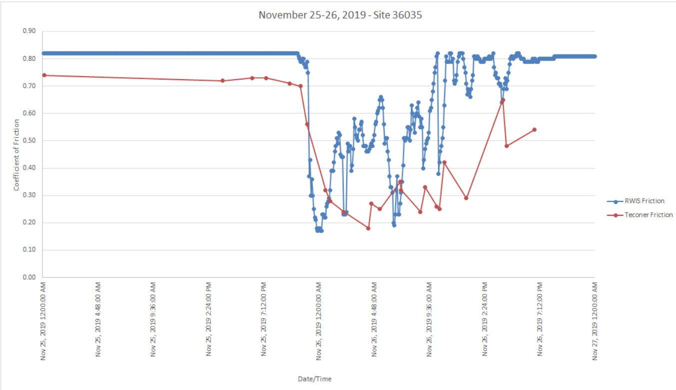
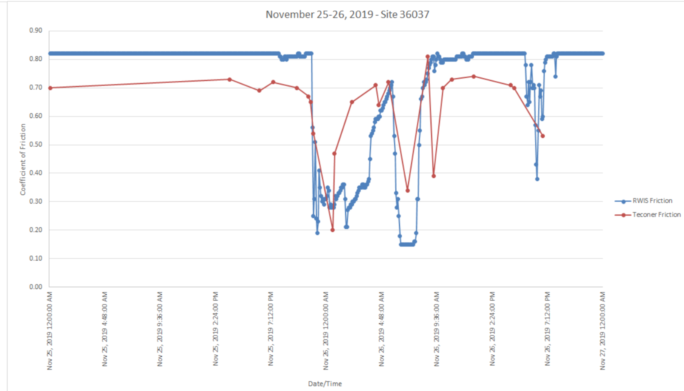


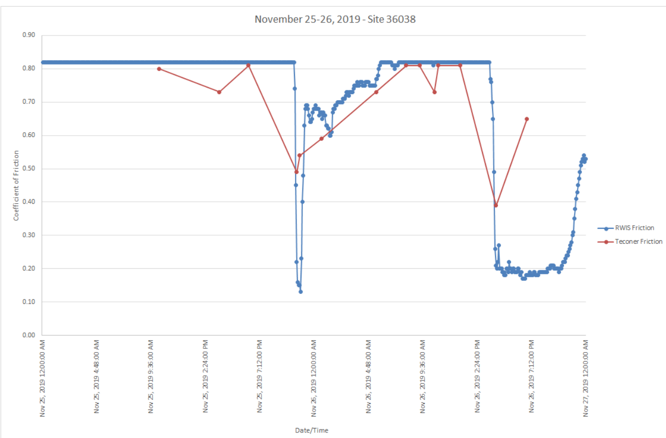
Figure 18. A-J show RWIS and Teconer friction data from RWIS locations along I-70 during the Oct.28-30, 2019 storm event. Additional graphs are provided in Appendix A. Summary of Identified Literature. Extra graphs from I-70 RWIS and Teconer friction data comparison.

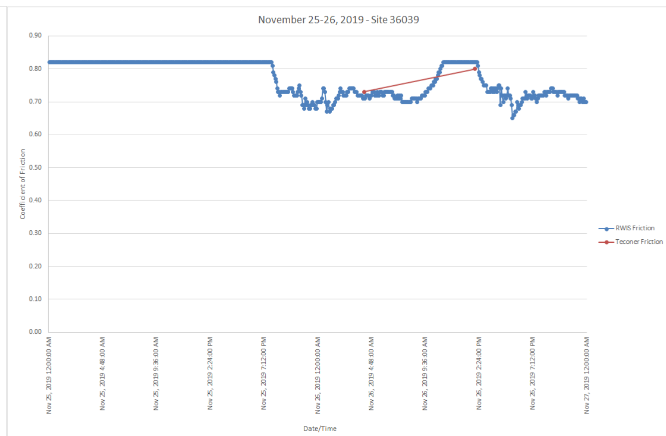
A) B)



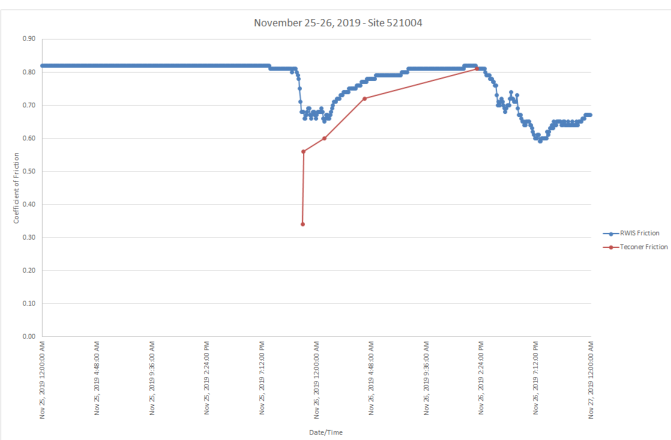


C) D)





E) F)



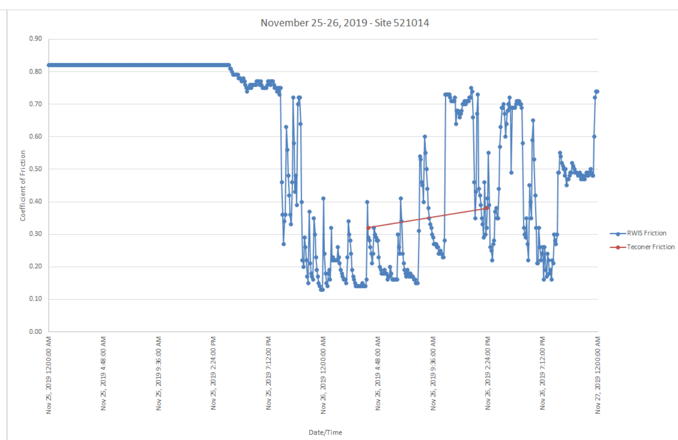


Figure 19. A-F shows RWIS and Teconer friction data from RWIS locations along I-70 during the Nov. 25-26, 2019 storm event Additional graphs are provided in Appendix A. Summary of Identified Literature Extra graphs from I-70 RWIS and Teconer friction data comparison.

Considering Figure 17, Figure 18, and Figure 19 and the average percent difference and standard deviation between the RWIS stationary and the Teconer mobile friction values for each RWIS site along the I-70 test section from Table 13 the following conclusions can be made:

- When sufficient Teconer data are collected, both Teconer and RWIS data sets follow similar trends.
- Generally, more Teconer data were available on the western end (near Frisco) of the I-70 test section than the eastern end.
- The bulk of the Teconer data are collected by a few specific sensors/individuals, while other sensors have limited to no available data.
- The average difference in friction values between the stationary and mobile sensors is highly variable and can be large. This may be due to data collection occurring at different locations on the roads surface, the smoothing algorithm Teconer uses, and/or limited Teconer data collected.
- The average difference between the stationary (RWIS-based) and mobile sensor (Teconer) friction values on I-70 were significantly greater than I-25. This may be due to an imbalance in the data from the two data sets, with much less Teconer data available over the entire I-70 test section when compared to RWIS-based data on I-70 and both the RWIS and Teconer data available from I-25.

Friction Data Discussion

There has been some preliminary analysis of RWIS-based and Teconer friction data sets, which has suggested that they do not report similar results (personal communication, J. Yount, CDOT). This can be observed in Figure 13, Figure 14, Figure 15, Figure 16, Figure 17, Figure 18, and Figure 19, but many factors could influence the difference in values reported by each friction data set. Considerations when looking at the RWIS-based and Teconer friction data sets include:

- The RWIS-based friction data are “stationary,” meaning they are collected from a fixed location on the pavement (approximately 2 sq ft), which is most often located in the exterior wheel path of the exterior lane. An RWIS-based sensors collects and reports real-time friction data for that location continuously and should be calibrated and cleaned at least annually.
- Teconer friction data is collected from a sensor mounted onto a moving vehicle that points at the road surface for data collection. Data is collected from a 2.3 inch (60 mm) wide section of the pavement when mounted at 3.2 ft (1 m) above the pavement surface, which collects and reports real-time friction data from where the vehicle traveled. This data may or may not be collected from the exact same location as the RWIS-based friction data, instead it may be collected from a different lane, or from the inside or outside of the wheel path. Because of this, Teconer friction values will vary more than those from an RWIS-based friction sensor. A Teconer friction sensor should be calibrated and cleaned daily.
- RWIS sensors are more invasive than Teconer units because they are integrated into the near road hardware.
- The two separate friction data collection methods, stationary and mobile, create a situation where the RWIS-based friction data is robust for the stationary locations, but the Teconer friction data provides a general picture of roadway friction of where the vehicle has traveled.
- Teconer uses a smoothing algorithm to report a running average friction value and does not provide raw friction data.

Table 14 provides a quick-glance summary of key qualities of both the RWIS-based (stationary) and Teconer (mobile) friction data collection options.

Table 14. Comparisons of Data Captured by RWIS versus Teconer.

Qualities	RWIS	Teconer
State	Stationary	Mobile
Calibration	Annually	Daily
Real-Time Friction Data	One Location	Anywhere the Vehicle Travels
Values	More Consistent	Vary Widely
Cost	More Expensive*	Less Expensive
Big Picture	Robust Data for a Fixed Location	General Picture of Roadway Friction
Friction Data Capture	Raw Data	Smoothed Data

*Note – If an RWIS station is already located in an area where friction measurements are needed, a friction sensor can be added to the station making this a less costly option.

Given that the difference in the friction data sets could be attributed to various factors, is it possible to take a high level look at the data and see if the RWIS and Teconer friction values fall within critical thresholds (for example, safe (high friction values at or above $\mu = 0.6$), watch carefully (friction is decreasing $0.6 > \mu > 0.4$), treatment required (low friction values $\mu \leq 0.4$)). Friction thresholds used by other US states and internationally are discussed in the Background section of this paper. An example of this is shown in Figure 20, where friction values at or above 0.6 are green (safe), friction values between 0.4 and 0.6 are yellow (concern), and friction values at or below 0.4 are red (dangerous) and require treatment. In this one instance, the Teconer friction data gives the impression of worse road conditions (lower friction values) than the RWIS friction data.

The RWIS-based friction data set should be used in this project effort.

Based on the limited quantity of Teconer data available, it is recommended that for now only **the RWIS-based friction data set should be used in this project effort**.

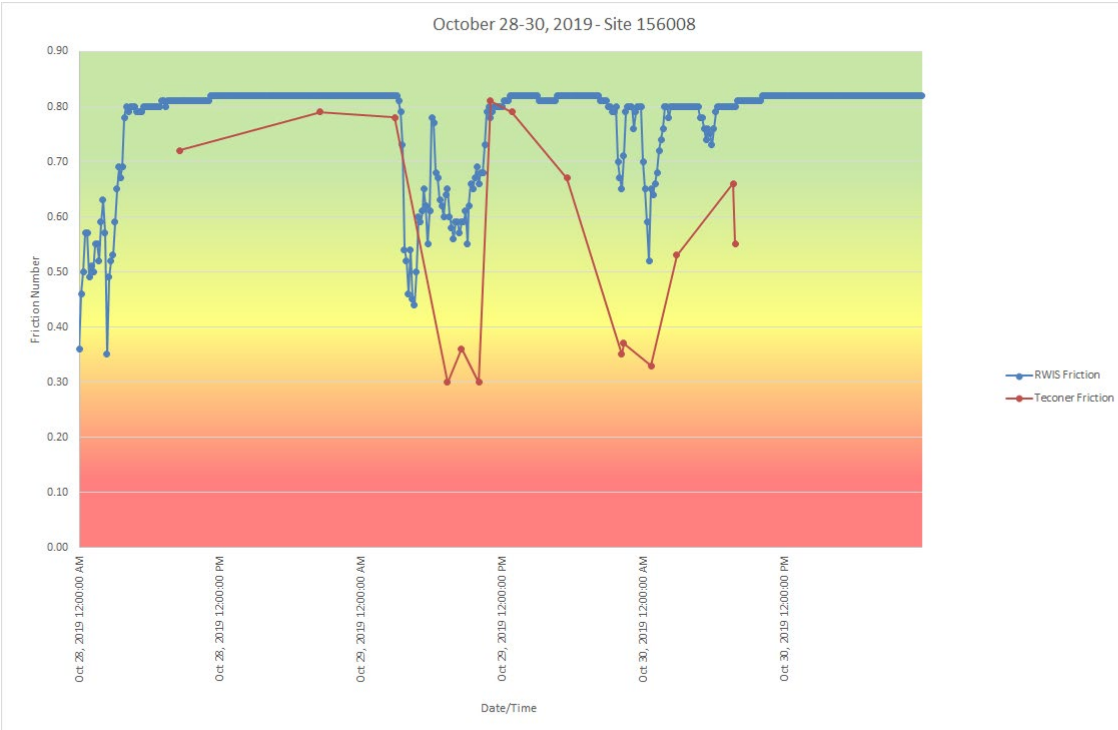


Figure 20. Comparing RWIS and Teconer Friction Data Along Specified Friction Thresholds

RWIS Friction Data Thresholds

The following section looks at all the RWIS friction data from the I-25 and I-70 test section for the winter 2017-2020 seasons (October through March). The purpose of this is to identify typical friction value ranges that can be used to establish friction thresholds for future work on the performance management tool.

