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Assessment of Connected Vehicle Friction Measurement Data on DOT Winter Maintenance Use Cases

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Aurora Project 2023-01

Final Report
August 2024

About Aurora

The Aurora program is a partnership of highway agencies that collaborate on research, development, and deployment of road weather information to improve the efficiency, safety, and reliability of surface transportation. The program is administered by the Center for Weather Impacts on Mobility and Safety (CWIMS), which is housed under the Institute for Transportation at Iowa State University. The mission of Aurora and its members is to seek to implement advanced road weather information systems (RWIS) that fully integrate state-of-the-art roadway and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures.

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16. Abstract

In winter season 2023–2024, Aurora program member states had the opportunity to evaluate connected vehicle friction measurement (CVFM) data provided by NIRA Dynamics's connected vehicle (CV) fleet. A detailed analysis was conducted in Colorado, Pennsylvania, and Utah to evaluate how the CVFM data can be utilized in three use cases: variable speed limits (VSLs), chain laws, and winter maintenance forensics.

For VSLs, a proof-of-concept friction signal was developed that proved capable of detecting slipperiness on the chosen corridors. A side-by-side comparison with historical speed restriction data demonstrated the value in utilizing a friction signal as an additional parameter for VSL decision-making.

The friction signal algorithm was applied to the chain law use case and showed reliable performance on I-70 in Colorado. During snowstorms over the winter of 2024, the friction signal was able to detect the presence of low friction. Using the friction signal alongside existing weather data could improve methods for issuing chain restrictions.

For winter maintenance forensics, several methods to measure a winter maintenance key performance indicator (KPI) using CVFM data were explored. Two methods used CVFM data to calculate KPIs for winter storm mitigation on individual roads, one providing an illustrative overview of the impact of a winter season on a road and one providing a detailed analysis of how CVFM reflects the impact of a snowstorm on a road stretch. A third approach involved calculating a KPI based on CVFM data during periods of snowfall for larger road networks. The KPI provided a reliable measure of how snowfall affects road networks and how maintenance work mitigates these effects. The results can be used for post-season evaluation of the maintenance work to find areas of improvement.

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ASSESSMENT OF CONNECTED VEHICLE FRICTION MEASUREMENT DATA ON DOT WINTER MAINTENANCE USE CASES

Final Report
August 2024

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The authors additionally would like to acknowledge the Colorado, Pennsylvania, and Utah departments of transportation (DOT) for sharing their use cases of interest and for their collaboration and support during this study.

EXECUTIVE SUMMARY

In this project, spanning winter season 2023–2024, the 19 states of the Aurora program had the opportunity to evaluate connected vehicle friction measurement (CVFM) data provided by NIRA's connected car fleet. Three states were selected by the Aurora members for a detailed analysis of how NIRA's CVFM data can be utilized in the states' individual use cases. The three states (Colorado, Pennsylvania, and Utah) requested the analysis to be done on variable speed limits (VSLs), chain laws, and winter maintenance forensics.

For VSLs, a proof-of-concept friction signal was developed that showed good capabilities in detecting slipperiness on the chosen VSL corridors. A side-by-side comparison was made with historical speed restriction data. This comparison demonstrated the value in utilizing a friction signal as an additional parameter for making appropriate VSL decisions.

The proof-of-concept friction signal algorithm developed for VSL was applied to the chain law use case and showed reliable performance on the chosen mile marker stretches for I-70 in Colorado. The impact of snowstorms during winter 2024 was reflected by the friction signal, which was able to detect the presence of low friction. The produced friction signal, in combination with existing weather data, could be used to improve current methods when issuing chain restrictions.

For winter maintenance forensics, several methods to measure a winter maintenance key performance indicator (KPI) using CVFM data were explored. Two methods that involved using CVFM data to calculate KPIs for winter storm mitigation on individual roads were developed.

Method 1 provided an illustrative overview of the impact of a winter season on a road. A KPI was produced by setting a desired level of low friction measurements from the CVFM data and an accepted timeframe in which maintenance work was expected to mitigate a snowstorm's impacts.

Method 2 was developed for detailed analysis of how CVFM reflects the impact of a snowstorm on a road stretch. Along with department of transportation (DOT) historical data, an analysis can be done to study how maintenance work impacted the mitigation of low friction.

A third approach was explored that involved calculating a KPI based on CVFM data during periods of snowfall for larger road networks. The KPI provided a reliable measure of how snowfall negatively affects road networks and how the work of maintenance crews mitigates these effects. The produced KPI and the illustrative graphs can be used for post-season evaluation of the maintenance work to find areas of improvement.

1. INTRODUCTION

Knowing road friction has been, and still is, the holy grail for winter maintenance, both for vehicles traveling the roads as well as for winter maintenance operations. Road conditions can only be assessed through evaluation of on-the-ground accessibility and safety during winter conditions, both of which translate into the ability of vehicles to safely perform maneuvers. Friction measurements have been used by Scandinavian departments of transportation (DOTs) for many years with the purpose of procuring an acceptable level of service for their road networks.

The main motivation for this work can be summarized by the following quote by Lord Kelvin: "If you cannot measure it, you cannot improve it." Connected vehicle friction measurement (CVFM) provides continuous information over the road network when the network is traversed by vehicles. These continuously collected data, in combination with weather parameters, form the basis of a winter maintenance key performance indicator (KPI). Friction information is valuable when, for instance, a variable speed limit (VSL) should be lowered or restored to give the traveling public confidence in the mandated speed limit and to promote compliance with VSLs. Another tactical use case is to understand road conditions throughout the state, that is, where roads are slippery and where they are wet.

NIRA Dynamics, the market leader in the provision of real-time friction data, typically onboards one to two (national, in Europe) DOTs per year, and two full winter seasons are typically required to fully demonstrate the value provided by the insights derived from the friction data. In this project, spanning one winter season and 19 states, a deep dive was carried out in three states to demonstrate the states' use cases and the value drawn from the data. The three states assessed were as follows:

- Colorado, due to its long winter season and guarantee of snow and its more northern climate
- Utah, which has intense weather due to its mountain ranges and has a small number of corridors carrying the majority of the traffic
- Pennsylvania, which has the highest penetration of connected vehicles (CVs)

The remaining 16 DOTs had full access to the online tools for their own use and testing.

During the project initiation phase, three research questions were posed:

- Can CVFM data be used to activate and deactivate VSLs?
  - Utah and Pennsylvania
- How can CVFM be used in forensic scenarios, for example, in understanding the effects of a storm and its aftermath?
  - Colorado
- Can CVFM data be used to inform chain laws?
  - Colorado

Chain laws and VSLs have almost the same function, in that they have the same inputs and outputs but with slightly different usages.

1.1. Connected Vehicle Friction Measurement Data

NIRA's friction data come from a fleet of CVs. NIRA's integrated software in the cars uses the existing vehicles' sensor arrays to measure and calculate a wide range of values. Friction measurements are one set of such values. To provide accurate measurements across multiple car platforms, the software is customized, optimized, and validated for each car platform integration.

Additional data validation is also performed in the cloud service for all generated friction measurements to guarantee a high confidence for each friction measurement used in the final product.

CVFM data are aggregated every 10 minutes for 75 ft long sections of a road. These small sections, referred to as subsegments, are then classified as high- or low-friction subsegments.

Each measurement from the vehicles provides a friction interval. This interval is specified by the values muUpper and muLower, as illustrated in Figure 1. Both are used in subsegment aggregation.

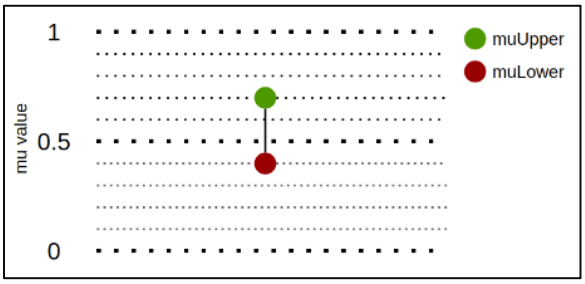


Figure 1. One friction measurement and its highest measured friction (muUpper) and lowest measured friction (muLower)

The presence of low values of muUpper indicates slipperiness on the subsegment, whereas the presence of high values of muLower indicates good road conditions. To determine a friction value with high confidence for a subsegment, all measurements from the CV fleet during a 10-minute period are aggregated. In the aggregation, the lowest muUpper and the highest muLower of all measurements are extracted, resulting in values called lowestMuUpper and highestMuLower. The aggregation is illustrated in Figure 2.

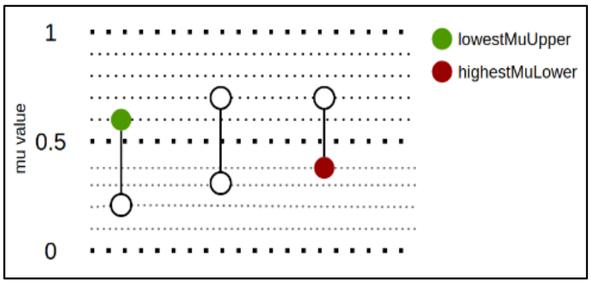


Figure 2. Three friction measurements during a 10-minute period for one subsegment, with the lowest measured muUpper and highest measured muLower selected as output values from the aggregation

2. PROJECT CHALLENGES

2.1. Coverage Loss during Low-Friction Events

In the initial phase of the project, it was observed that the number of road segments with CVFM data dropped unexpectedly when roads became slippery. After investigation, it was determined that this was related to the composition of the vehicle fleet in the project regions (which nearly exclusively consisted of all-wheel drive [AWD] vehicles), in combination with a backend software configuration that had been defined based on a market dominated by two-wheel drive (2WD) vehicles.

To address this challenge, a backend software configuration that makes smarter use of AWD vehicle data was created and deployed on January 24, 2023. In the United States, this increased the coverage during low-friction conditions by a factor of four.

2.2. Low-Coverage States

In states or in rural areas within a state with low vehicle coverage, it was challenging to use the friction information on a subsegment level. The data, however, provided valuable insights on the holistic level. This was achieved by viewing all CVFM data in a fixed area as generated by an extra road weather information system (RWIS) station, providing a better overview of the state of the road network (Figure 3).

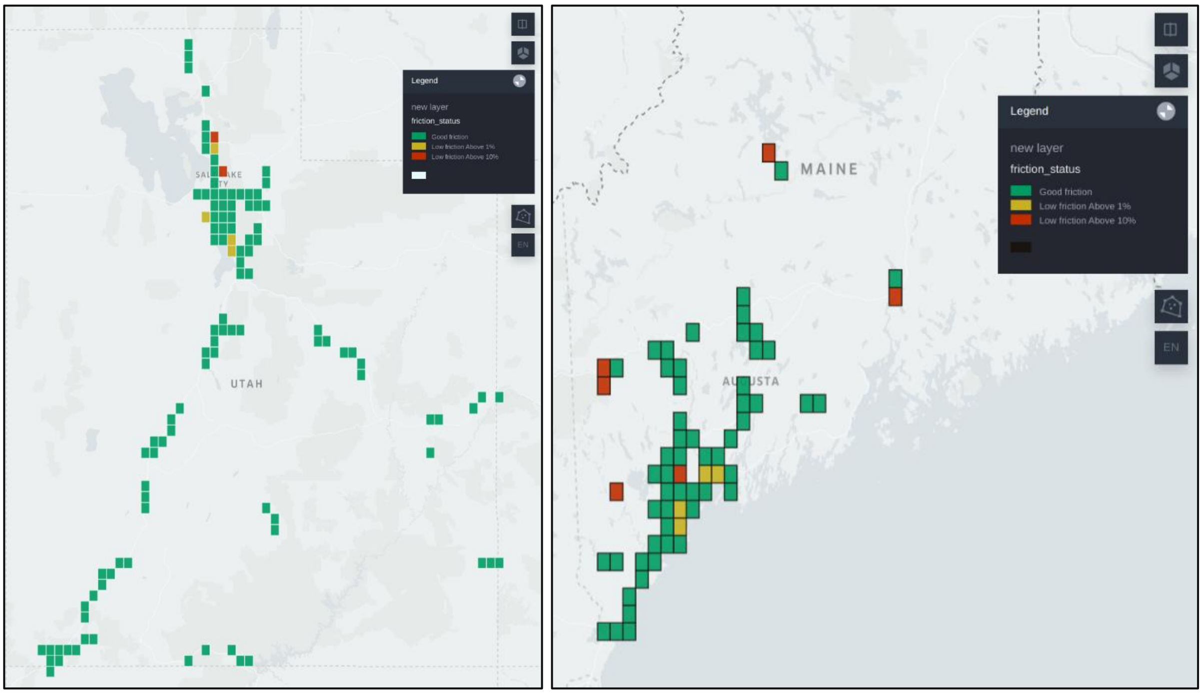


Figure 3. Friction measurements for 30 minutes in Utah (left) and Maine (right), illustrating how CVFM can be viewed as mobile RWIS stations

2.3. Ground Truth

The Swedish Transport Administration (Trafikverket) has been analyzing and confirming the accuracy of friction measurements from CVFM data (Asp et al. 2021). However, since concerns about accuracy are often raised, a study in the United States was conducted by LSM Analytics, LLC (Mahlberg and Li 2024).

As described in the report for that study (Mahlberg and Li 2024), the feasibility of using CVFM data for winter maintenance was investigated during five storms in early 2024. The study found that the decision-making of winter maintenance can be supported when data aggregated at one-hour intervals are used. The report correlates low friction levels with photographs taken at locations with ongoing snow and below-freezing temperatures. A specific observation was made with the detection of low friction (0.1 μ) adjacent to a crash site.

3. USE CASE DESCRIPTION

The use cases to be investigated in this study were brainstormed together with the three selected DOTs (Colorado, Utah, and Pennsylvania) during a project kickoff meeting.

3.1. Variable Speed Limits

VSLs are used to modify speed restrictions for congestion and safety purposes across the United States. The VSL corridors analyzed in this study are presented in Table 1.

Table 1. Selected VSL corridors for analysis

State	Road	Route	VSL Triggers	VSL Control
Pennsylvania	I-80	Entire state stretch	Weather forecast Manual observations	Manual
Pennsylvania	I-81	Entire state stretch	Weather forecast Manual observations	Manual
Pennsylvania	I-76	Between I-276 and US 1	INRIX traffic data	Automated
Utah	I-15	Baker Canyon	RWIS data	Automated Manual
Utah	I-80	Parleys Canyon	RWIS data	Manual

3.1.1. Use Case Definition

Analyze car fleet friction data for VSL corridors and create a proof-of-concept friction signal for road slipperiness. Identify whether the signal can be used as a basis for making appropriate VSL decisions.

3.1.2. Purpose

Making appropriate VSL decisions is of critical importance in ensuring the safety of road users. In supporting decision-making, the variation, reliability, and consistency of the underlying data are paramount.

The purpose of this use case is to study how a friction signal provided by NIRA’s car fleet can be used as an additional decision support in VSL decision-making.

3.1.3. Analysis

The CVFM data used for this use case were aggregated every 10 minutes for each 75 ft long road subsegment. See Section 1.1 for more details. By setting thresholds for lowestMuUpper and highestMuLower, each subsegment was classified as either a high- or low-friction subsegment.

The criteria listed in Table 2 were set for this analysis.

Table 2. Criteria for high- and low-friction subsegment classifications

High-Friction Subsegment	Low-Friction Subsegment
highestMuLower above 0.5 and lowestMuUpper above or equal to 0.61	lowestMuUpper below 0.61

The following requirements were set for the friction signal:

- The signal should be able to detect slipperiness on any chosen road.
- The signal should provide a slipperiness classification for any chosen road.
- The classifications should be easy to interpret and therefore have a small number of clear classifications.
- The signal classifications chosen were as follows:
  - **Red**: High presence of slipperiness
  - **Yellow**: Low presence of slipperiness
  - **Green**: No presence of slipperiness
  - **White**: Low coverage
- The thresholds for classifying should be easy to understand and allow finetuning by the DOT.

The process for setting the thresholds for friction classification is detailed on the following pages.

A first analysis of the friction data was done on I-80 and I-81 in Pennsylvania to study the coverage and determine which thresholds would be most appropriate to use in the implementation of a friction signal. During this analysis, it was discovered that the confidence filter discarded most friction measurements during low-friction conditions. See Section 2.1 for more details.

To compensate for the discarded friction measurements, I-76 between Philadelphia and Harrisburg was selected due to the higher number of vehicles traveling the road compared to I-80 and I-81.

The graph shown in Figure 4 presents the ratio (left y axis) between low and high friction subsegments represented as red and blue triangles. The green line shows the percentage (right y axis) of subsegments with friction measurements. The x axis represents time.

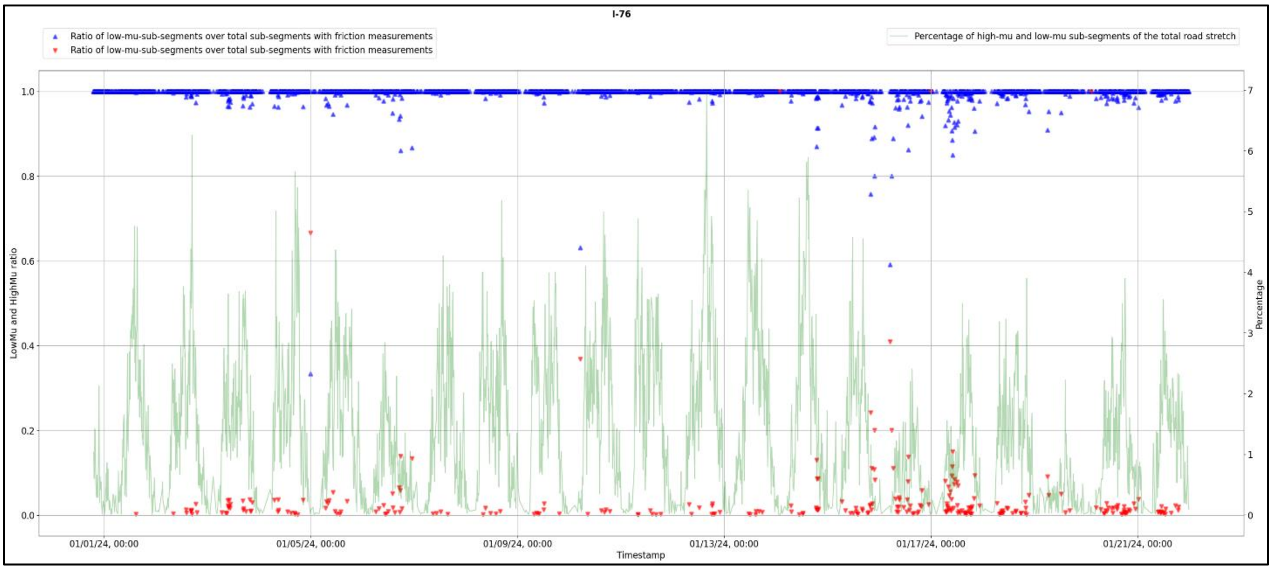


Figure 4. Ratio between subsegments classified as low friction and high friction and the percentage of subsegments that were classified for the entire road stretch – I-76 between Philadelphia and Harrisburg

Figure 4 was used as the basis for the thresholds for friction signal classifications. The determined thresholds described in Table 3 for the red and yellow signal classifications come from studying the graph in Figure 4 during known winter storms. The threshold described in Table 3 for the green friction signal classification was set by studying the green line in Figure 4.

Table 3. Signal classifications and thresholds

Signal Classification	Thresholds
Red: High presence of slipperiness	Over 10% of subsegments with CVFM data are low-friction subsegments, and at least 2 subsegments exhibit low friction measurements
Yellow: Low presence of slipperiness	1% to 10% of subsegments with friction measurement data indicate low friction, and at least 2 subsegments exhibit low friction measurements
Green: No presence of slipperiness	More than 3% of subsegments on a road indicate high friction
White: Low coverage	None of the above thresholds fulfilled

3.1.4. Producing the Friction Signal for a Road

Using the criteria for classifying subsegments as low or high friction, and using the thresholds for signal classification, a friction signal was generated for each road.

DOTs' historical VSL data were used to determine the VSL corridors for which a friction signal should be produced. The same DOT data were also used to extract the time periods when an active VSL event was present.

In Pennsylvania, the I-80 and I-81 corridors were split at county lines due to the long distance of the VSL corridors. Friction signals were therefore produced for each county. For Utah's VSL corridors, a friction signal was produced for the whole stretch of the corridor.

Considering that roads might have higher traffic flow in one direction versus the other during the day and that winter maintenance actions might differ by direction too, it was decided to produce a signal for each direction.

Figure 5 shows the produced friction signals for the VSL corridors on I-81. Each row represents a VSL corridor for one county and one direction of travel. The x axis represents time. The produced friction signal is represented as green, yellow, or green bars. The white areas of the figure represent low coverage.

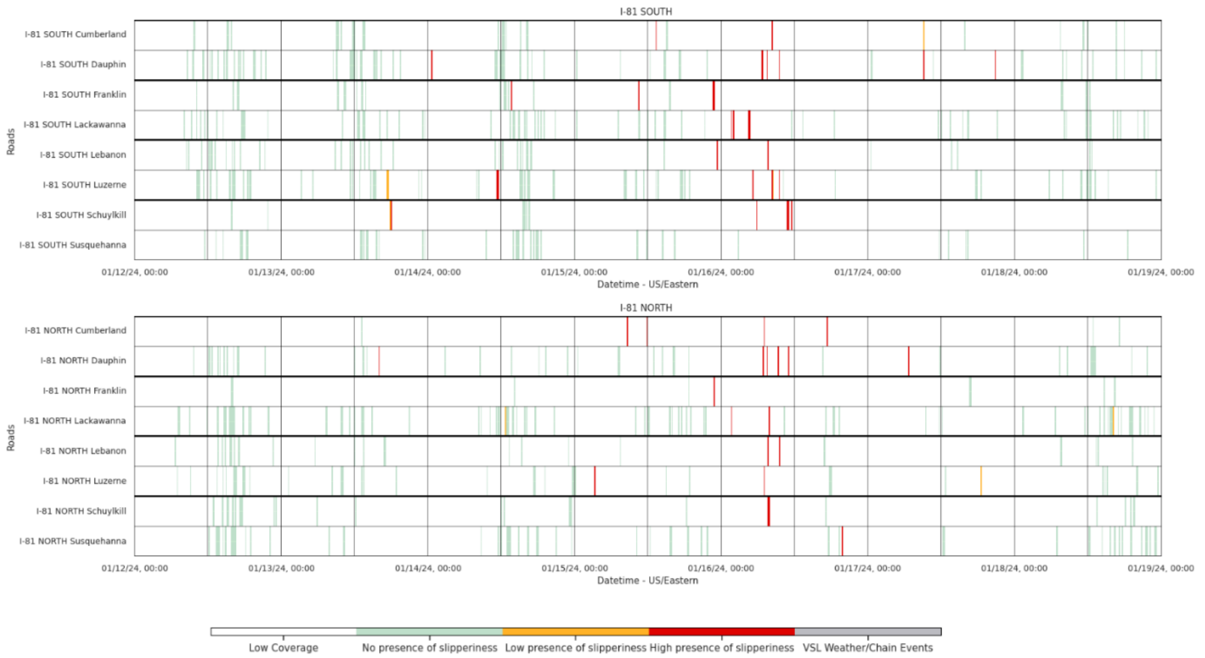


Figure 5. Produced friction signals for I-81

Figure 5 provided the following insights:

1. The available CVFM data were enough to detect the presence of slipperiness on the selected road stretches.
2. The general threshold for *no presence of slipperiness* might be set too high.

To produce a signal that is more stable without changing the thresholds, the concept of a sliding window was introduced. The idea is that high- and low-friction subsegments from the previous six 10-minute periods of aggregated friction data should be considered when setting the signal classification. This allowed for a friction signal to be set based on accumulated friction subsegments over a given period.

This approach did slightly impact the signals for high (red) and low (yellow) presence of slipperiness. Some red signals would need to meet their threshold with a higher number of accumulated high-friction subsegments from previous six 10-minute periods, resulting in those signals becoming yellow. The approach would, however, help to dilute the presence of false low-friction subsegments.

In Figure 6, each bar represents 10 minutes of friction data, and each color represents the 10-minute period from which the data originate. The horizontal dashed line represents a desired threshold to be met before making any decisions.

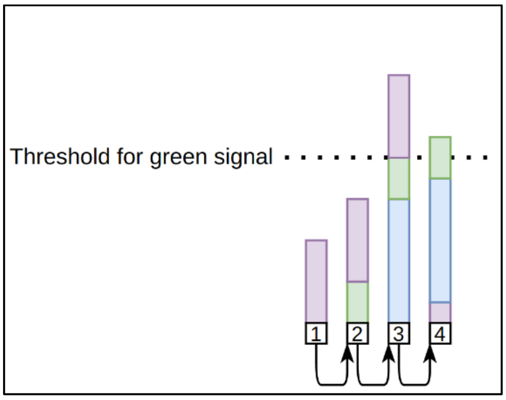


Figure 6. 30-minute sliding window

During the first 10 minutes of friction measurements, the threshold for a green signal has not been met. When producing a signal for the next 10 minutes, the previous measurements, illustrated by purple, are added to the total, but the threshold has still not been passed. The same principle is applied for the third 10 minutes, and this time measurements from the previous 20 minutes are added, illustrated as green and purple. For this 10-minute period, the threshold has been met and a green signal is produced.

The results of applying a 60-minute sliding window when producing the friction signals for I-81 can be seen in Figure 7.