Provided hereafter is a summary of the analysis of RWIS data by 1) winter season, and 2) all years combined. The results for I-25 will be presented first and the results for I-70, second.

I-25 Test Section

The RWIS stations along the I-25 test section were assigned numerical values 1-6 from north to south. The numerical values for each RWIS station are provided the Table 15. Renaming the RWIS Stations from north to south allowed for easy viewing of topographic and weather patterns that may influence the test section. The numerical values assigned to each RWIS Station along I-25 are used in Figure 21 through Figure 28.

Table 15. RWIS Station ID numbers and Numerical Values assigned to each RWIS station to align the stations North to South on Figure 21 through Figure 28.

RWIS Station ID number	Numerical Value (1 = North, 6 = South)
156007	1
156033	2
156008	3
156016	4
156003	5
156032	6

2017-2018 Winter Season

One hundred twenty-five thousand, three hundred ninety-three friction data points collected from five RWIS stations along the I-25 corridor were used in this analysis. Note that RWIS site 156016 (or number 4) was excluded due to a significant number of missing values. The mean friction value of the data was μ = 0.80 (Figure 21). When looking at all the RWIS data from 2017-2018 there is no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2017-2018 winter season, there are 2,288 data points with a mean value of μ = 0.24 (Figure 22) (recall that 0.6 represents the threshold change from safe to watch carefully). The five RWIS sites show typical friction values of 0.23 to 0.55, with the exception of RWIS Site 156008 (or number 3).

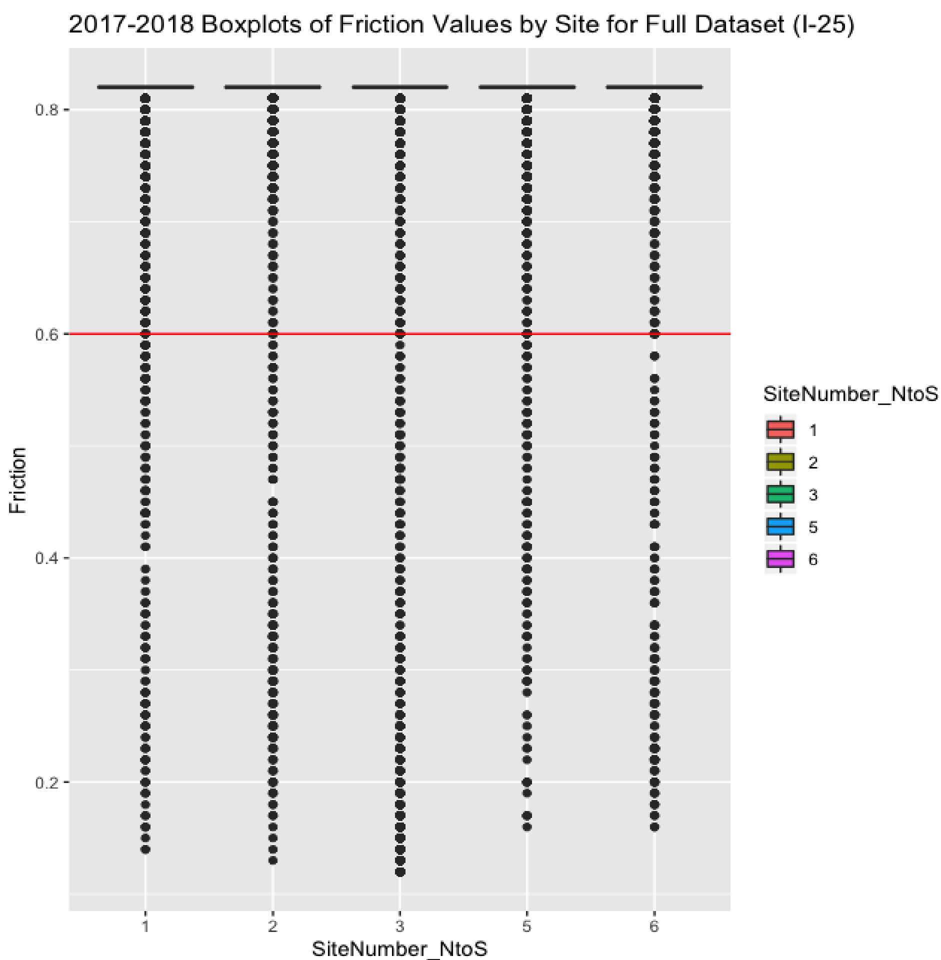


Figure 21. RWIS stationary friction data from October 2017 – March 2018 from five RWIS sites along the I-25 corridor.

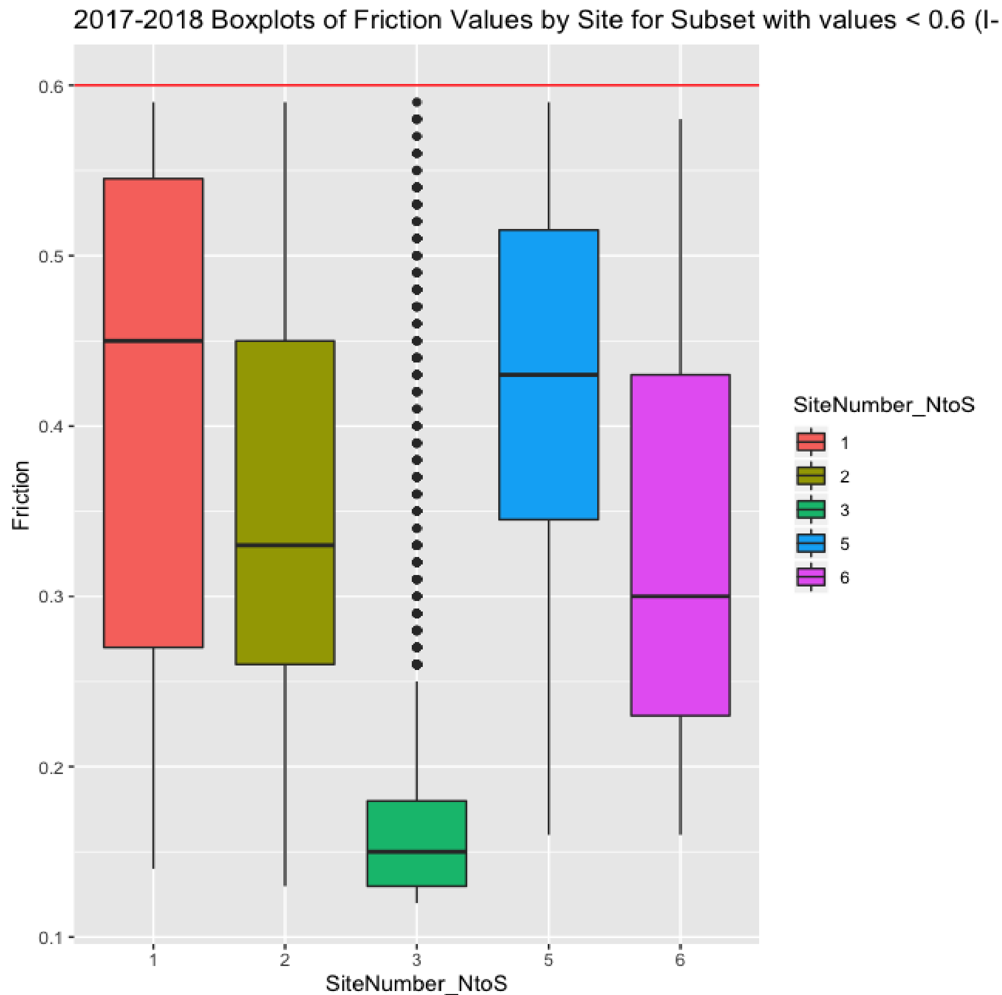


Figure 22. Box plot of RWIS stationary friction data from October 2017 – March 2018 from five RWIS sites along the I-25 corridors when only looking at friction values from 0.0 - 0.6.

2018-2019 Winter Season

One hundred twenty-three thousand, three hundred twenty-five friction data points collected from five RWIS stations along the I-25 corridor were used in this analysis. Note that RWIS site 156016 (or number 4) was again excluded due to a significant number of missing values. The mean friction value of the data was μ = 0.81 (Figure 23). When looking at all the RWIS data from 2018-2019, there is no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 – 0.6 for the 2018-2019 winter season there are 1,312 data points with a mean of μ = 0.35 (Figure 24). The five RWIS sites show typical friction value ranges from 0.16 to 0.53.

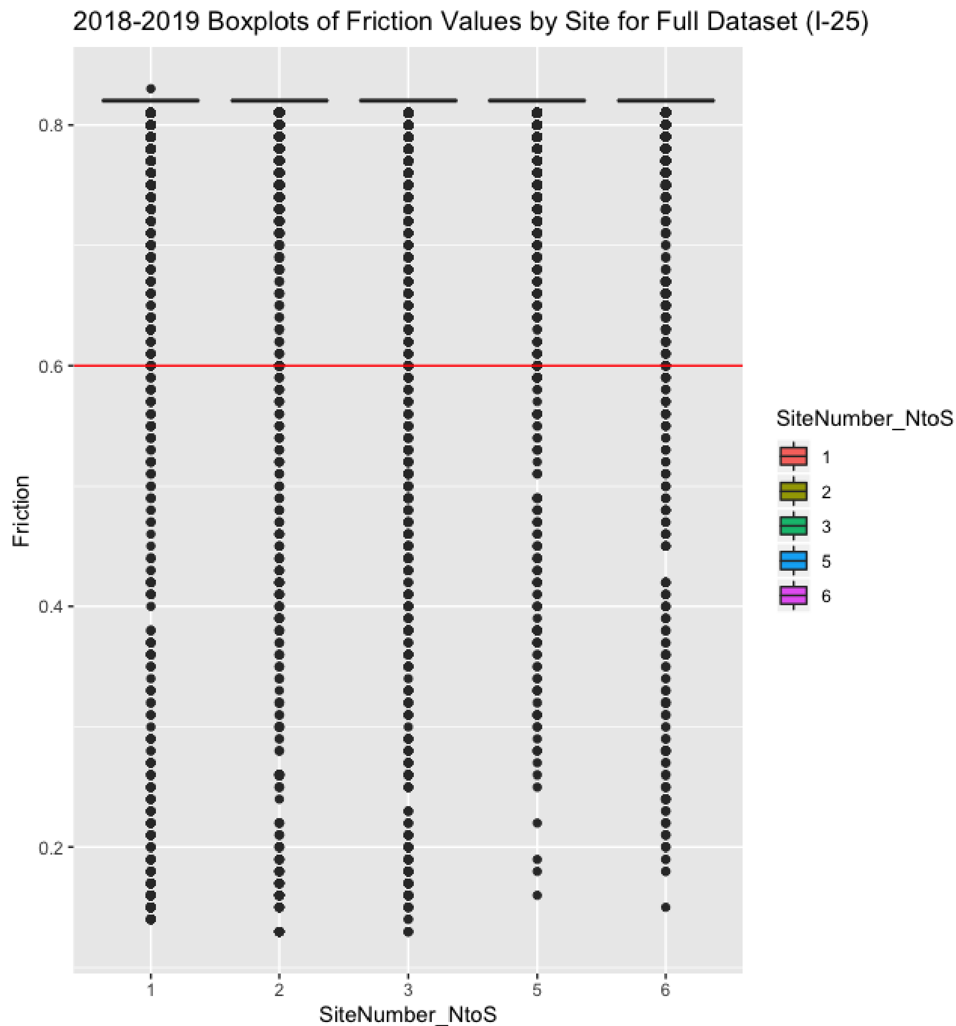


Figure 23. RWIS stationary friction data from October 2018 – March 2019 for five RWIS sites along the I-25 corridor.