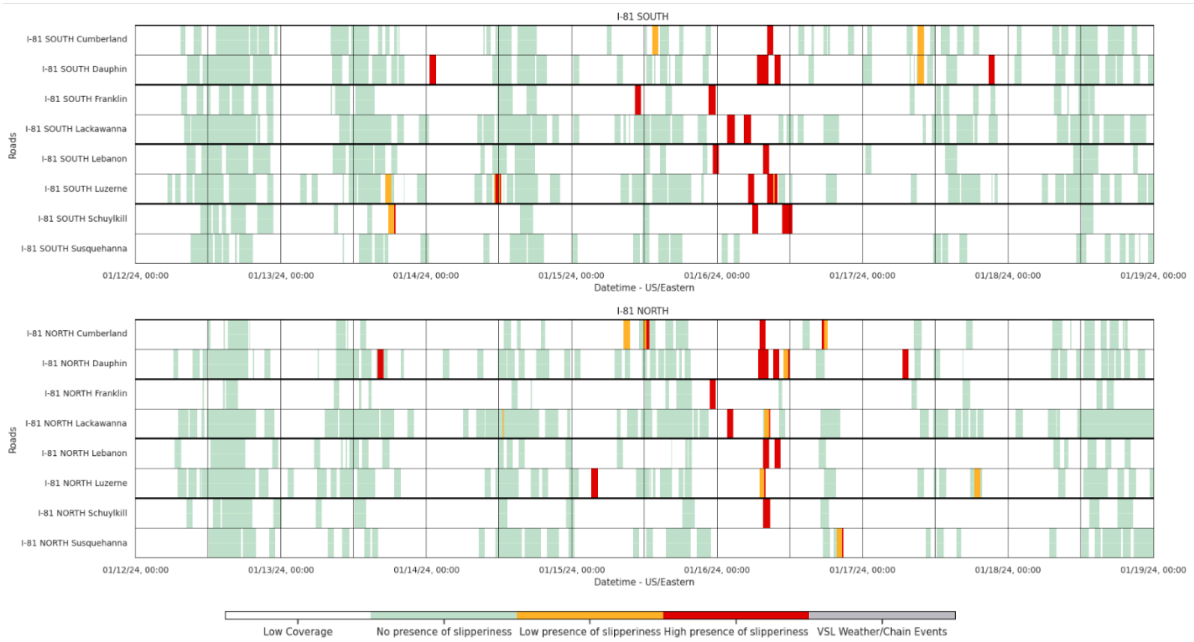
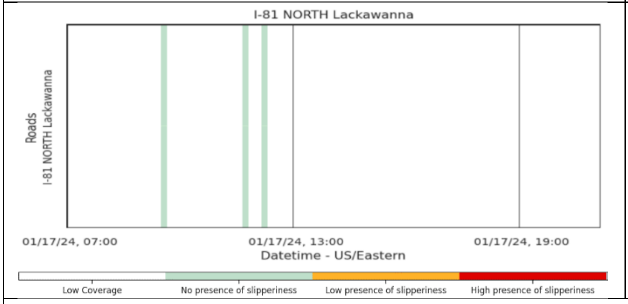
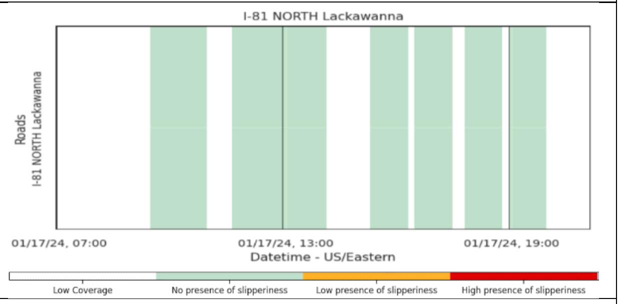
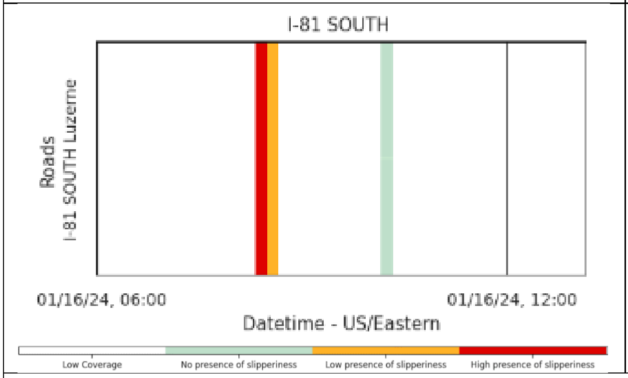
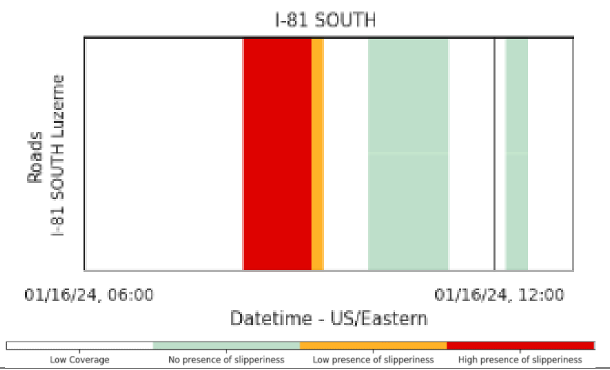


Figure 7. Produced friction signals for I-81 using a 60-minute sliding window

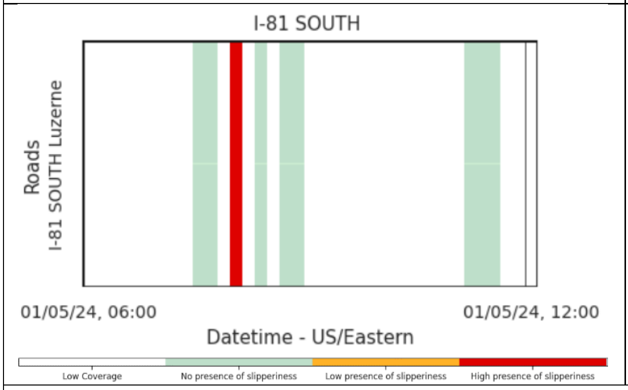
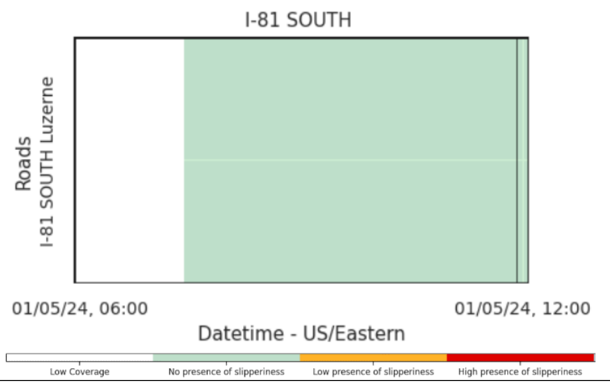
Detailed examples of the results of applying a 60-minute sliding window are described in Figure 8.

No sliding window, 10 minutes of friction data	*60-minute sliding window, 60 minutes of friction data*
	

Applying a 60-minute sliding window produces a more stable green friction signal compared to that produced using only 10 minutes of friction data.

No sliding window, 10 minutes of friction data	*60-minute sliding window, 60 minutes of friction data*
	

Applying a 60-minute sliding window produces a more stable red friction signal compared to that produced using only 10 minutes of friction data.

No sliding window, 10 minutes of friction data	*60-minute sliding window, 60 minutes of friction data*
	

Applying a 60-minute sliding window removes the presence of a short red friction signal. This indicates that the red friction signal was weak when evaluated using only a 10-minute sliding window. The red friction signal was probably produced from low friction measurements generated by a vehicle driving on the road shoulder. Applying a 60-minute sliding window is an effective way to filter out these unwanted effects.

Figure 8. Detailed examples of the results of applying a 60-minute sliding window

Applying a 60-minute sliding window to produce the friction signals showed the following results:

- The signals produced were active for a longer time.
- Weak red and yellow friction signals were discarded, raising the confidence for all friction signal types.
- Additional green signals were able to be produced.

The results showed an overall improvement in the produced friction signals, leading to the decision to apply a 60-minute sliding window to produce all friction signals for the VSL corridors.

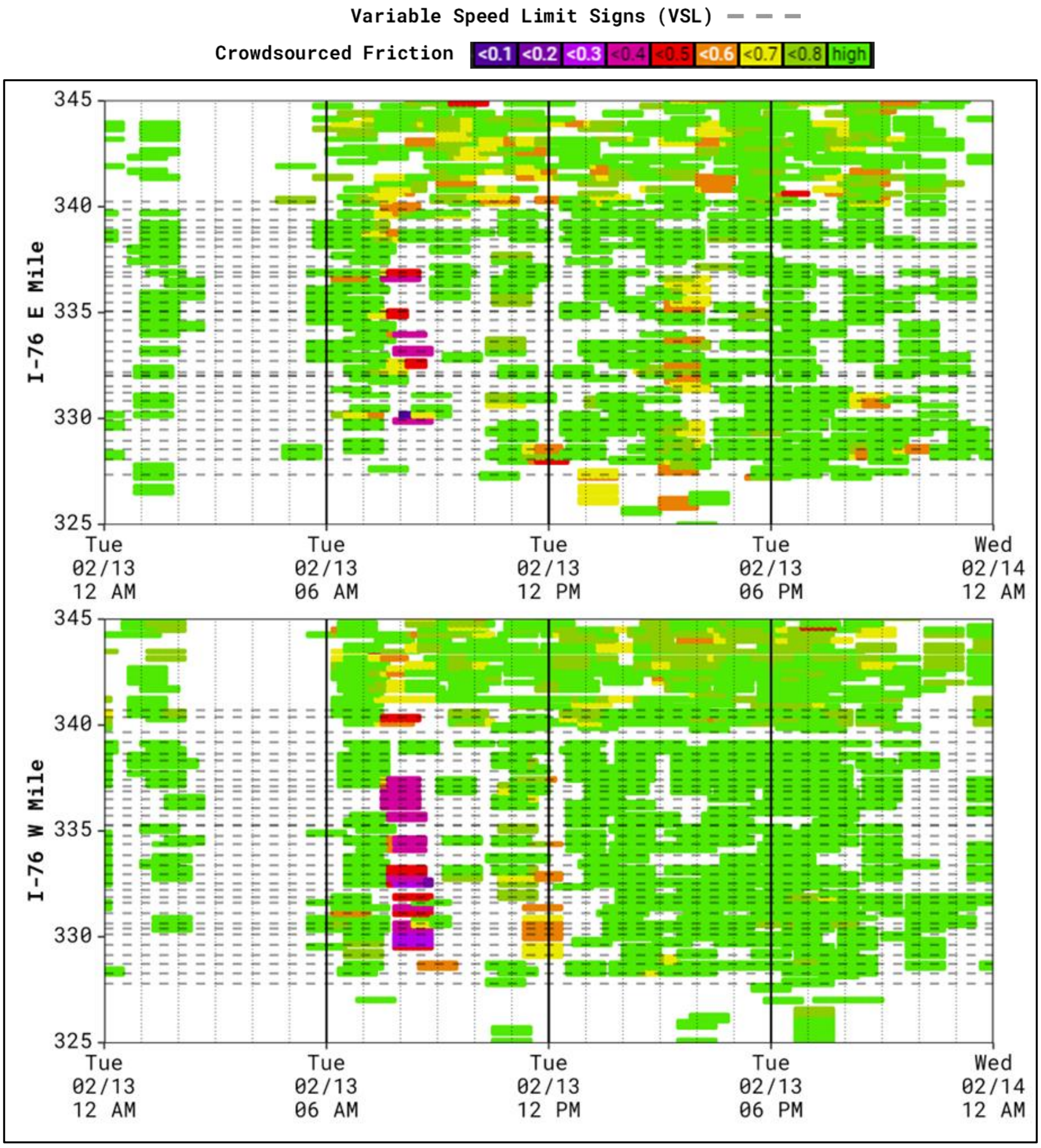
3.1.5. Results

The following sections highlight the friction signals produced with a sliding window of 60 minutes for the VSL corridors in Pennsylvania and Utah. As a comparison, the respective DOTs' historical VSL decisions have been added to the figures presented in these sections.

3.1.5.1. Pennsylvania I-76

In addition to the study performed on I-76 in the present research, a parallel study was done by LSM Analytics (Mahlberg and Li 2024) on the same VSL corridor during the same period. The goal of the latter study was to evaluate crowdsourced vehicle friction data to determine the potential for supporting operational decisions.

Figure 9, from the LSM Analytics report (Mahlberg and Li 2024), shows friction data measurements across I-76, from mile markers 325 to 345, represented by the y axis. The friction data come from NIRA's maintenance-aggregation algorithm, which represents a different way of merging and representing friction values based on an older aggregation algorithm because the new one is not yet accessible through the external NIRA application programming interface (API). The data are aggregated over 60 minutes using a friction average approach, resulting in a wider spectrum of friction measurements. Friction data are represented by a color bar ranging from below 0.1 μ to above 0.8 μ with 0.1 μ intervals. The road is separated into westbound and eastbound.



Mahlberg and Li 2024

Figure 9. Crowdsourced friction in Pennsylvania, February 13, 2024

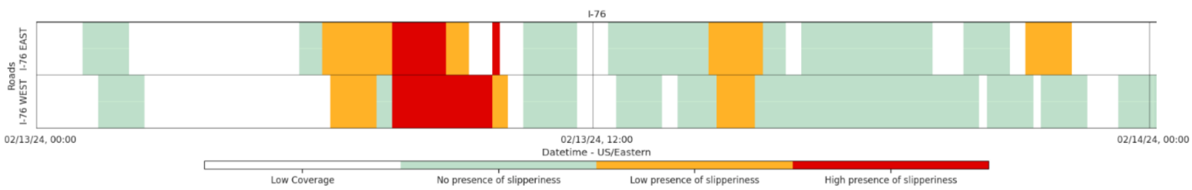


Figure 10. Friction signals for the VSL corridor on I-76 in Pennsylvania

A difference in the results between Figure 9, which is from the LSM Analytics report (Mahlberg and Li 2024), and Figure 10, which shows the friction signal for the same road segment, can be seen around 12 p.m. The friction signal in Figure 10, which uses a stricter approach (detailed in the previous report sections) to classify friction, classifies this period as “low coverage,” whereas the analysis by LSM Analytics (Figure 9) in the westbound direction, which uses friction average, shows friction values of 0.6 µ and above.

Using both analysis, aggregated friction data (Figure 9) and friction signal (Figure 10), allows for a wider understanding of the friction performance of a selected road. This understanding can help DOTs finetune the friction signal thresholds.

Combining the two studies together provides a more detailed picture of the friction measurements for the entire VSL corridor. In Figure 9, extracted from the LSM Analytics report (Mahlberg and Li 2024), we can see that the overall coverage for the I-76 VSL corridor is high, covering large sections of the road stretch during extended periods of the day.

3.1.5.2. Pennsylvania I-81

In summary, the friction signal produced on I-81 shows positive results in detecting slipperiness on all parts of the VSL corridor.

The following figures highlight some interesting findings when pairing the friction signals with DOT VSL weather events. Figure 11 presents the friction signals produced for Cumberland and Dauphin Counties between midnight on January 6 and midnight on January 7, 2024.

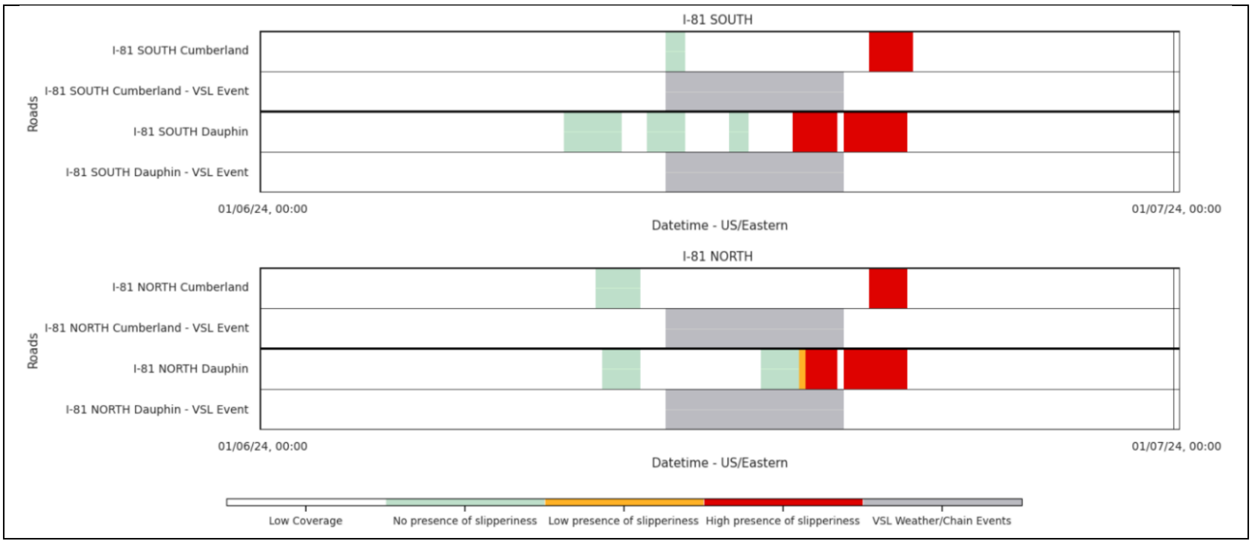


Figure 11. I-81 Dauphin and Cumberland Counties, Pennsylvania – Frictions signal with DOT VSL events

Here, a high presence of slipperiness is observed after the DOT VSL weather event expires, indicating that the speed restriction should have been kept active for a longer time. Observing the produced friction signals for Dauphin in both directions indicates that the issued speed restriction was turned on too early and turned off too soon.

Figure 12 presents the friction signals produced for Lackawanna, Luzerne, and Susquehanna Counties between midnight on January 6 and midnight on January 8, 2024.

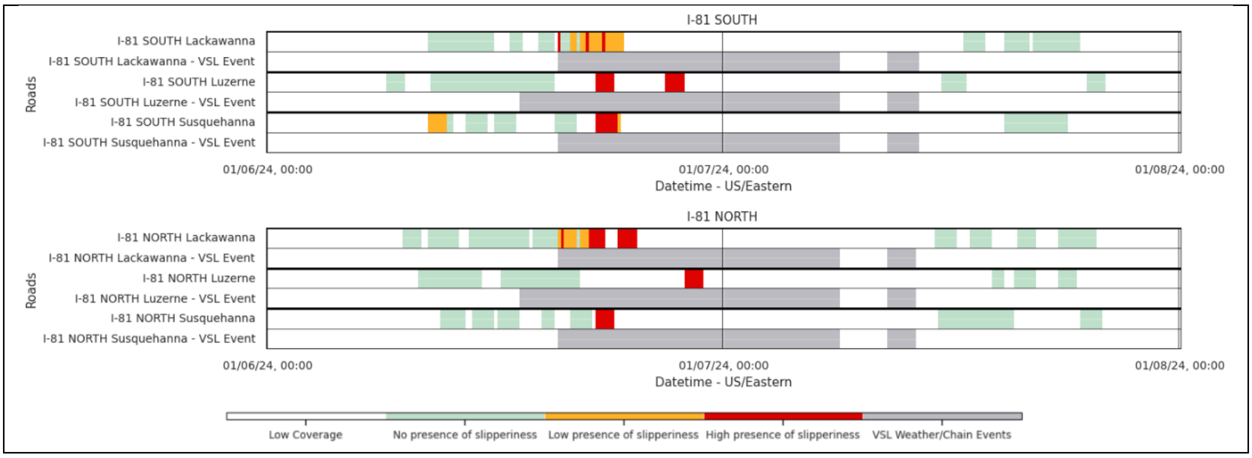


Figure 12. I-81 Lackawanna, Luzerne, and Susquehanna Counties, Pennsylvania – Friction signals with DOT VSL events

Here it is observed that on January 6, a red and yellow friction signal is produced that overlaps with the DOT's speed restriction weather events, giving additional basis for the DOT's decision to reduce speeds. For the southbound portions of Luzerne and Susquehanna Counties, a green signal is produced in the beginning of the active speed restriction, which indicates that the restriction might have been turned on too soon.

Additional figures showing interesting cases and figures showing produced friction signals from December 2023 through February 2024 can be found in Section A.1 of Appendix A.

3.1.5.3. Pennsylvania I-80

The friction signals for I-80 show results comparable to those produced for I-81, where several signals indicating high and low presence of slipperiness were produced.

Figure 13 presents the friction signals produced for Centre and Clearfield Counties between January 14 and 16, 2024.

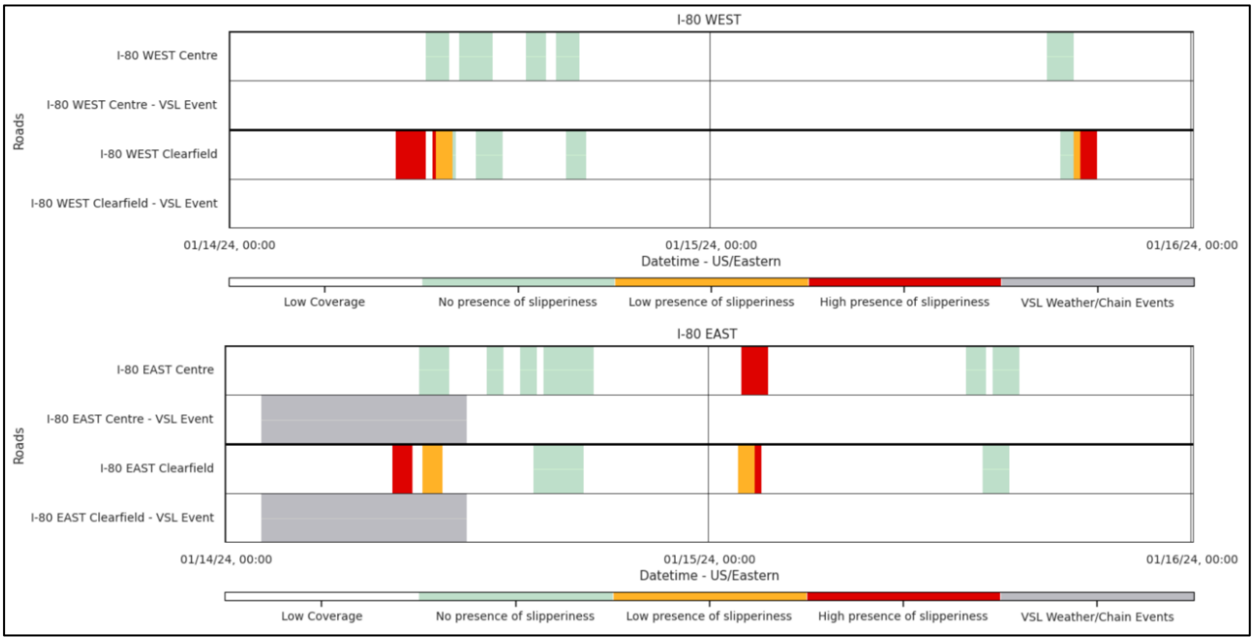


Figure 13. I-80 Centre and Clearfield Counties, Pennsylvania – Friction signals with DOT VSL events

On January 15, an active VSL weather event was issued in Clearfield and Centre Counties in the eastbound direction. In Clearfield County, the decision for an active VSL weather event is strengthened by a produced friction signal indicating low and high presence of slipperiness. A friction signal indicating high presence of slipperiness is also produced in the westbound direction for Clearfield County, providing a basis to also activate a speed restriction in that direction, but no VSL event was produced.

For Centre County, a green friction signal is produced during morning traffic for both the westbound and eastbound directions, indicating that the speed restrictions could have been turned off earlier than the current VSL weather event data show.

Figure 14 presents the friction signals for Centre, Clearfield, Clinton, and Union Counties on January 16 and 17, 2024.

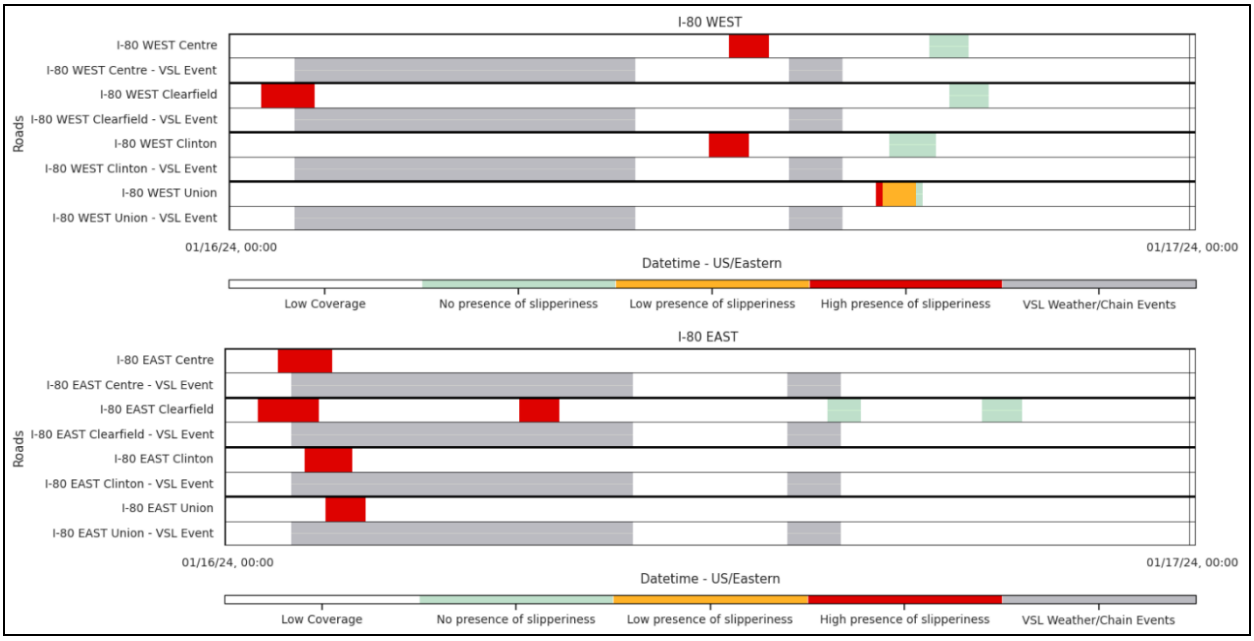


Figure 14. I-80 Centre, Clearfield, Clinton, and Union Counties, Pennsylvania – Friction signal with DOT VSL events.

On January 16, the speed restrictions can be backed up by the red friction signals. For Centre and Clearfield Counties, a red friction signal is generated earlier than the VSL weather event becomes active. Utilizing the friction signal in this case would have helped in activating the VSL speed restrictions earlier, in line with the road conditions.

The VSL weather events show that speed restrictions were deactivated too early and then reactivated. In this case, the friction signal produced for Centre and Clinton Counties would provide a basis to turn on the restrictions earlier or never deactivate them in the first place, keeping them active for an additional 6 hours.

Additional figures showing interesting cases and figures showing produced friction signals from December 2023 through February 2024 can be found in Section A.2 of Appendix A.

3.1.5.4. Utah I-15 and I-80

I-80 in Utah shows the strongest friction signal performance of all of the roads analyzed. Stable friction signals are produced for all slipperiness classifications. This is demonstrated in Figure 15, which presents the friction signals for Parleys Canyon between January 13 and 15, 2024.

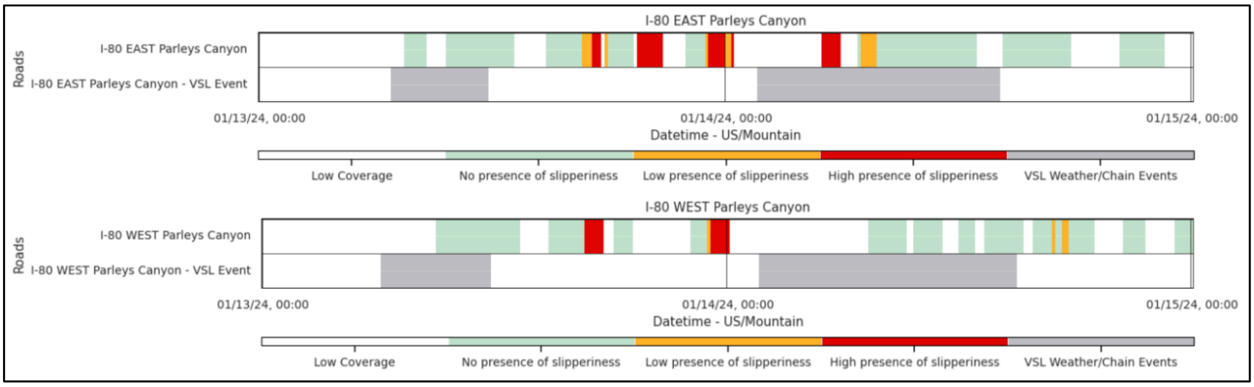


Figure 15. I-80 Parleys Canyon, Utah – Friction signals with DOT VSL events

Here it can be seen that the friction signals indicate presence of slipperiness several hours before the speed restrictions are issued. A stable signal for no presence of slipperiness is also active during active speed restrictions. This indicates that using friction signals would have improved the accuracy of the decision-making in this case.