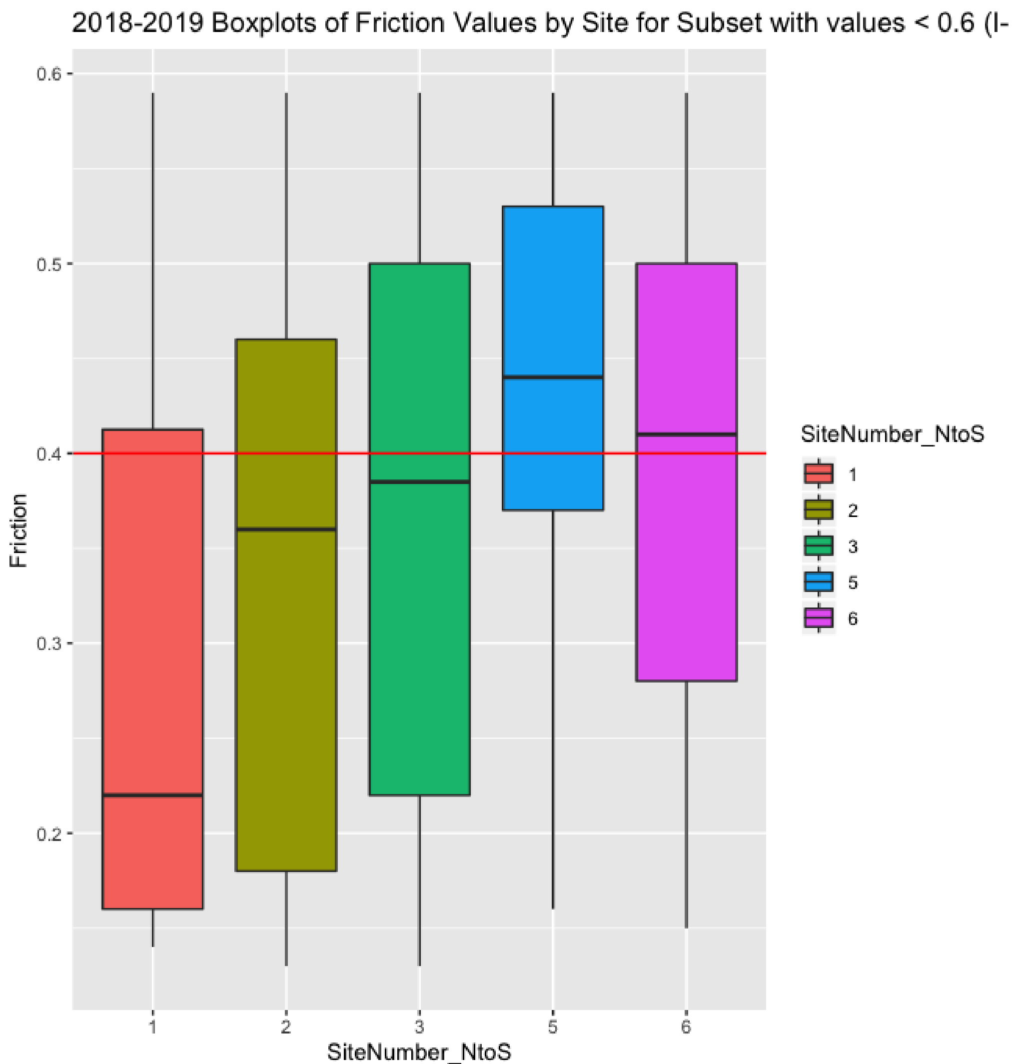


Figure 24. Box plot of RWIS stationary friction data from October 2018 – March 2019 for five RWIS sites along the I-25 corridors when only looking at friction values from 0.0 - 0.6.

2019 – 2020 Winter Season

One hundred fifty-four thousand, three hundred seventy-two friction data points were collected from the six RWIS stations along the I-25 corridor; no RWIS sites were excluded during the 2019-2020 winter season. The mean friction value of all the data was μ = 0.80 (Figure 25). When looking at all the RWIS data from this winter season, there was no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6, there were 3,356 data points with a mean of μ = 0.34 (Figure 26). All six RWIS stations reported similar friction value ranges of 0.18 to 0.52.

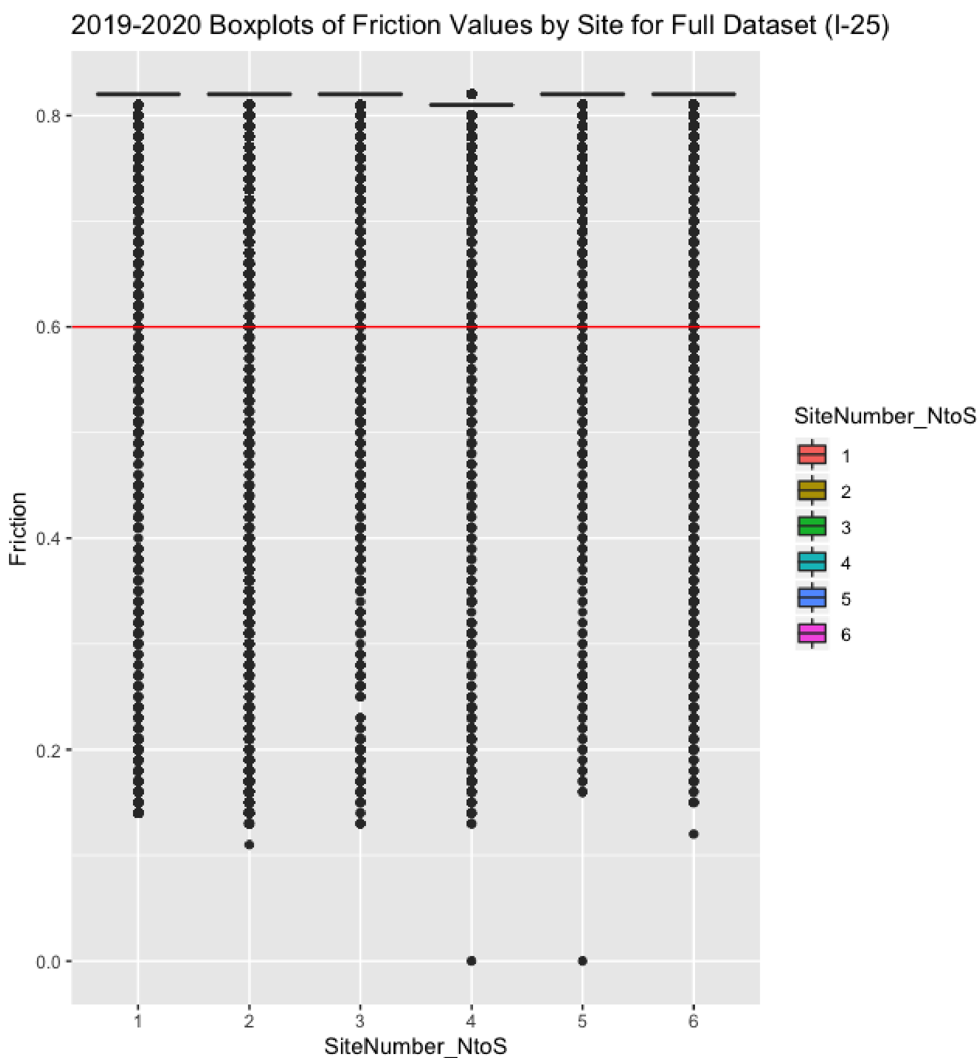


Figure 25. RWIS stationary friction data from October 2019 – March 2020 for six RWIS sites along the I-25 corridor.

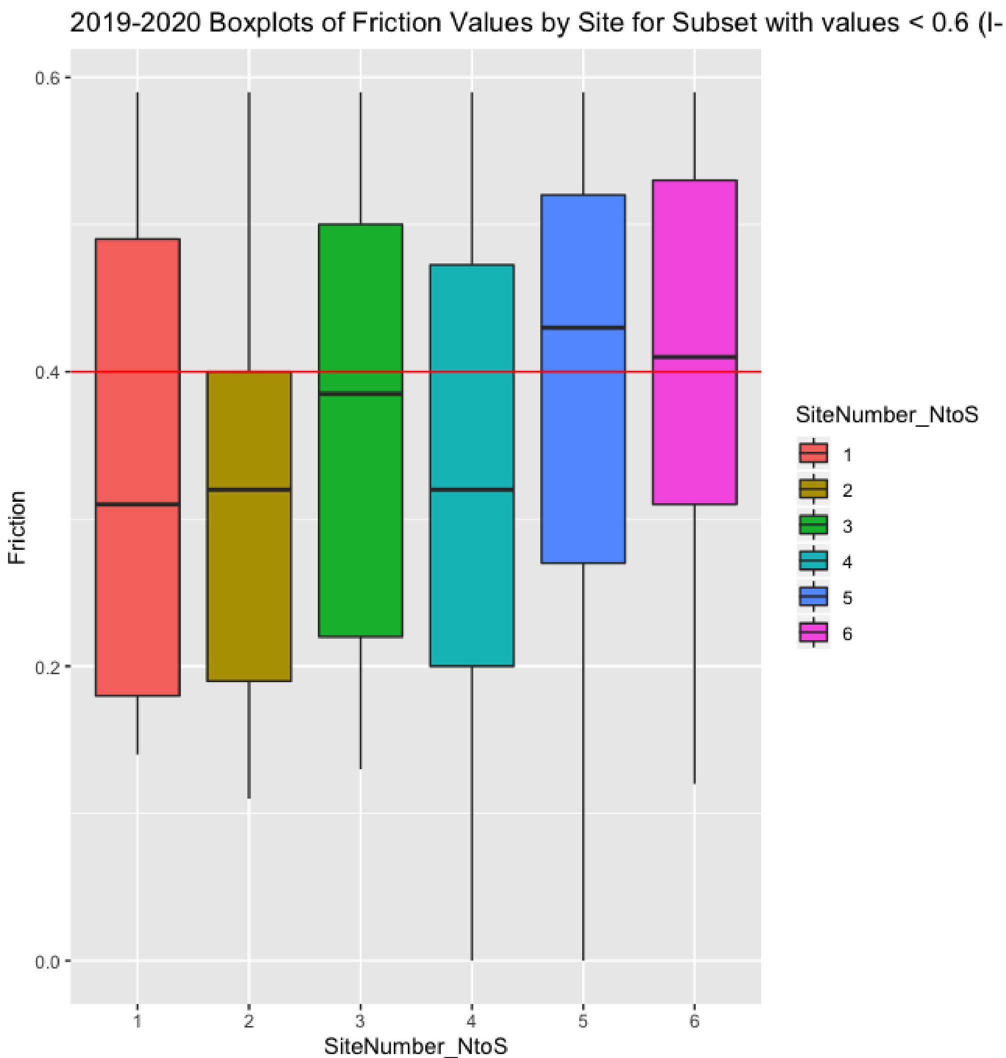


Figure 26. Box plot of RWIS stationary friction data from October 2019 – March 2020 from six RWIS sites along the I-25 corridors when only looking at friction values from 0.0 - 0.6.

2017-2020 All Winter Seasons Combined

Four hundred three thousand and ninety friction data points were collected from the six RWIS stations along the I-25 corridor (with RWIS site 156016 (number 4) only providing data for the 2019-2020 winter season). The mean friction value of all the data was μ = 0.81 (Figure 27). When looking at the RWIS data from 2017-2020 there was no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2017-2020 winter seasons there were 7,056 data points with a mean μ = 0.31 (Figure 28). Friction values ranged from 0.17 to 0.52 across the 2017-2020 winter seasons.

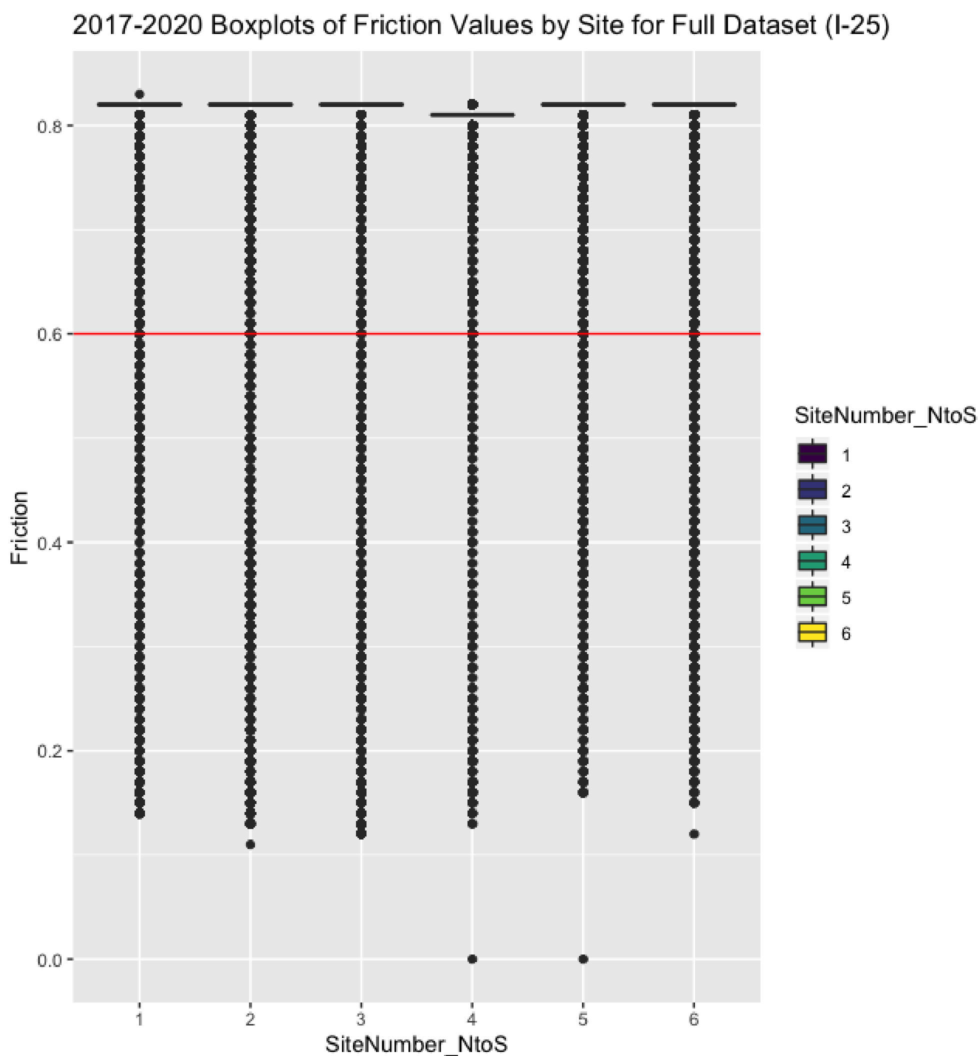


Figure 27. RWIS stationary friction data for 2017-2020 from October – March from six RWIS sites along the I-25 corridor.

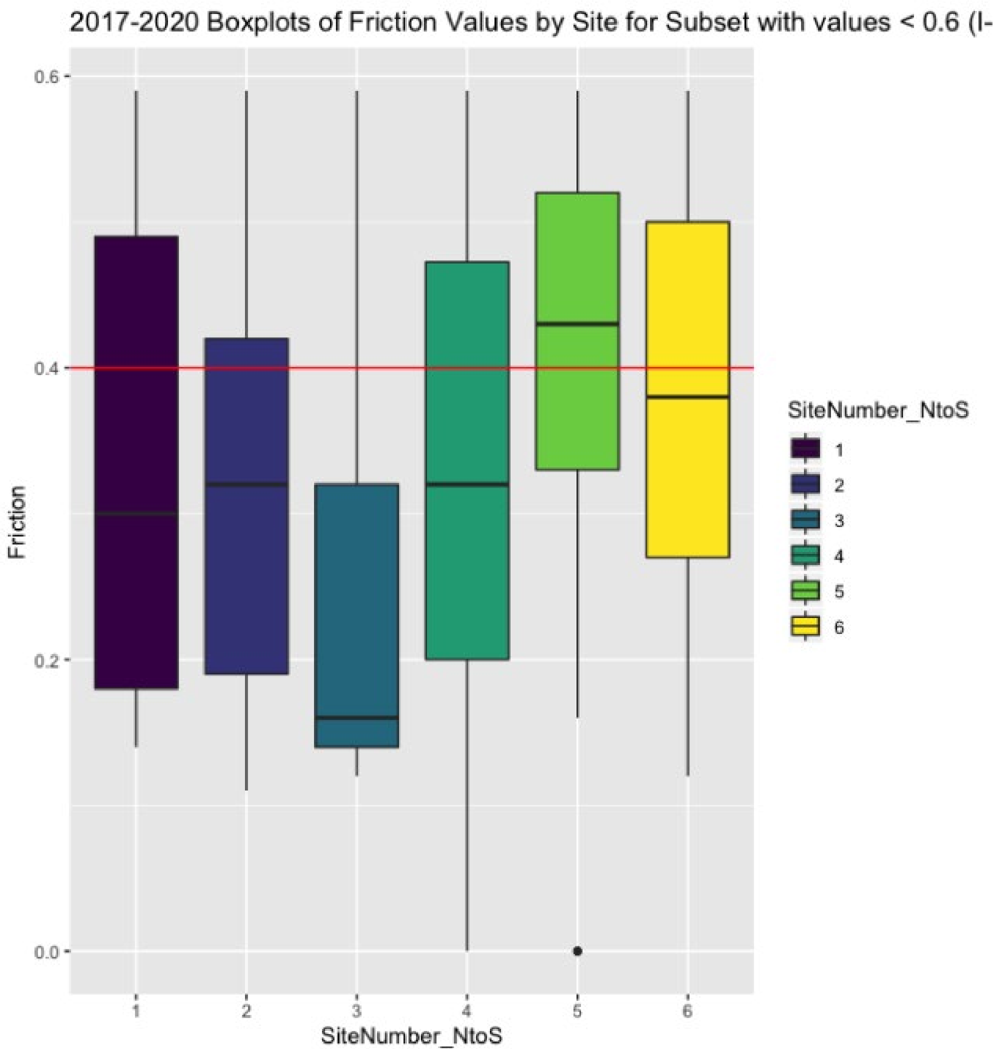


Figure 28. Box plot of RWIS stationary friction data for 2017-2020 from October – March from six RWIS sites along the I-25 corridors when only looking at friction values from 0.0 - 0.6.

I-70 Test Section

The RWIS stations along the I-70 test section were assigned numerical values 1-18 from east to west. The numerical values for each RWIS station are provided in Table 16. Renaming the RWIS Stations from east to west allowed for easy viewing of topographic and weather patterns that may influence the test section. The numerical values assigned to each RWIS Station along I-70 are only used in Figure 29 through Figure 36.

Table 16. RWIS Station ID numbers and Numerical Values assigned to each RWIS station to align the stations East to West on I-70

RWIS Station ID number	Numerical Value (1 = East, 18 = West)
36025	1
36024	2
36030	3
36045	4
36047	5
36046	6
521015	7
521014	8
521013	9
521012	10
36040	11
36042	12
521016	13
36039	14
521004	15
36038	16
36037	17
36035	18

2017-2018 Winter Season

Nine hundred two thousand, nine hundred seventy-five friction data points from 18 RWIS stations along the I-70 corridor were used in this analysis. The mean friction value of the data was $\mu = 0.77$ (Figure 29). When looking at all the RWIS data from 2017-2018 there was no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2017-2018 winter season there were 62,474 data points with a mean $\mu =$ 0.29 (Figure 30). All 18 RWIS stations reported friction values ranging between 0.15 and 0.48, with a few exceptions, most notably RWIS site 36045 (number 4).

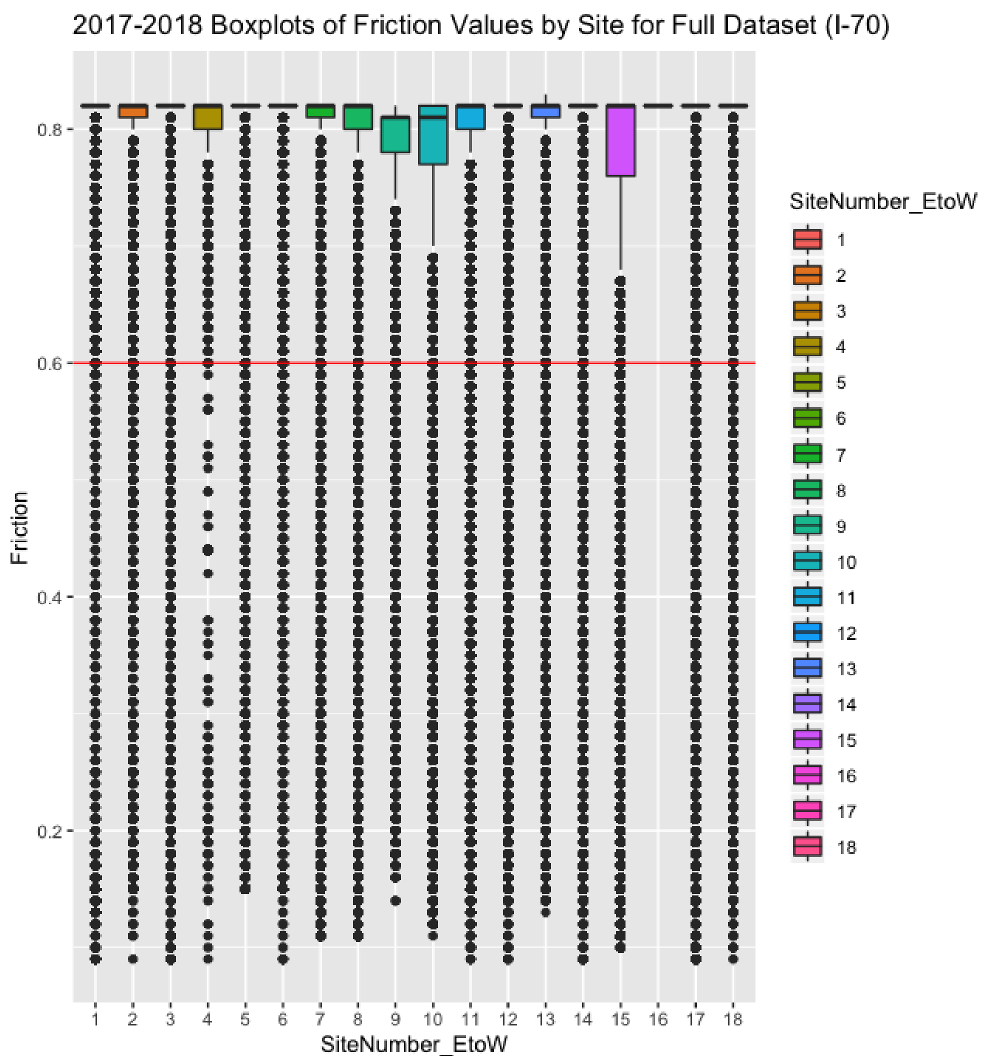


Figure 29. RWIS stationary friction data from October 2017 – March 2018 from 18 RWIS sites along the I-70 corridor.

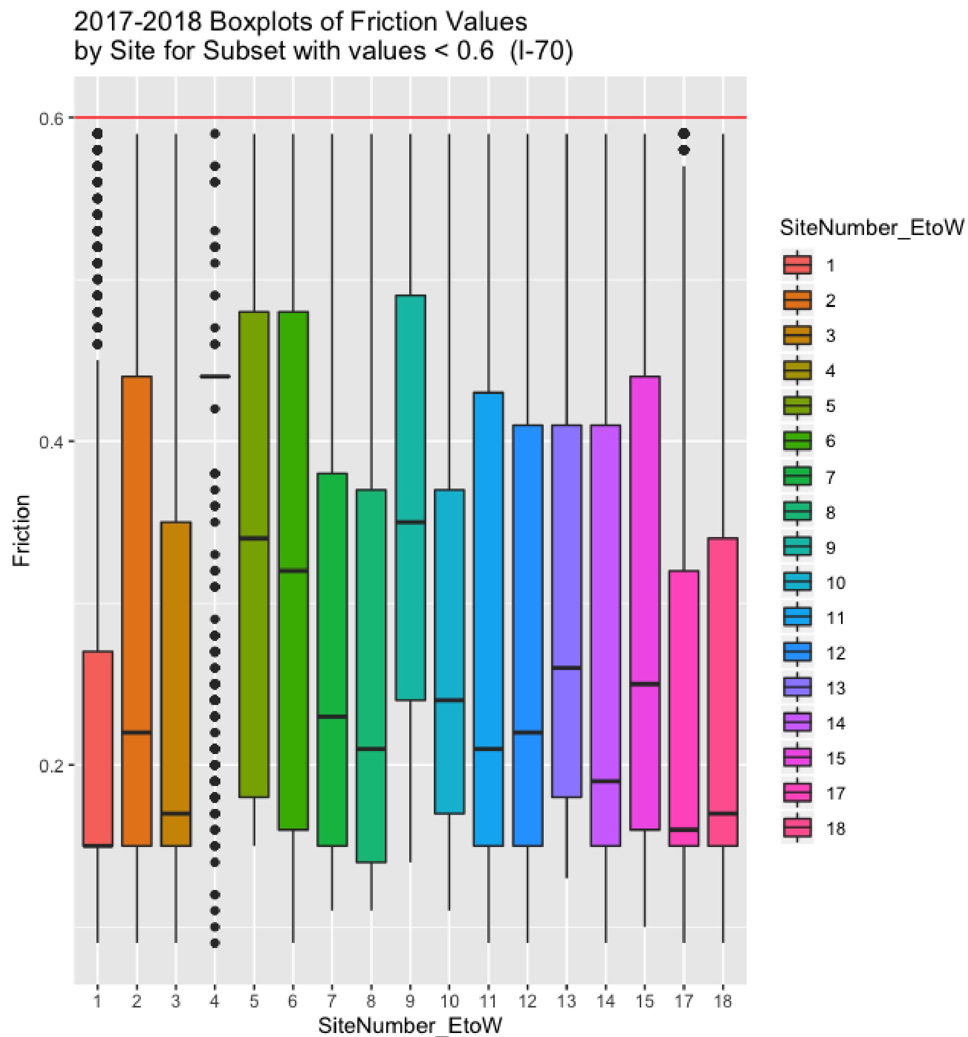


Figure 30. Box plot of RWIS stationary friction data from October 2017 – March 2018 from 18 RWIS sites along the I-70 corridors when only looking at friction values from 0.0 - 0.6.