Figure 16 presents the friction signals produced for Baker Canyon between December 13 and 14, 2023.

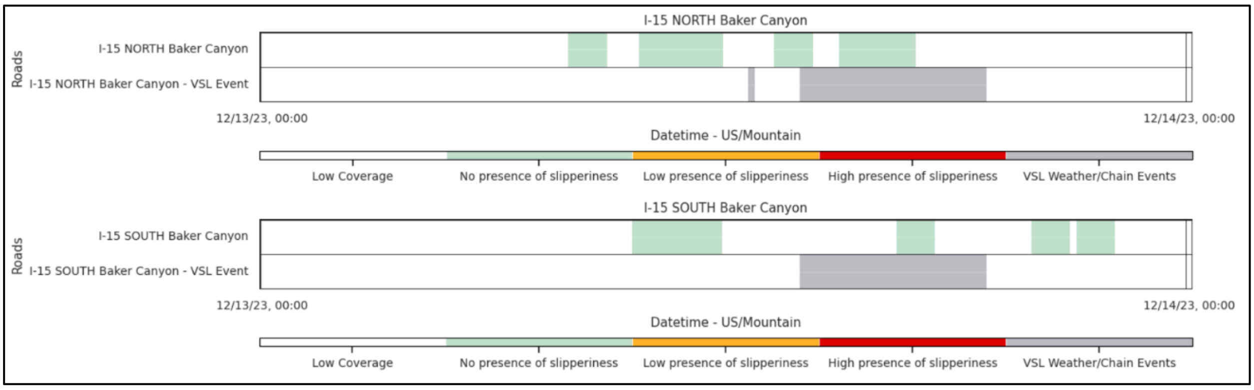


Figure 16. I-15 Baker Canyon, Utah – Friction signals with DOT VSL events

This case exhibits the weakest presence of friction signals. Since a yellow or red signal could be produced on I-80 in Utah and I-81 in Pennsylvania during low-coverage conditions, the results in this case might indicate that I-15 is not as affected by winter weather as the other roads. As stated by the Utah DOT, however, a different type of vehicles use I-15 than use I-80. Namely, the road stretch is more commonly used by commercial vehicles than personal vehicles, and the fact that NIRA data are collected through the personal vehicle fleet might explain the weak friction signal.

The use of friction signals to improve the accuracy of the VSL speed restrictions would still be valid, as seen in the results for December 13. A VSL weather event is active even though a stable green signal is produced during several hours.

Additional figures showing interesting cases and figures showing produced friction signals from December 2023 through February 2024 can be found in Section A.3 of Appendix A.

3.1.6. Conclusion

A proof-of-concept friction signal was produced for VSL corridors in Pennsylvania and Utah. The signal was produced using raw CVFM data, collected every 75 ft in 10-minute periods. To provide a more consistent signal, an additional 60-minute sliding window was applied, prolonging the signal's effect. The result of the aggregation is high-confidence friction values for the lowest and highest available friction.

In analyzing a road with high traffic flow, in this case I-76 in Pennsylvania, common thresholds were defined for the following friction signal levels:

- **Red**: High presence of slipperiness
- **Yellow**: Low presence of slipperiness
- **Green**: No presence of slipperiness
- **White**: Low coverage

The produced signals showed good capabilities in detecting slipperiness on the chosen VSL corridors. A side-by-side comparison was made with historical speed restriction data. This comparison demonstrated the value in utilizing a friction signal as an additional parameter for making appropriate VSL decisions.

The production of a green signal, indicating no presence of slipperiness, varied in performance across the different VSL corridors. For VSL corridors I-76 and I-81 in Pennsylvania and I-80 in Utah, with high coverage of connected vehicles, a friction signal can be utilized as an additional parameter in turning off speed restrictions. The VSL corridors on I-15 in Utah and I-80 in Pennsylvania, for which a sparser set of green signals was observed, can benefit from utilizing the signals but should not purely rely on them for turning the speed restrictions off, at least not for the analyzed winter season of 2023–2024.

The proof-of-concept friction signal was designed to allow for finetuning of any of the thresholds through the following:

- Friction thresholds
- Ratio between low and high friction for detecting slipperiness
- Friction coverage thresholds for green signals

When combining the friction signal with existing methods such as the use of RWIS, weather forecasts, and live observations, dedicated thresholds should be finetuned to meet the characteristics of each VSL corridor.

3.2. Chain Laws

The state of Colorado implements chain laws from September 1 to May 31 that require all commercial vehicles traveling on I-70 between the Dotsero and Morrison exits to have sufficient winter chains equipped.

Traversing the steep climbs in the mountain areas during bad winter conditions without chains can lead to vehicles becoming disabled and stranded, causing traffic delays, road closures, and an increased risk to motorists.

3.2.1. Use Case Definition

Analyze CVFM data for corridors subject to chain laws and create a proof-of-concept friction signal for slipperiness on a road. The signal can be used as a basis for issuing chain requirements.

3.2.2. Purpose

The purpose of this use case is to study how a proof-of-concept friction signal provided by NIRA's CVFM data can be used as an additional basis for chain law decision-making.

3.2.3. Analysis

The friction signal developed for the VSL corridors was used in this use case. For details about this friction signal, see Section 3.1.

For chain law analysis, the Colorado DOT's maintenance data were used to find snowstorms and evaluate the value a produced friction signal would add to chain law decision-making.

Figure 17 shows the mile marker stretches on I-70 in Colorado that were selected for the friction signal analysis.

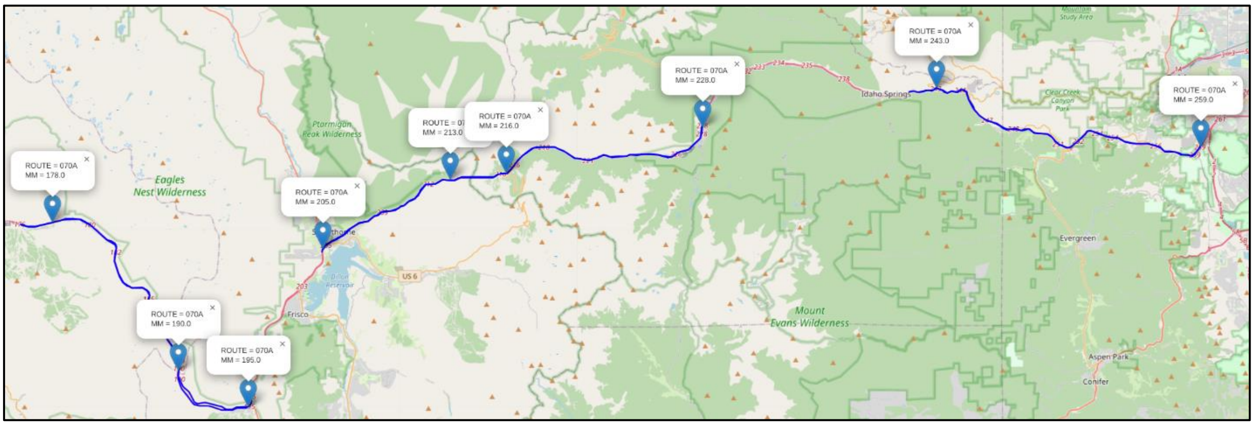


Figure 17. I-70 Colorado mile marker stretches: 205–213, 243–259, 216–228,178–190, 190–195

3.2.4. Results

Applying the proof-of-concept friction signal algorithm from the VSL use case to a set of mile marker stretches for I-70 resulted in strong friction signals. Red friction signals, indicating high presence of slipperiness, were produced for all mile marker stretches.

Figures showing produced friction signals from December 2023 to February 2024 can be found in Appendix B.

Figure 18 shows the friction signals on I-70 mile marker stretch 205–213 during snowfall days covering January 4 through 6, 2024. Maintenance decision support system (MDSS) data for snow depth, road condition, precipitation probability, and temperature were extracted from WebMDSS (Iteris n.d.) and added to provide comparable data for the produced friction signals. Red (R.1 and R.2) and green (G.1 and G.2) vertical lines are included in the figure to highlight interesting points in time.

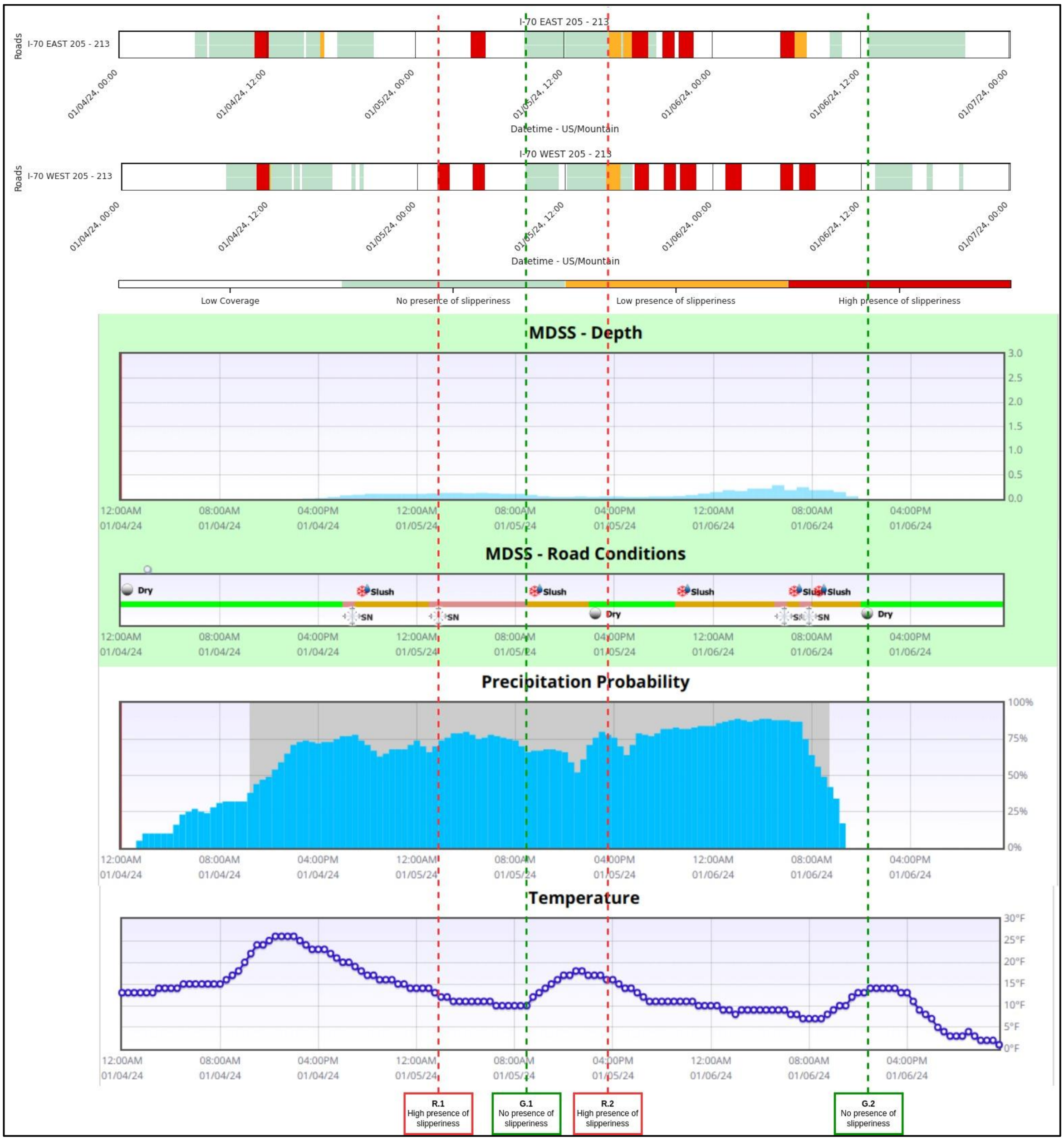


Figure 18. I-70 Colorado mile marker stretch 205–213 – Friction signals with Colorado DOT maintenance data

Figure 18 shows that during the period from 8 a.m. to 6 p.m. on January 4, 2024, when the probability of snowfall was 25% to 75%, the friction signals are strong and produce green signals for most of the period indicated. During the 30 minutes after 4 p.m., a yellow signal is produced, which could indicate that the snowfall has started and that there might be pockets of ice or snow gathering on the road. At 4 p.m., the probability of snow precipitation has reached 75%, which is detected by the MDSS depth sensor shortly after. The MDSS also measures the road condition to be slush. Due to nighttime conditions, the CV fleet coverage is too low to produce a reliable friction signal.

The first red friction signal (R.1 dotted line in Figure 18) is produced at 1 a.m. on January 5, 2024. At the same time, the MDSS gives a strong indication that the road conditions are getting worse, and the road is classified as snow covered. The friction signals and MDSS data combined provide a strong case to apply chain laws on this road at this time.

The morning traffic on January 5, 2024 (G.1 dotted line in Figure 18) measures high friction, resulting in a stable green signal for 6 hours between 9 p.m. and 3 a.m. During this period, the MDSS data show the snow depth to be below 0.5 in. and the road condition to be classified as slush. Utilizing only the friction signal in this case would indicate that the chain law restriction should be deactivated.