2018-2019 Winter Season

Eight hundred forty-nine thousand, nine hundred thirty-eight friction data points from 18 RWIS stations along the I-70 corridor were used in this analysis. The mean friction value of the data was μ = 0.73 (Figure 31). When looking at all the RWIS data from 2017-2018 there is no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2018-2019 winter season, there were 113,980 data points with a mean μ = 0.35 (Figure 32). All 18 RWIS stations reported friction values ranging from 0.15 to 0.52, with a few exceptions, most notably RWIS sites 36045 (number 4), 36040 (number 11), and 36037 (number 17).

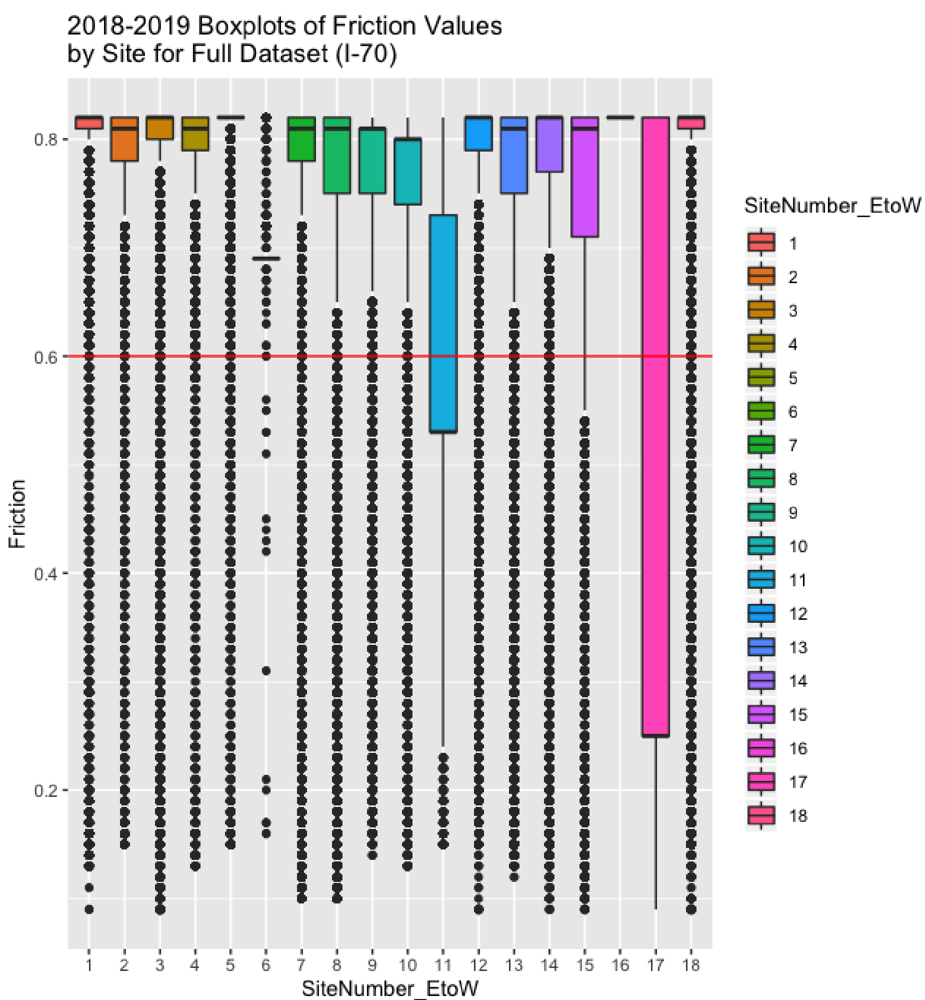


Figure 31. RWIS stationary friction data from October 2018 – March 2019 from 18 RWIS sites along the I-70 corridor.

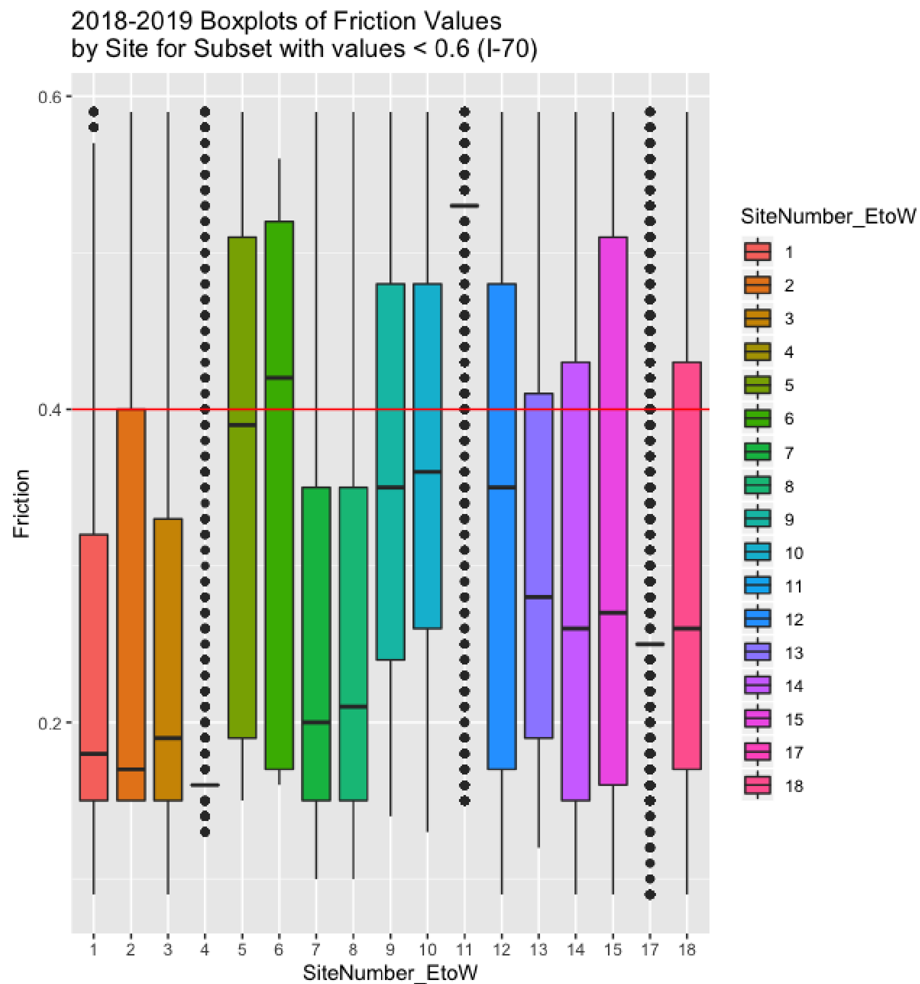


Figure 32. Box plot of RWIS stationary friction data from October 2018 – March 2019 from 18 RWIS sites along the I-70 corridors when only looking at friction values from 0.0 - 0.6.

2019 – 2020 Winter Season

Nine hundred two thousand, eight hundred seventeen friction data points from 18 RWIS stations along the I-70 corridor were used in this analysis. The mean friction value of the data was μ = 0.76 (Figure 33). When looking at all the RWIS data from 2017-2018 there was no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2019-2020 winter season there were 78,902 data points with a mean of μ = 0.26 (Figure 34). All 18 RWIS stations reported friction values from 0.13 to 0.53.

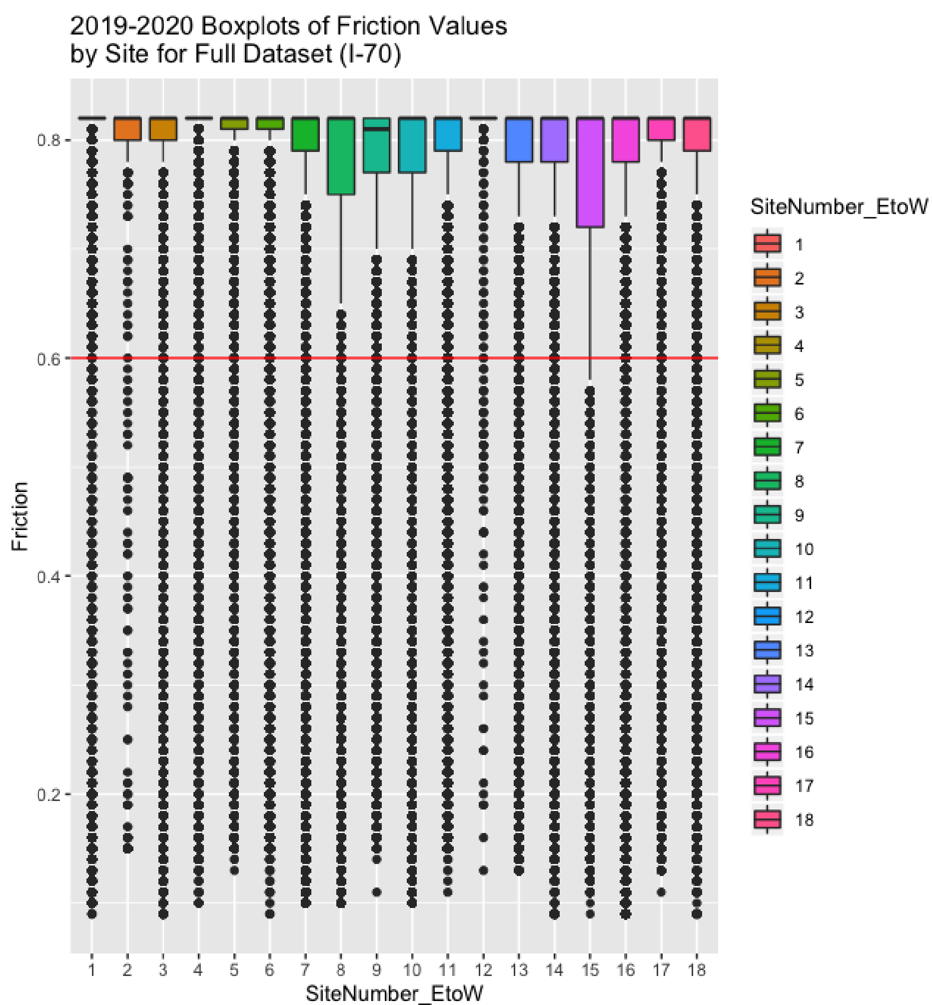


Figure 33. RWIS stationary friction data from October 2019 – March 2020 for 18 RWIS sites along the I-70 corridor.

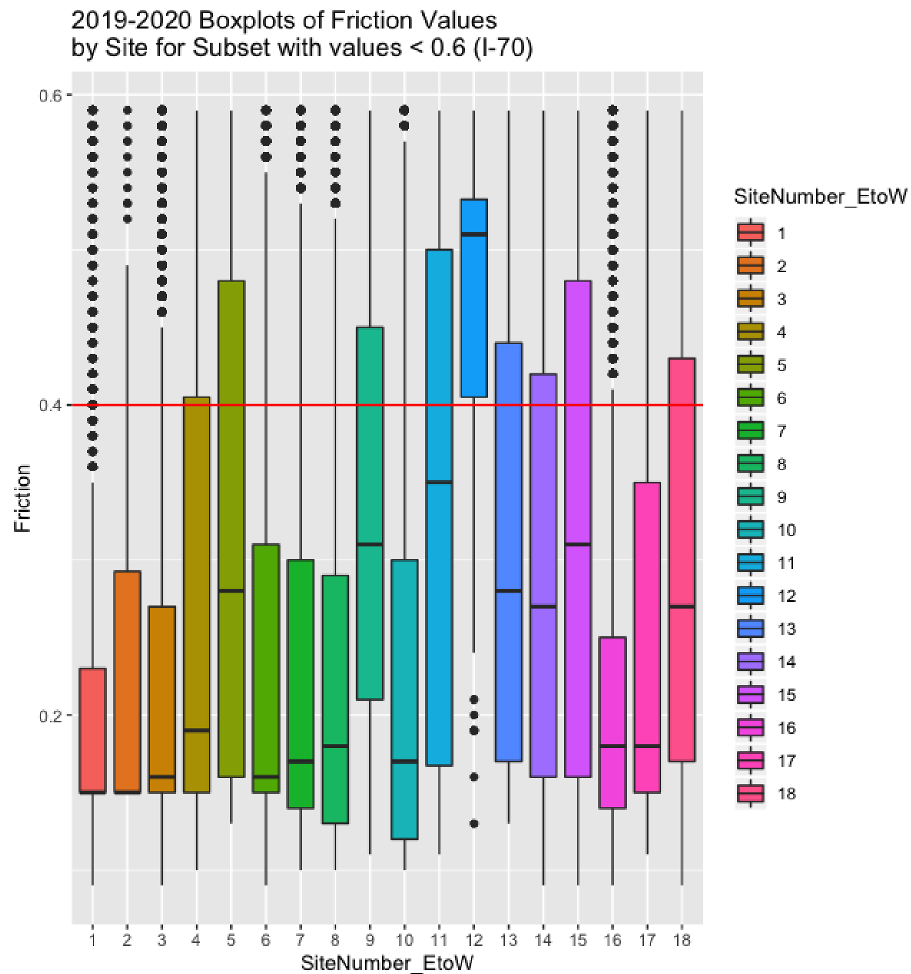


Figure 34. Box plot of RWIS stationary friction data from October 2019 – March 2020 for 18 RWIS sites along the I-70 corridors when only looking at friction values from 0.0 - 0.6.

2017-2020 All Winter Seasons Combined

Two million, six hundred fifty-five thousand, seven hundred thirty friction data points from 18 RWIS stations along the I-70 corridor were used in this analysis. The mean friction value of the data was μ = 0.75 (Figure 35). When looking at all the RWIS data from 2017-2020 there was no statistical difference in friction values among the stations. When looking at friction values (μ) from 0.0 - 0.6 for the 2017-2020 winter season there were 255,356 data points with a mean of μ = 0.31 (Figure 36). All 18 RWIS stations reported friction values from 0.15 to 0.48, with a few exceptions, most notably RWIS sites 36040 (number 11) and 36037 (number 17).

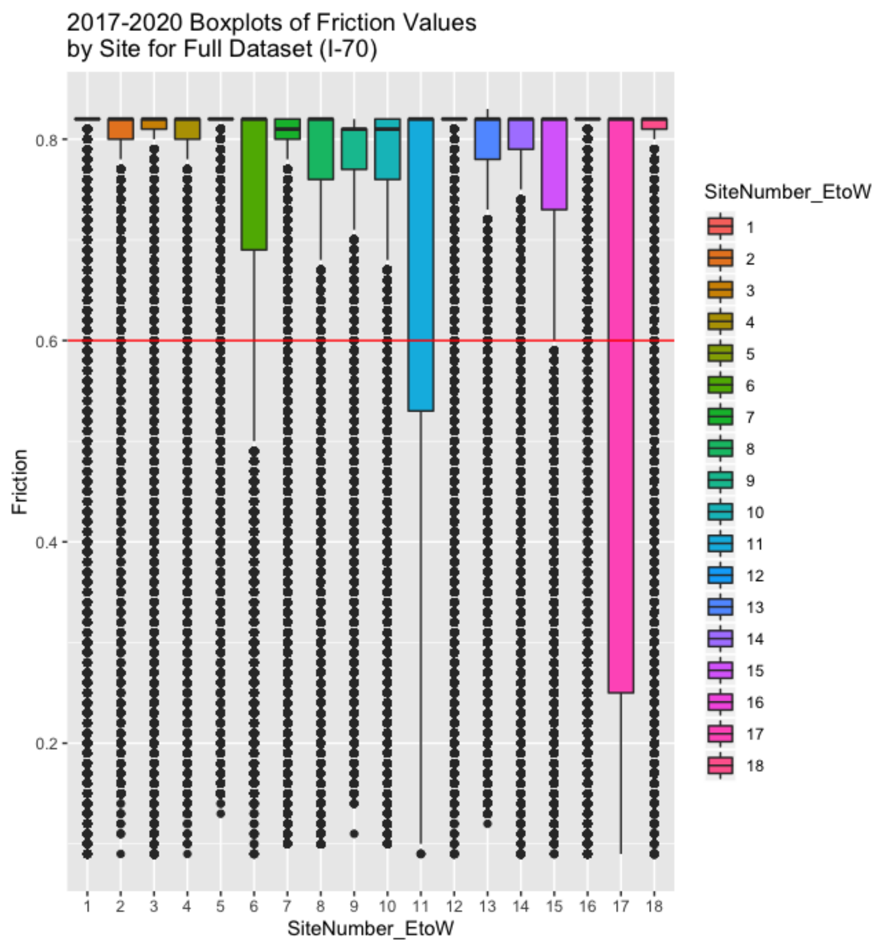


Figure 35. RWIS stationary friction data for 2017-2020 from October – March for 18 RWIS sites along the I-70 corridor.

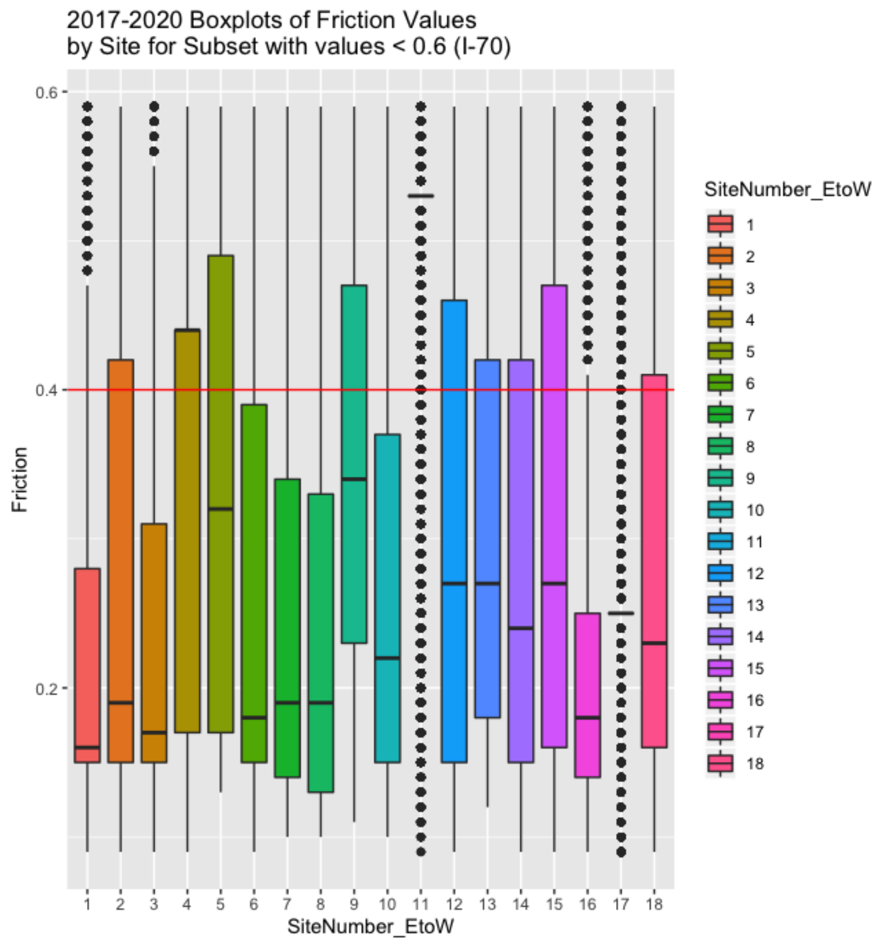


Figure 36. Box plot of RWIS stationary friction data for 2017-2020 from October – March for 18 RWIS sites along the I-70 corridor when only looking at friction values from 0.0 - 0.6.

Both I-25 and I-70 have similar friction value ranges of 0.2 to 0.5, with I-70's means trending slightly lower than that of I-25.

Table 17 shows the friction value ranges for all RWIS data from October to March, 2017-2020, when only looking at friction values below μ = 0.6 for the I-25 and I-70 test sections. Both the I-25 and I-70 test sections have **similar typical friction values ranges of 0.2 to 0.5**, with slightly lower friction ranges on the I-70. This information will be used to inform the CDOT performance measurement tool and implementation guide that will be developed in future tasks for this research effort.

Table 17. Summary of typical RWIS friction value ranges when only looking at friction data below 0.6.

Winter Seasons Considered	I-25 Friction values ranges below 0.6	I-70 Friction values ranges below 0.6
2017-2018	0.23 to 0.54	0.15 to 0.48
2018-2019	0.16 to 0.53	0.15 to 0.52
2019-2020	0.18 to 0.52	0.13 to 0.53
2017-2020	0.17 to 0.52	0.15 to 0.48

Using this information and applying friction values ranges to commonly used performance guidelines, the following could apply to CDOT:

- Amount of time to return to $\mu = 0.5$ (Regain time)
- $\mu > 0.5$ green (safe), $\mu < 0.5$ and ≥ 0.3 yellow (watch carefully), and $\mu < 0.3$ unsafe (red) (winter maintenance operations needed)

Note that this information is based on the RWIS friction data. Colorado DOT staff and project panel members indicated they would be more comfortable using a road threshold value of 0.6. Both values are discussed in Reducing the Roadway Friction Threshold.

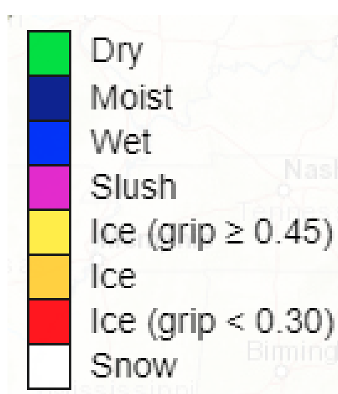


Figure 37. Teconer provided guidance for friction values and surface state (roadweather.online).

Teconer provides some guidance for friction values and road surface state (Figure 37) such that friction values greater than 0.45 represent pavement conditions of slush, wet, moist, or dry; friction values of 0.45 to 0.30 represent pavement conditions of ice; and friction values less than 0.30 can represent pavement conditions of snow. As is shown in Figure 37, the surface state reported by Teconer is color coded for easy viewing on their map display (roadweather.online).

Can the Same Friction Data Thresholds Apply to Both Data Sets?

To determine if the Teconer friction data could be used to fill in the gaps between RWIS stations and/or have the RWIS-based friction thresholds apply, we wanted to look at the agreement, or lack thereof, between the RWIS and Teconer friction values. Table 18 provides a summary of the average percent difference in friction values between the Teconer and RWIS for I-25 and I-70 test sections.

Table 18. Average Percent Difference Between Teconer and RWIS Friction Records

Test Section	Site	Total Teconer Data Records Pulled Over Selected Storm Dates	Average Percent Difference Between RWIS and Teconer Coefficient of Friction	Standard Deviation
I-25	156007	29	5.0%	47.6
I-25	156033	30	38.3%	55.0
I-25	156008	35	14.5%	30.8
I-25	156016	34	10.2%	43.4
I-25	156003	49	27.2%	16.6
I-25	156032	15	10.0%	28.0
I-70	36025	6	169.7%	106.0
I-70	36024	4	47.6%	25.2
I-70	36030	6	183.0%	93.4
I-70	36045	1	11.7%	N/A
I-70	36047	4	24.3%	67.5
I-70	336046	8	71.3%	64.7
I-70	521015	3	35.1%	62.7
I-70	521014	11	63.7%	89.9
I-70	521013	11	15.9%	39.6
I-70	521012	9	3.5%	65.8
I-70	36040	1	17.1%	N/A
I-70	36042	14	18.6%	23.6
I-70	521016	14	3.5%	34.1
I-70	36039	14	5.3%	48.6
I-70	521004	20	6.9%	48.0
I-70	36038	39	88.9%	125.3
I-70	36037	80	31.3%	75.4
I-70	36035	74	3.4%	60.1

When more Teconer data was present the average percent difference in friction values between the Teconer and RWIS-based for I-25 ranged from 5% to 38%, or an average difference of approximately 20%. A 20% difference in friction values between the Teconer and RWIS-based was reasonable, given the threshold range, and allowed for much of the available Teconer data to be considered for I-25. When looking at I-70, the average percent difference in friction values between the Teconer and RWIS was 3% to 183%, or an average difference of about 45%, suggesting that the current I-70 Teconer data should not be used to fill in the gaps between RWIS stations. The higher average difference in data sets on I-70 may be attributed to less Teconer data being collected and available for use. Given that a key recommendation of this work is the development of a Teconer use guide, revisiting this following implementation of a more robust Teconer data collection plan may yield better results.

Regression-Kriging Analysis of RWIS Friction Data

Kriging interpolates "the value of a variable over a continuous spatial field[‡]," which, in this case, is roadway friction. Ordinary or simple kriging gives the best linear unbiased prediction of the intermediate values, or, in this case, estimated friction values between RWIS stations. Simple kriging works by assuming the local friction means at each RWIS station are relatively constant and equal to the population mean whereas RK is a spatial interpolation technique that combines regression of the dependent variable on auxiliary variables with "simple" kriging of the regression residual. RK has been used extensively in other fields of research and within the transportation community, but only applied to a limited extent on road weather data (Kwon et al., 2017; Gu et al., 2018; Wu et al., 2021).

Given the analysis of the RWIS data along the I-25 and I-70 test sections, the researchers wanted to try applying simple kriging analysis methods to the RWIS friction data set to determine if the friction values reported were spatially similar enough to interpolate between locations. Note that

[‡] www.publichealth.columbia.edu/research/population-health-methods/kriging-interpolation

this was only a preliminary look at the use of simple kriging on roadway friction data and additional work is needed for publication of these results.

I-25 Test Section RK Results

> If similar road conditions are present between RWIS station locations, roadway friction along the I-25 should be at or similar to the nearest RWIS station locations.