After 3 p.m. (R.2 dotted line in Figure 18), a yellow friction signal in both directions indicates that road conditions might be getting worse, and around 5:30 p.m. a red friction signal is again active. A red friction signal in both directions is seen from 5:30 p.m. on January 5, 2024, to 5:30 a.m. on January 6, 2024. During this period, the MDSS data classify the road condition to be dry, and later when the snow precipitation is increasing, the road classification becomes slush. During the period when the MDSS classifies the road as dry, a red friction signal indicates that the road has started to freeze again and that the road has a high presence of slipperiness. The refreezing can be explained by looking at the temperature for this period, which starts dropping after 2 p.m. Due to the weather conditions, low temperatures, and snowfall, there is a possibility that the MDSS dry classification of the road during this period is wrong.

Since the friction signal shows a high presence of slipperiness and the MDSS data mostly classify the road conditions as slush, the road might be suffering from severe weather, and a chain law restriction should be issued.

After noon on January 6, 2024, a stable green friction signal can be seen in both directions (G.2 dotted line in Figure 18), indicating that the road conditions are improving. This can be used as a basis for deactivating chain law restrictions on the road stretch.

3.2.5. Conclusion

The proof-of-concept friction signal algorithm that was developed for the VSL use case and that was applied to the chain law use case showed reliable performance on the chosen mile marker stretches on I-70 in Colorado. The impact of snowstorms during the winter of 2024 is reflected by the friction signals, as can be seen in Appendix B.

Only utilizing friction signals as the basis for making chain law restriction decisions can be challenging. The friction signal algorithm detects slipperiness on the road and does not classify road conditions as covered in snow or slush. If it is desirable to activate chain law restrictions only during snowfall, friction signals could be used with existing weather data to distinguish icy roads from snow-covered roads.

3.3. Forensics

The following use cases within forensics were presented to and discussed with the Colorado, Utah, and Pennsylvania DOTs:

- Regain of the roads, a forensic analysis that measures the time a road has had unwanted road conditions based on low friction measurements
- Overproduction of salt
- Identification of roads prone to slipperiness

From these scenarios, the DOTs decided that the project should focus on regain of the roads. As an addition to road regain, a way of measuring the overall performance of winter season maintenance for a larger road network was explored.

3.3.1. Regain of the Roads

Within the scope of this use case, two different approaches to measure and analyze road regain were explored:

- Road regain seasonal KPI
- Road regain detailed view

3.3.1.1. Use Case Definition

Evaluate winter maintenance treatments during and after a storm, including how the status of the roads developed during the storm and how long it took until the roads regained an acceptable condition.

3.3.1.2. Purpose

Knowing the impact of a winter snowstorm and executing the correct maintenance actions are complex tasks. The purpose of this section is to utilize CV fleet friction data together with external weather data (OpenWeather n.d.) to measure the impact of snowstorms on road conditions. Through an overview of road conditions, categorized by weather, each snowstorm can be analyzed in retrospect, giving the opportunity to learn how to handle future snowstorms.

By defining a KPI that can be tracked continuously over a winter season, specific road maintenance plans can be evaluated to meet KPI thresholds.

3.3.1.3. Method 1 – Road Regain Seasonal KPI

Regain is defined as the time from when a road is lost to when it returns to an acceptable state (Figure 19). A road is considered lost when the number of low friction measurements is above a required percentage, such as above 10%, 20%, or 30%, of the total number of measurements. A road is considered to be in an acceptable state when the number of low friction measurements is below the decided threshold.

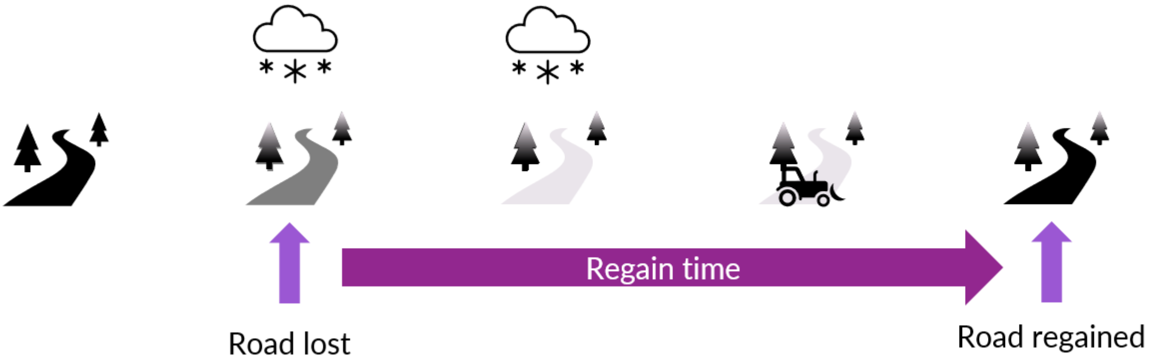


Figure 19. Illustration of road regain

Road regain was determined as follows:

- Set the requirement parameters:
  - The threshold of the percentage of allowed low friction measurements
- For a given road stretch over a relevant period and for each 30 minutes:
  - Compute the percentage of low and high friction measurements, respectively.
  - Find out when the road is lost.
  - Compute the time until the road returns to an acceptable state.
- Set a desired level for the highest accepted regain time. A time of 2 hours was used for this analysis.

A road regain KPI was produced as follows:

- Count the number of regains meeting the desired accepted regain time, as accepted-regains.
- Count number of total regains, as total-regains.
- Calculate the KPI as accepted-regains/total-regains.

To provide a more equitable way to compare one road regain to another, snowfall per hour and current temperature were used to classify each road and show the impact of current weather.

The color-coded road classification scheme can be seen in Figure 20, which shows snowfall precipitation on the y axis and temperature on the x axis. A total of nine weather categories were used in this analysis, ranging from mild winter storm conditions (light blue) to intense winter conditions (dark blue).

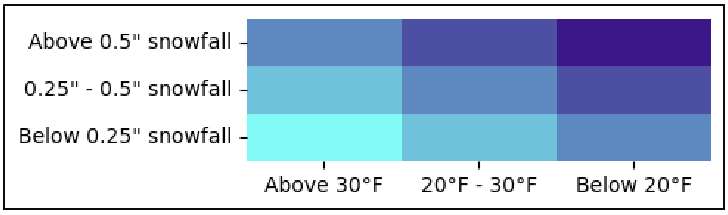


Figure 20. Color mapping used to illustrate the different weather conditions for each road regain analysis

Results. The roads used for the development of the road regain seasonal KPI are I-70, divided into west and east of Denver, and I-25.

For this analysis, I-70 west of Denver was chosen. A road regain chart was generated for each of the following:

- Mile markers 180–201 and 243–269
- I-70 west of Denver (Appendix C)
- I-70 east of Denver (Appendix C)
- I-25 (Appendix C)

Figure 21 shows the mile marker stretches, represented in blue, presented in this analysis.

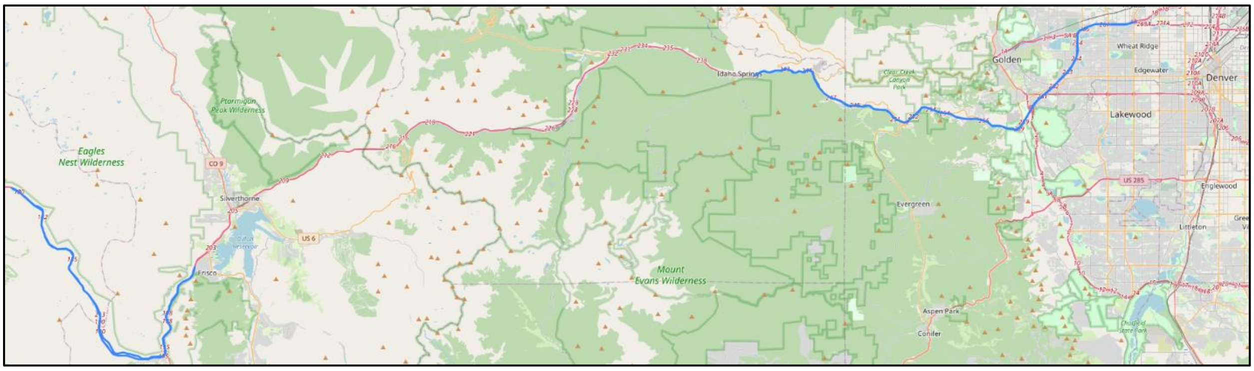


Figure 21. I-70 Colorado mile marker stretches chosen for analysis: 180–201 (left) and 241–269 (right)

Figure 22 illustrates all occurrences of a lost road where low friction measurements were above 10%. Each rectangle represents one occurrence of a lost road, and the color scheme shows under what type of weather conditions the road was lost. The y axis represents the number of lost road occurrences, and the x axis represents how long the road was lost.

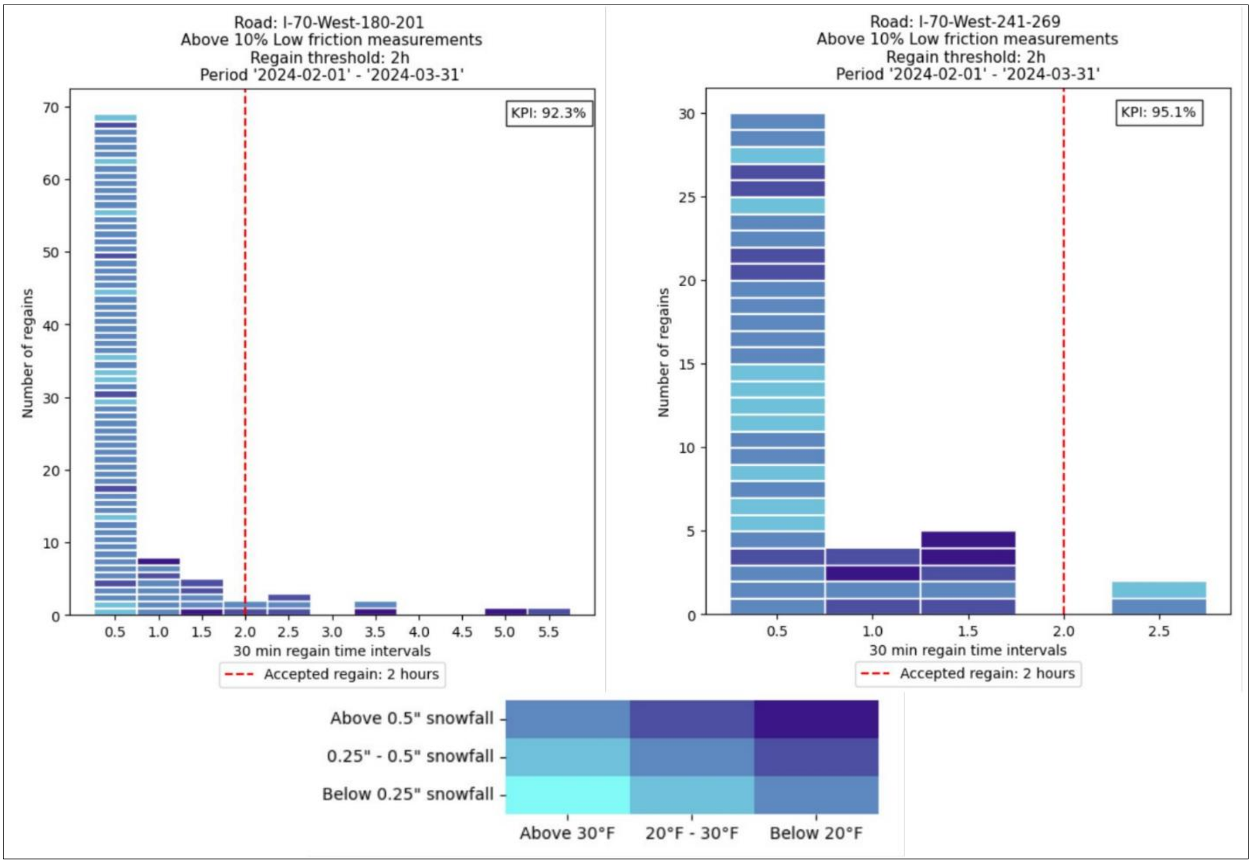


Figure 22. All occurrences of a lost road where low friction measurements were above 10% for I-70 west of Denver

The graphs in Figure 22 show a clear difference in how the two I-70 mile marker stretches are affected by winter storms. Mile marker stretch 241–269 shows a KPI of 95.1%, indicating that the road meets the set threshold of 2 hours of regain time very well. Mile marker stretch 180–201 passes through a mountain pass and is therefore expected to be more affected by the winter season. A lower KPI of 90.5% is still a positive indicator that the winter maintenance work has performed well.

For mile marker stretch 241–269, there are two road regain occurrences that do not meet the set criterion of 2 hours of road regain. Since these occurrences are not classified to be in the harsher portion of the weather condition spectrum, a more detailed analysis, using the method described in Section 3.3.1.4, is needed to understand why the threshold of 2 hours was not met.

For mile marker stretch 180–201, there are several road regain occurrences that do not meet the 2 hours regain time threshold. These occurrences are classified in the harsher portion of the weather condition spectrum, which explains the problem of mitigating snowstorm impacts during these periods.

3.3.1.4. Method 2 – Road Regain Detailed View

Results. Section 3.3.1.3 presents an overview of how road regain can be measured in a detailed way. Figure 23 focuses on I-70 between Denver and Downieville during the period of February

16 and 17, when there was snowfall. In Figure 23, red colors are places that were found to be more problematic than others in terms of low friction.

Figure 23. I-70 Denver – Downieville

Figure 24 shows the changes in road and weather conditions on I-70 between Denver and Downieville. The upper graph shows the percentages of measurements with low, medium, and high friction. White areas in the graphs are timeslots when there were not enough measurements from the CV fleet. The bottom graph shows the temperature and snow precipitation; for simplicity, the periods of snowfall are highlighted.