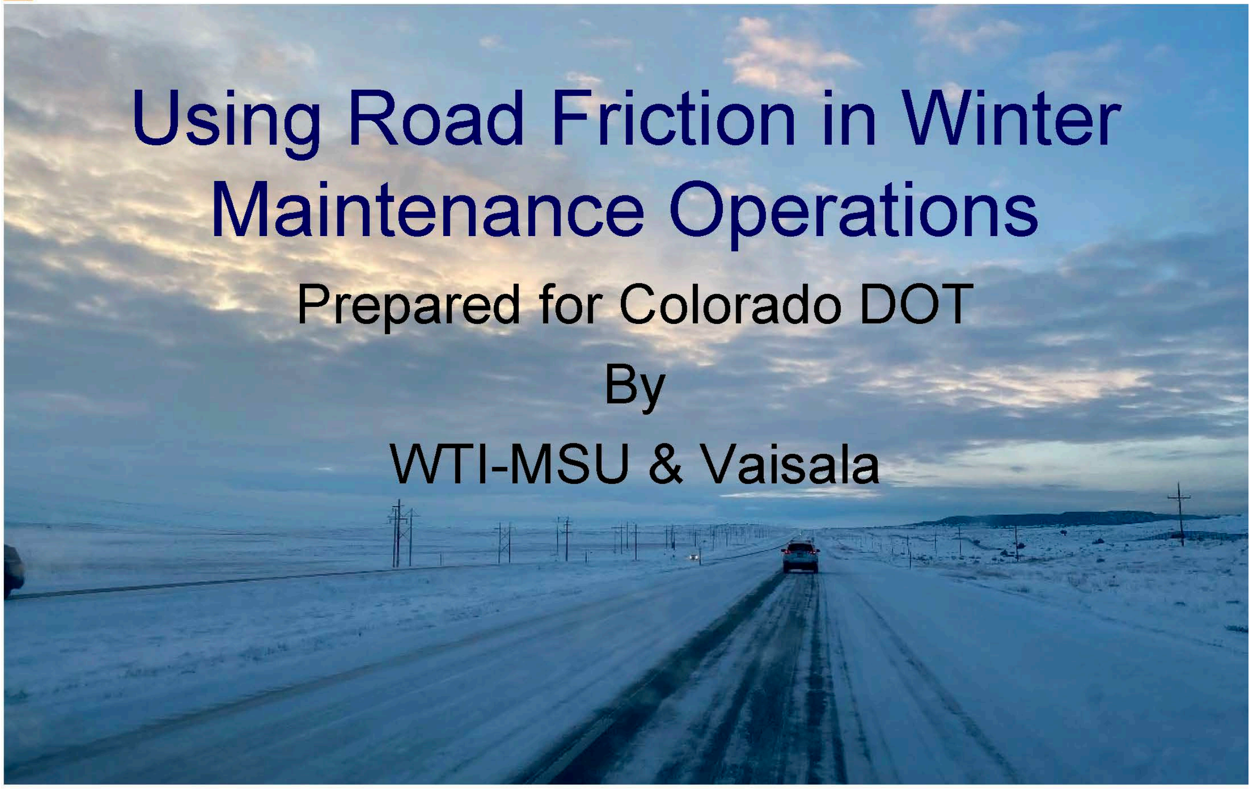
Given the relatively uniform placement of RWIS stations along this test section, the north-south trend of road, and high plains topography, the I-25 in Colorado provides a good test case for applying simple kriging to RWIS friction data. All the I-25 RWIS friction values from October-March of 2017-2020, with RWIS station 156016 (number 4) removed from 2017-2018 and 2018-2019, had kriging applied. The simple kriging analysis showed that the friction values at each RWIS station were statistically similar. Therefore, it can be assumed that **if similar road conditions are present between RWIS station locations, roadway friction along the I-25 should be at or similar to the nearest RWIS station locations**. This does not consider microclimates, winter maintenance operations and maintenance (re: plowing and deicing), traffic volumes, or storm events that may affect specific RWIS stations along this north-south corridor. The next step would be to perform RK using a variable such as pavement temperature to determine if proxy variables can used in place of friction data.

I-70 Test Section RK Results

Kriging was not attempted on I-70 due to the high variability of topography and highly variable RWIS station locations (shaded locations, varying elevations, etc.). This is an analysis that could be considered in the future.

Appendix C. Training Materials

Training materials were developed titled Using Roadway Friction in Winter Maintenance Operations, in Power Point [Road Friction_Training.ppt] and included speaker notes. Screenshots of the training slides from the Power Point are provided below.



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1

2

What is friction?

Dictionary

Find the meaning of....

fric·tion

/ˈfrikSH(ə)n/

noun

1. the resistance that one surface or object encounters when moving over another:
   "a lubrication system that reduces friction"

   Similar abrasion abrading rubbing chafing

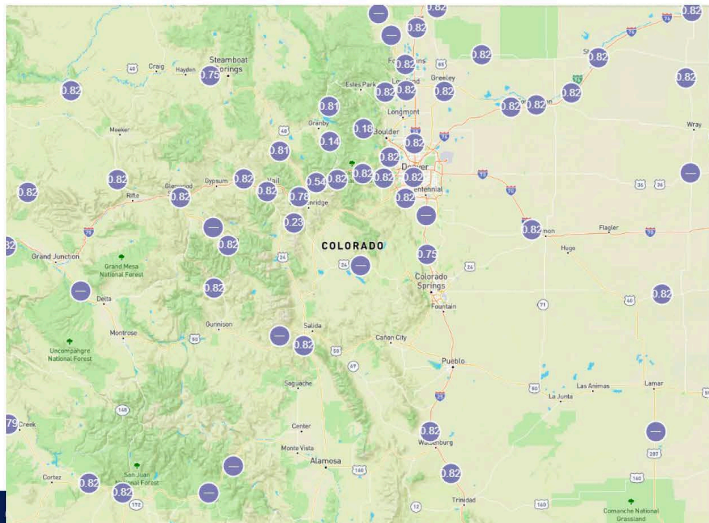
Powered by Oxford Dictionaries

More definitions, origin and scrabble points

www.merriam-webster.com › dictionary › friction

How is friction measured?

- Non-contact
  - Stationary

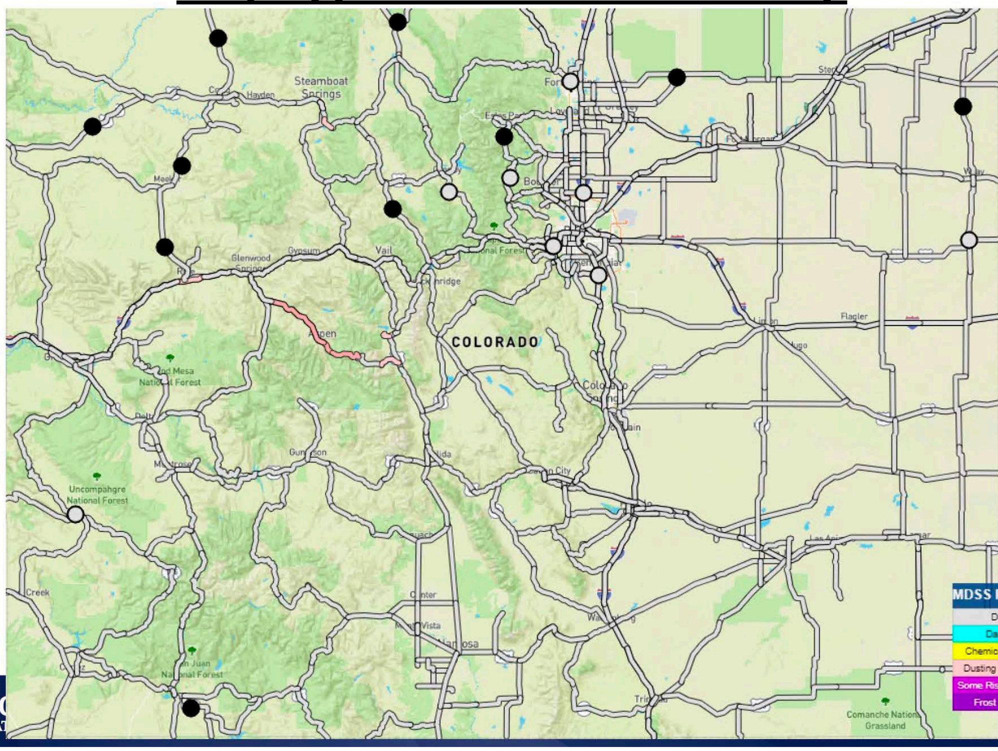


https://www.vaisala.com/en/products/weather-environmental-sensors/remote-surface-state-sensor-dsc211

4

Accessing the Data

https://www.webmdss.com/

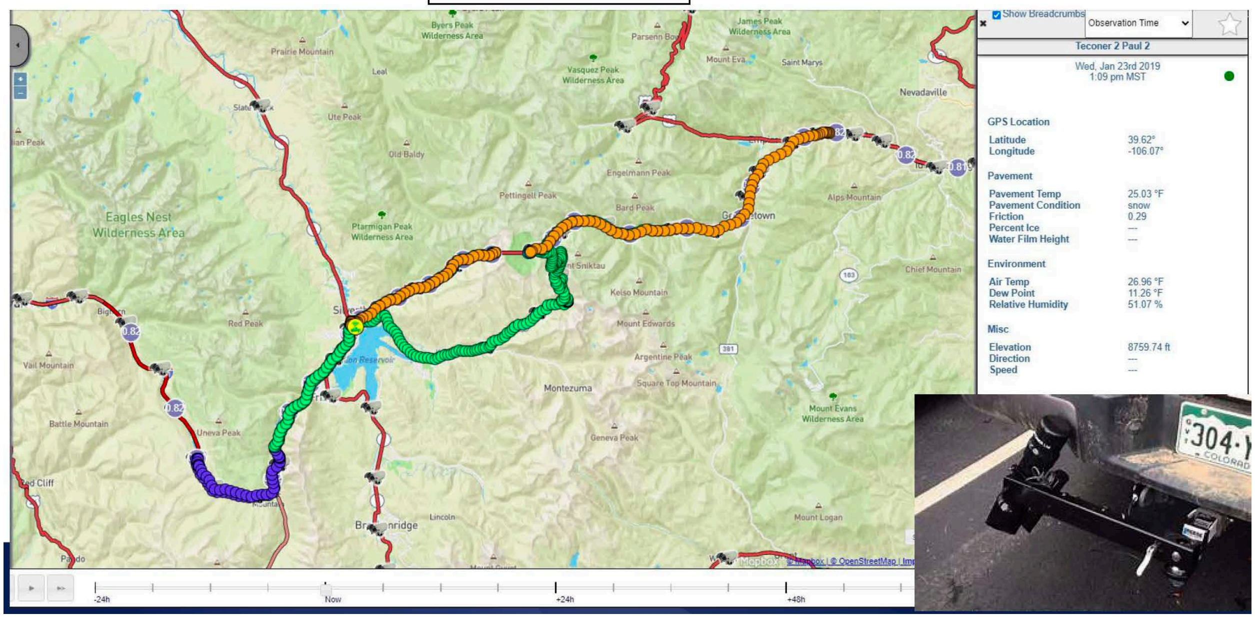


4

How is friction measured?

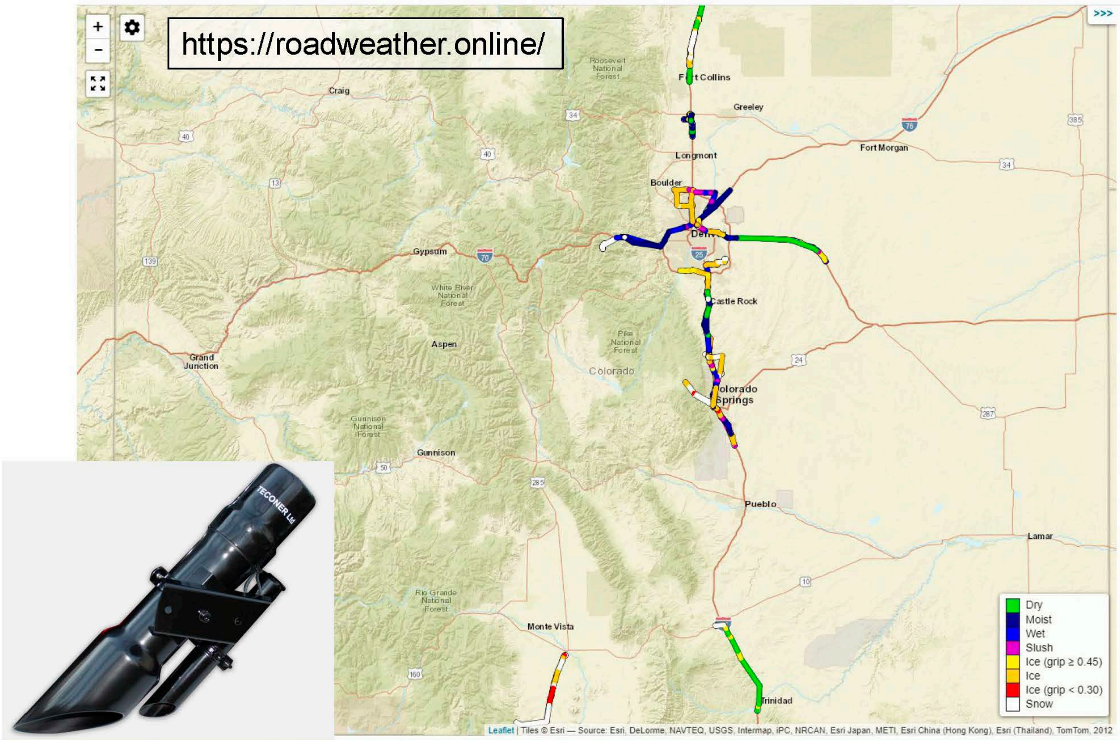
- Non-contact
  - Mobile

Viewed in MDSS



6

How is friction measured?