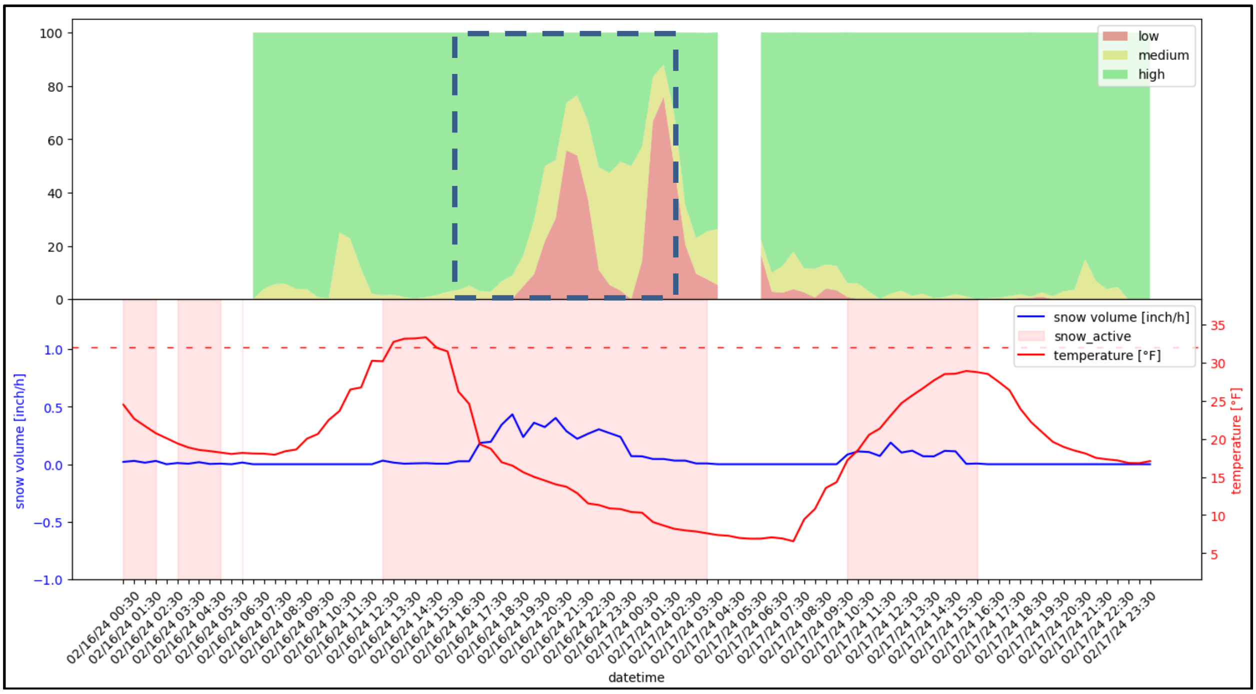


Figure 24. Evaluation graphs of I-70 Denver – Downieville

Figure 24 shows that in the hours after midnight on February 16, there was a small amount of snow precipitation as well as low temperatures. However, as the morning traffic hit the road, the friction conditions were good.

The next snowfall started at noon, when the temperature was mostly above 32°F and the precipitation amount was around 0.01 in./hour. At 4:30 p.m., a heavier snowfall started; the precipitation amount was between 0.2 to 0.35 in./hour. Precipitation intensity continued until 11:30 p.m., when it declined and finally ended at 3:00 a.m. on February 17. The friction level graph in Figure 24 shows that only low friction was measured when the snowfall got heavier, with two peaks of low friction:

- 56% low friction at 08:30 p.m. on February 16
- 76% low friction at 01:00 a.m. on February 17

Between the peaks there was an improvement in the road conditions that lasted for a brief period. The percentage of high friction measurements did not change, the percentage of low friction measurements decreased, and the percentage of medium friction measurements increased. The dotted black box in Figure 24 represents the period during which maintenance work was performed on the road, starting on February 16, 2024, at 4 p.m. and ending on February 17, 2024, at 1:30 a.m. This shows that while the maintenance substantially improved the roads, there were still parts of the roads that remained problematic. At 2:30 a.m., both the low and medium friction levels had increased to a point where most of the road was in a bad condition.

Another interesting scenario can be seen when the road was not lost despite the ongoing snowfall. At 9:30 a.m. on February 17, additional snowfall started and continued until 3:30 p.m. The snow precipitation was not as heavy compared to the previous event, between 0.08 and 0.12 in. per hour. The interesting part here is that even though there was a moderate amount of snowfall, the winter maintenance kept the road conditions in a good state throughout the precipitation.

In Figure 25, the regain time is visualized as shaded areas, with a required maximum of 10% low friction measurements.

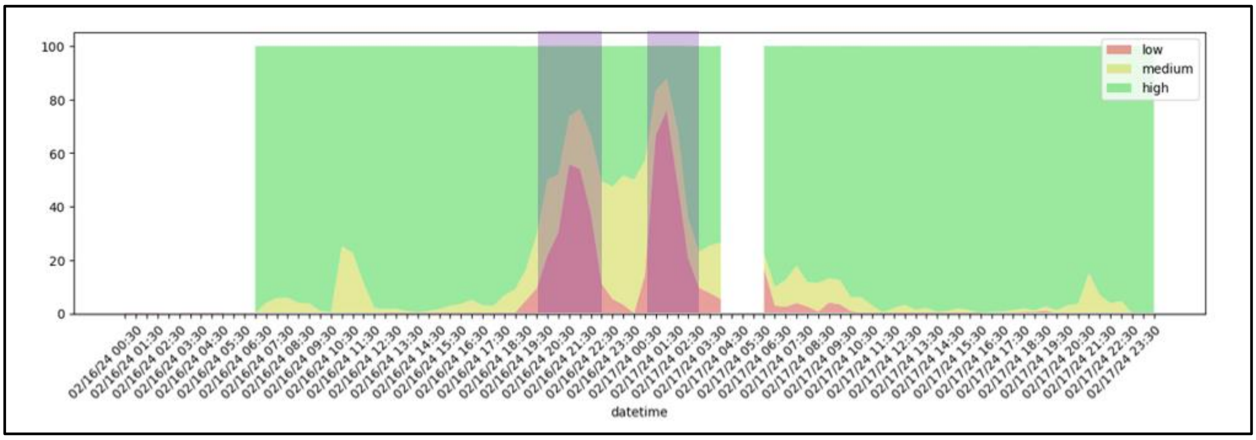


Figure 25. Evaluation graph of I-70 Denver – Downieville, with regain time visualized in grey shading

In Figure 25, the road is first lost at 7 p.m. and regained at 10 p.m., making 3 hours of regain time. At midnight, the road was lost again and regained at 2:30 a.m., making 2.5 hours of regain time.

3.3.1.5. Conclusion

CV friction data together with weather information was used to measure road regain time.

The produced road regain graph, presented in Section 3.3.1.3, provides an illustrative overview of the impact of a winter season on a stretch of road. Setting a desired regain time threshold is used to calculate a KPI, which can be used to quantify maintenance performance over time and from one season to another.

The following are some future improvements that can be applied to Section 3.3.1.3 to add detail and accuracy:

- Eliminate toggling of lost roads during consistent snowfall. This can be solved by low pass filtering or smoothing of the approved rate signal. This has not been tested in the scope of this report but can be customized based on user requirements.
- Separate lost time and regain time using the following definitions:
  - Lost time: The time during an ongoing period of snowfall for which roads do not meet the desired highest low-friction threshold.
  - Regain time: The time directly after a snowstorm for which roads do not meet the desired highest low-friction threshold.
- An argument can be made that road regain occurrences that happen during harsher weather conditions and that are resolved early should be valued more when determining the KPI than those resolved under calmer weather conditions. Additionally, road regain occurrences that happen during calmer weather conditions and that do not pass the road regain threshold should have a larger negative impact on the KPI. This could be solved by adding weights to the regain occurrences based on weather conditions and would allow for a more valid comparison of KPIs between roads and between the regain KPIs of different DOTs.

For each regain occurrence, a method such as that described in Section 3.3.1.4 can be used to study in detail how CV friction measurements change for a road stretch. Along with the use of DOT historical data, an analysis can be done to study how maintenance work impacts the mitigation of low friction.

3.3.2. Winter Season Maintenance KPI

3.3.2.1. Use Case Definition

Evaluate the effectiveness of winter maintenance mitigation during different snowfall intensities for a complete road network.

3.3.2.2. Purpose

It is important for DOTs to measure how well their planned winter maintenance activities and their road network overall performed over a previous winter period. Such an understanding can inform decisions regarding changes to current methods, methodological optimization, and more efficient use of resources.

3.3.2.3. Method

The following approach was used to calculate a winter season maintenance KPI:

- Set a threshold for the maximum accepted percentage of low friction measurements:
  - A threshold of 10% low friction measurements was used in this analysis.
- Divide weather data into groups based on snowfall intensity during the last hour:
  - An interval of 0.05 in. up until 0.5 in. of snowfall was chosen for this analysis.
  - Snowfall above 0.05 in. was grouped together.
- Aggregate CV friction data to 30 minutes and categorize them into a snowfall category.
- Produce the KPI by looking at the percentage of total accepted friction measurements during each 30-minute period for each snowfall category:
  - The size of each snowfall group is considered as a weight when calculating KPI.

The road networks chosen for this analysis were class 1 and 2 roads (which include freeways and dual carriageways) in Colorado (Figure 26).

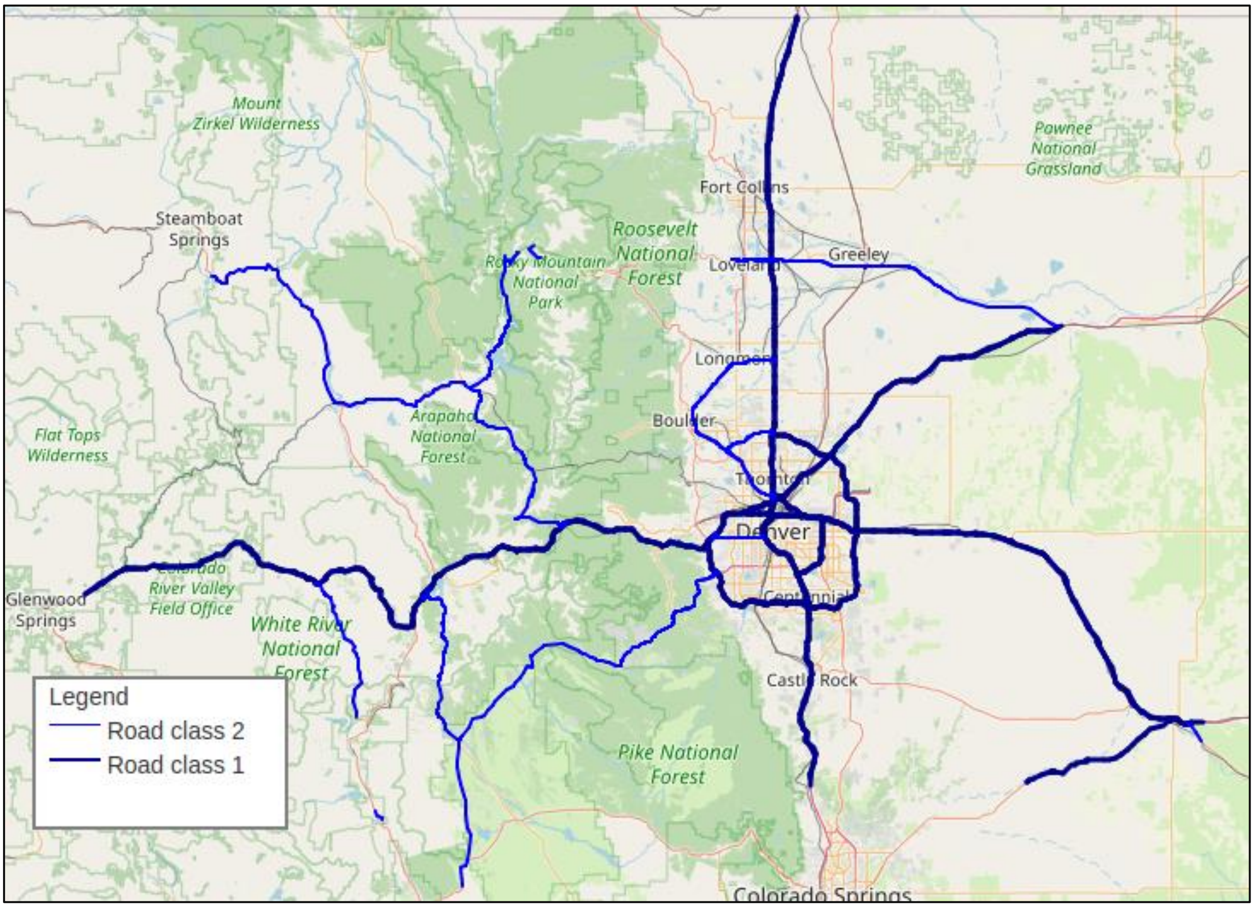


Figure 26. Map showing Colorado class 1 and 2 roads for which winter season maintenance KPIs were generated

3.3.2.4. Results

The winter season KPIs for Colorado's class 1 and 2 roads can be seen in Figure 27 and Figure 28, respectively. The width of each snowfall category illustrates the number of 30-minute periods with that type of snowfall intensity.