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How is friction measured?

- Contact – not used by CDOT
  - Used at DEN airport

Roadway Friction

- Roadway friction can tell us many things
  - How slippery is the pavement surface?
    - Pavement quality
    - Pavement surface state/condition
      - Wet
      - Icy
      - Snowy
    - Surface treatments
      - Overlays (example: chip seal)
      - Deiced/Anti-iced
      - Sand*

9

What do roadway friction values look like?

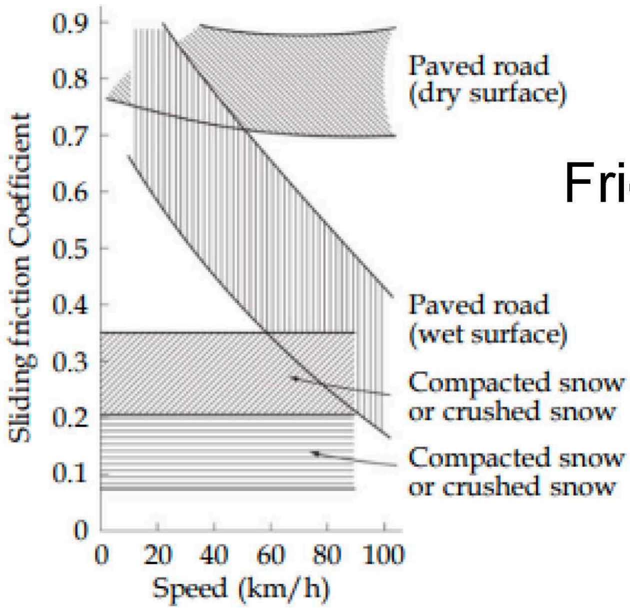

Figure 1. Sliding friction coefficient and road surface condition [1].

Friction (μ) = 0.0 to 1.0

Onoda, 2003

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Roadway Friction Values

CDOT Friction Guidelines

Friction Reading	Typical Road Conditions
0.80 to 1.0	Dry
0.60 to 0.79	Wet (icy spots possible on bridge decks, ramps)
0.45 to 0.59	Slushy and/or icy spots
0.31 to 0.44	Icy
<0.30	Icy and/or snow packed

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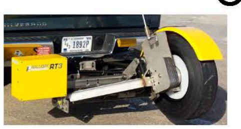
Pros and cons of each friction measurement method

- Non-Contact
  - Stationary (RWIS based)

    - Pros – incorporated into RWIS, access to data, linked with other data (example: road temperature, precipitation, etc.), continuous data from point locations, allows for trend analysis
    - Cons – field of view/data reported from a single, small area
    - Other – moderately expensive
  - Mobile (vehicle mounted)

    - Pros – real-time information, mapped data, access to data from vendor
    - Cons – limited to specific vehicles, needs to be turned on, reports an average value, needs cleaning/calibration/maintenance
    - Other – data reported from the lane vehicle drives (small field of view), moderately expensive
- Contact



    - Pros – great data quality
    - Cons – expensive, need to drive

12

Can we assume all friction data is the same?

- Yes and no….
  - Yes
    - friction ranges should be similar
  - No
    - The measured friction values at each location on the road may vary because
      - They are measured with different sensors
      - They are not measured in the exact same location at the same time

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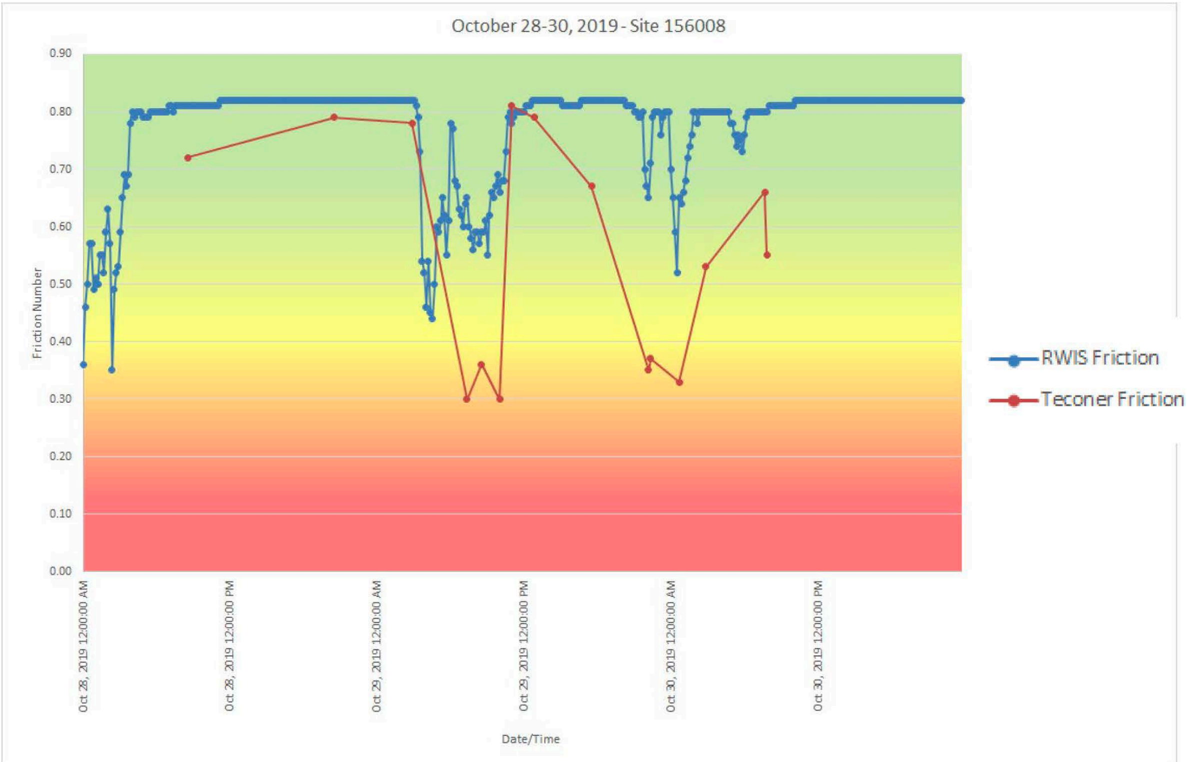


October 28-30, 2019 - Site 156008
Friction Number
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Oct 28, 2019 12:00:00 AM
Oct 28, 2019 12:00:00 PM
Oct 29, 2019 12:00:00 AM
Oct 29, 2019 12:00:00 PM
Oct 30, 2019 12:00:00 AM
Oct 30, 2019 12:00:00 PM
Date/Time
RWIS Friction
Teconer Friction

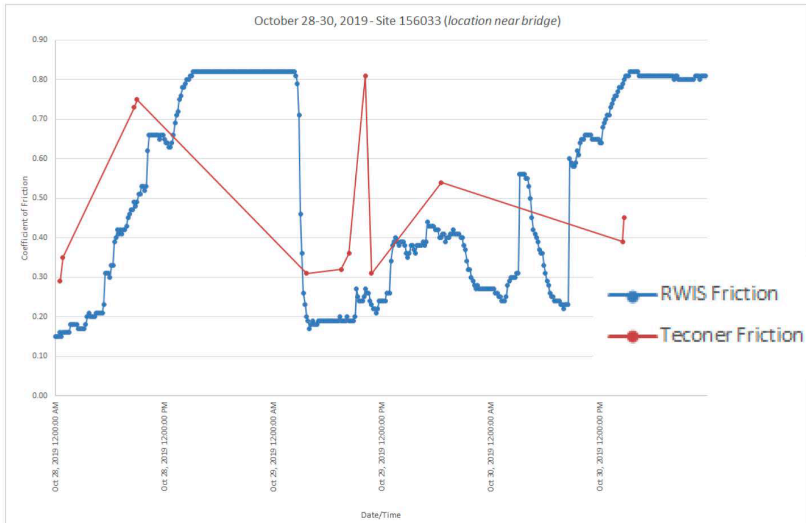
The importance of …

- Maintenance
  - Annual, seasonal? (See manufacturer guidelines)
  - Who is in charge of this?
  - Who is responsible for ensuring it gets done?
- Calibration
  - Each sensor has its own required calibration methods and frequency. (See manufacturer guidelines)
  - Example: Teconer non-contact mobile sensors are designed to be calibrated each time they are turned on by the vehicle operator.

15

What does it mean if the RWIS friction value is 0.3, but the mobile friction value in my truck is 0.8?

- Use as much information as is possible – check both data sources.



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How can you use roadway friction information?

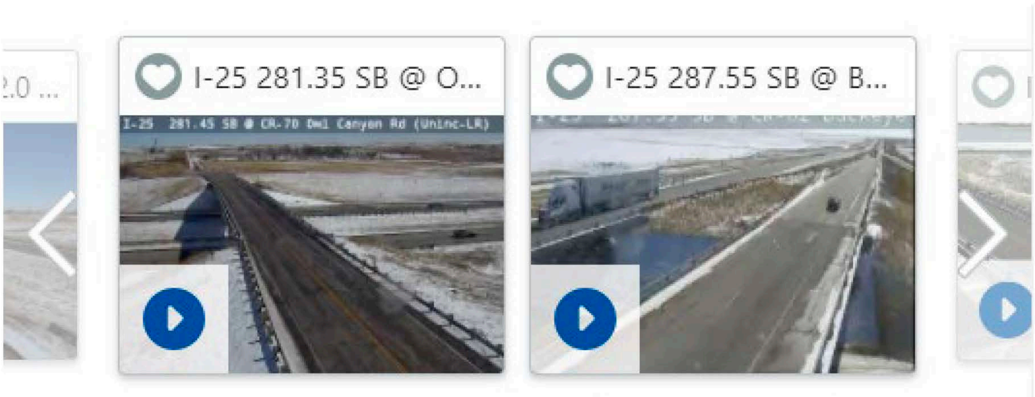
- Planning
- Real-time Decision Making
- Post Storm Review

Roadway Friction	
Above 0.6	Safe
0.6 to 0.45	Caution
Below 0.45	Danger

17

How do we use roadway friction information?

- Planning
- Real-time Decision Making
- Post Storm Review



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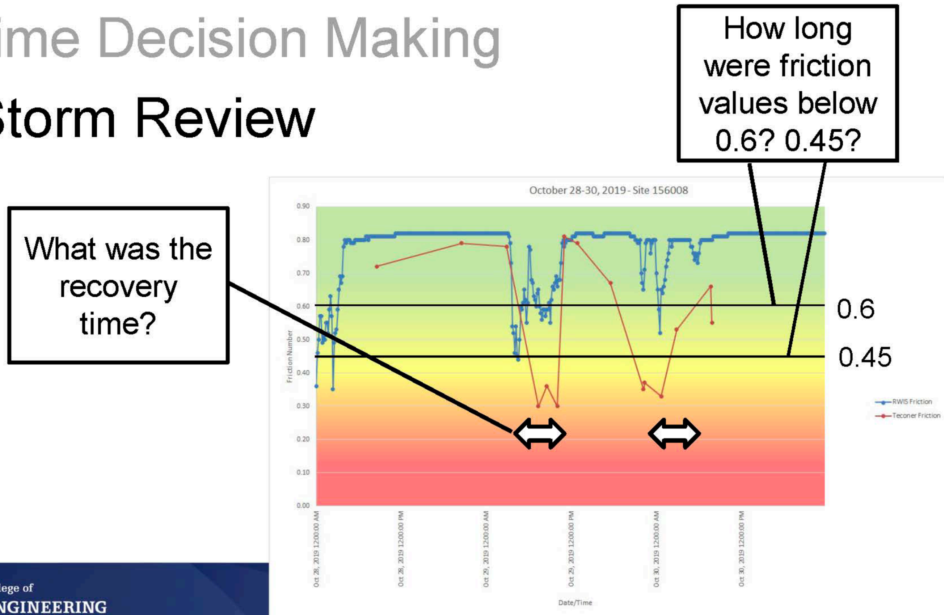
How do we use roadway friction information?

- Planning
- Real-time Decision Making
- Post Storm Review



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Information Sources

Assessing the Effectiveness of Friction as a Performance Management Tool in Colorado

https://www.codot.gov/programs/research/pdfs/2022

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