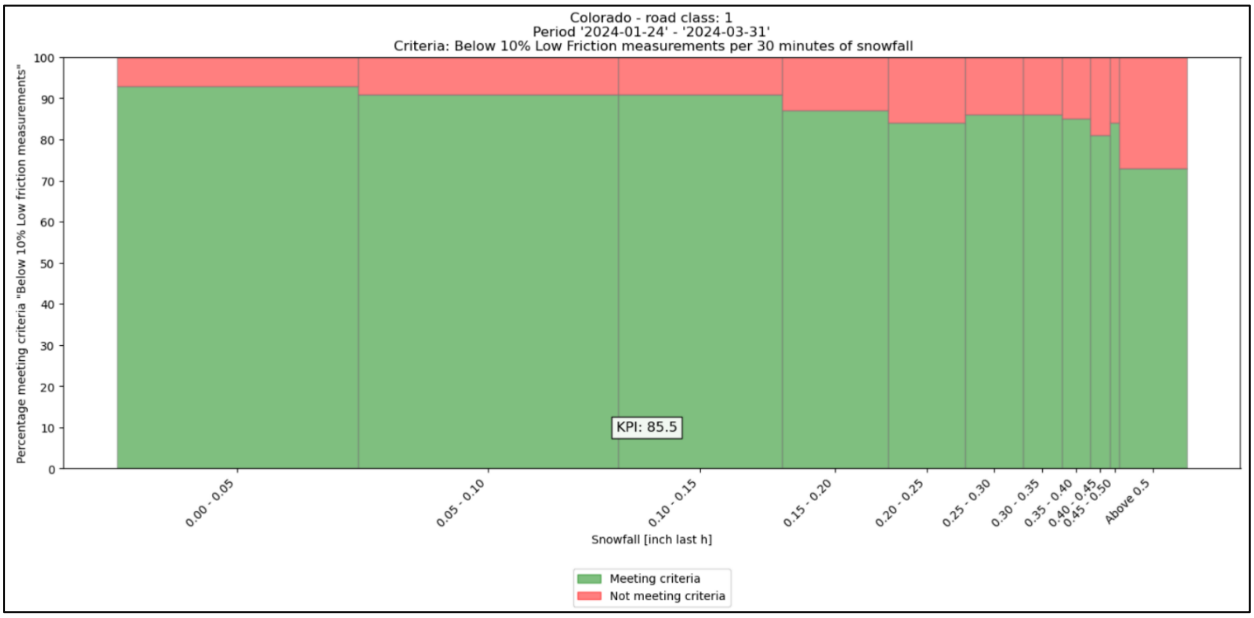


Figure 27. Winter season maintenance KPI for Colorado class 1 roads

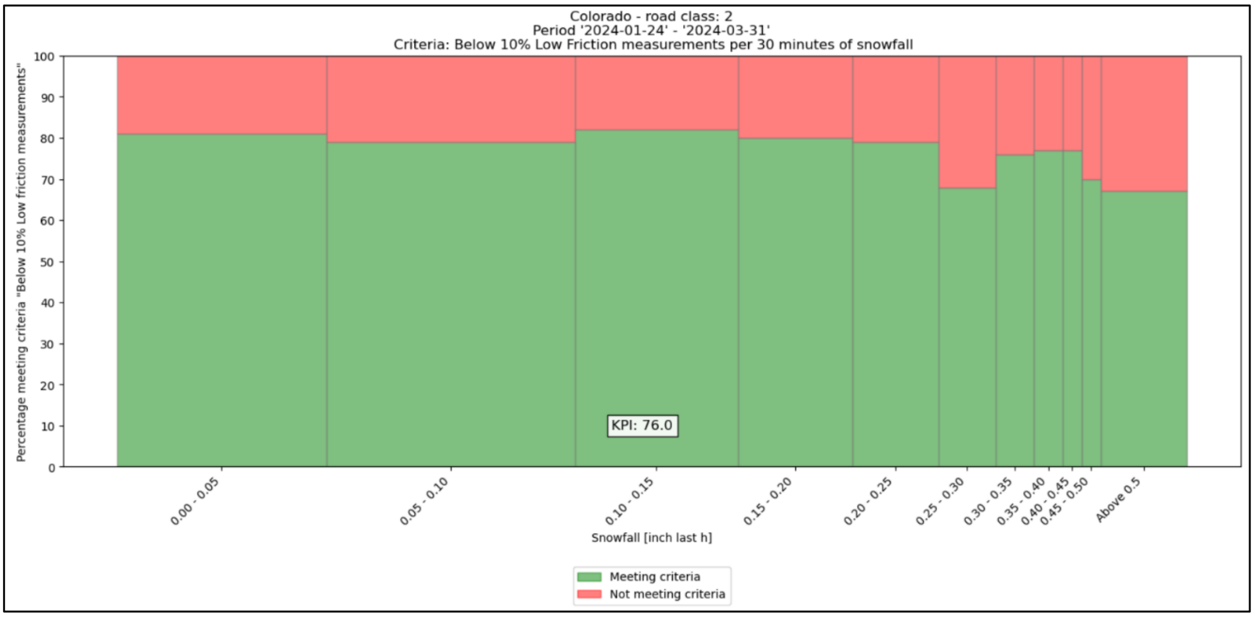


Figure 28. Winter season maintenance KPI for Colorado class 2 roads

A clear difference in KPI can be seen between the larger class 1 roads (Figure 27) and class 2 roads (Figure 28); the KPI of the class 1 roads is 85.5, which is 9.5 higher than that of the class 2 roads. This shows that maintenance work is performing better for these types of roads. A deliberate prioritized maintenance plan for class 1 roads can explain this difference.

In Figure 27 and Figure 28, 50% of all snowfall has an intensity of 0 to 0.15 in./hour. It is above this snowfall intensity that a decrease can be seen in the number of 30-minute periods below the threshold of 10% low friction measurements. The largest drop is seen in the *Above 0.5 in.* snowfall category, where approximately 70% of cases are below the threshold of 10% low friction measurements.

Graphs for 5% and 20% low friction thresholds are presented in Appendix D.

3.3.2.5. Conclusion

The winter season maintenance KPI is aimed at facilitating winter maintenance planning and evaluation. The KPI, based on detected friction measurements from the CV fleet during periods of snowfall, provides a reliable measurement of how snowfall negatively affects roads and how the work of maintenance crews mitigates these effects. The KPI and the illustrative graphs produced by the method described in this section can be used for post-season evaluation of the maintenance work to find areas of improvement.

Utilizing the KPI from one season to another can help in maintenance planning efforts prior to an upcoming winter season. The budget to achieve the desired service level can be calculated by setting a desired KPI. Based on previous seasons' KPIs, the budget might need to be adjusted between different road networks. Consistently monitoring the KPI during a winter season can help in the reallocation of resources between different road networks in order to reach the desired KPI.

Additionally, an upper snowfall precipitation limit can be set to consider the precipitation intensity at which maintenance work stops having an effect. This limit prevents the KPI from being negatively affected in scenarios that cannot be mitigated.

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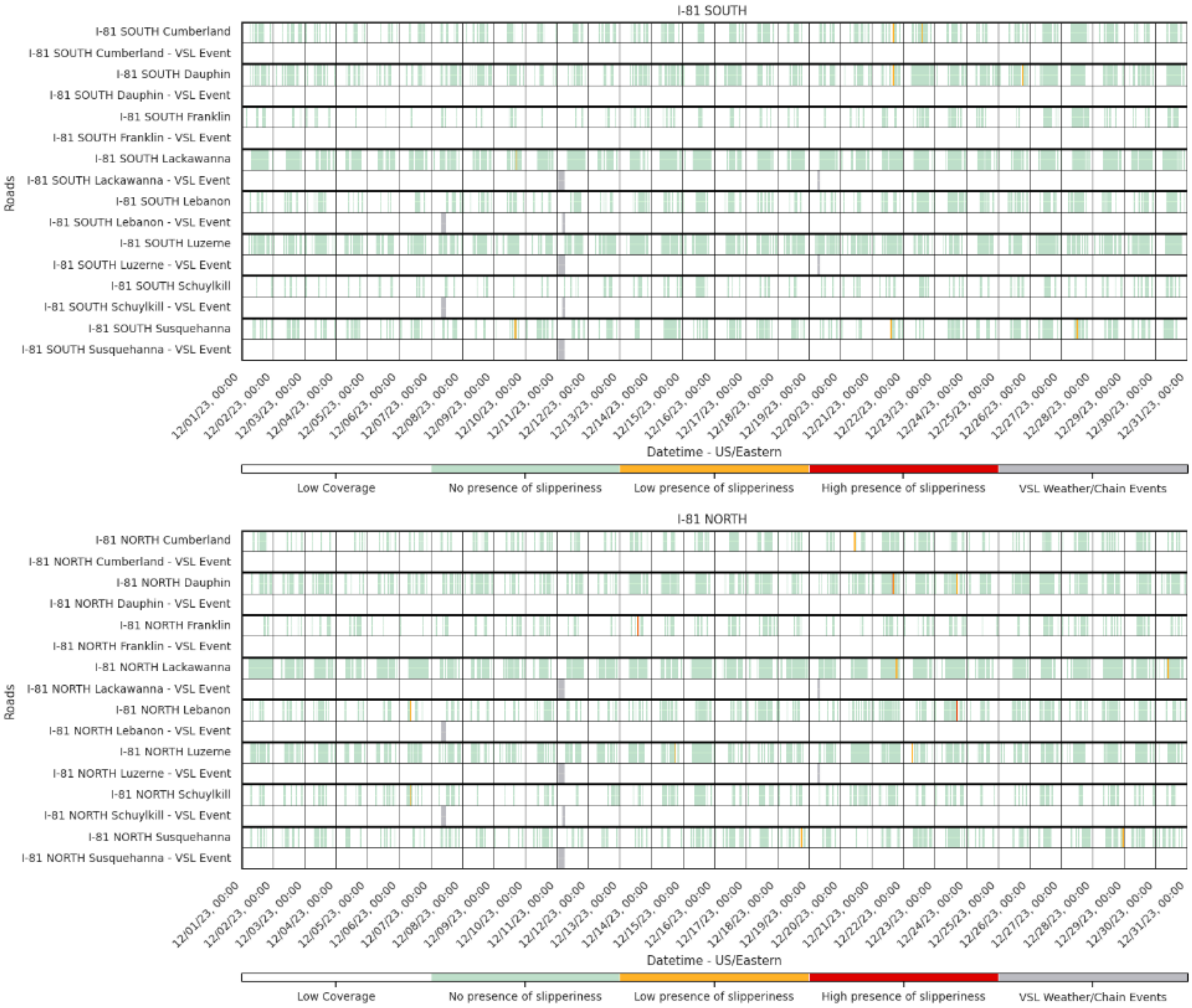
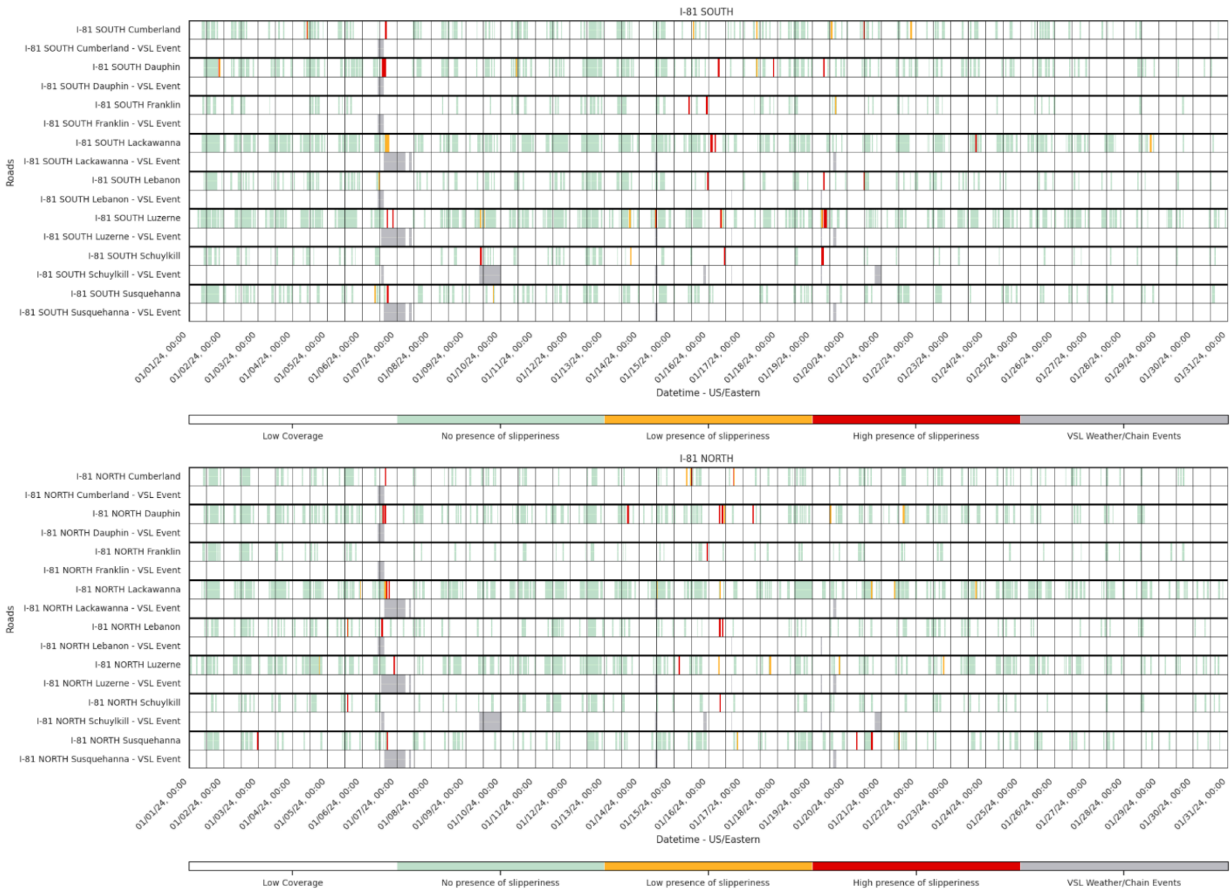
OpenWeather. n.d. OpenWeather. https://openweathermap.org/.

APPENDIX A. VSL

A.1. Pennsylvania I-81



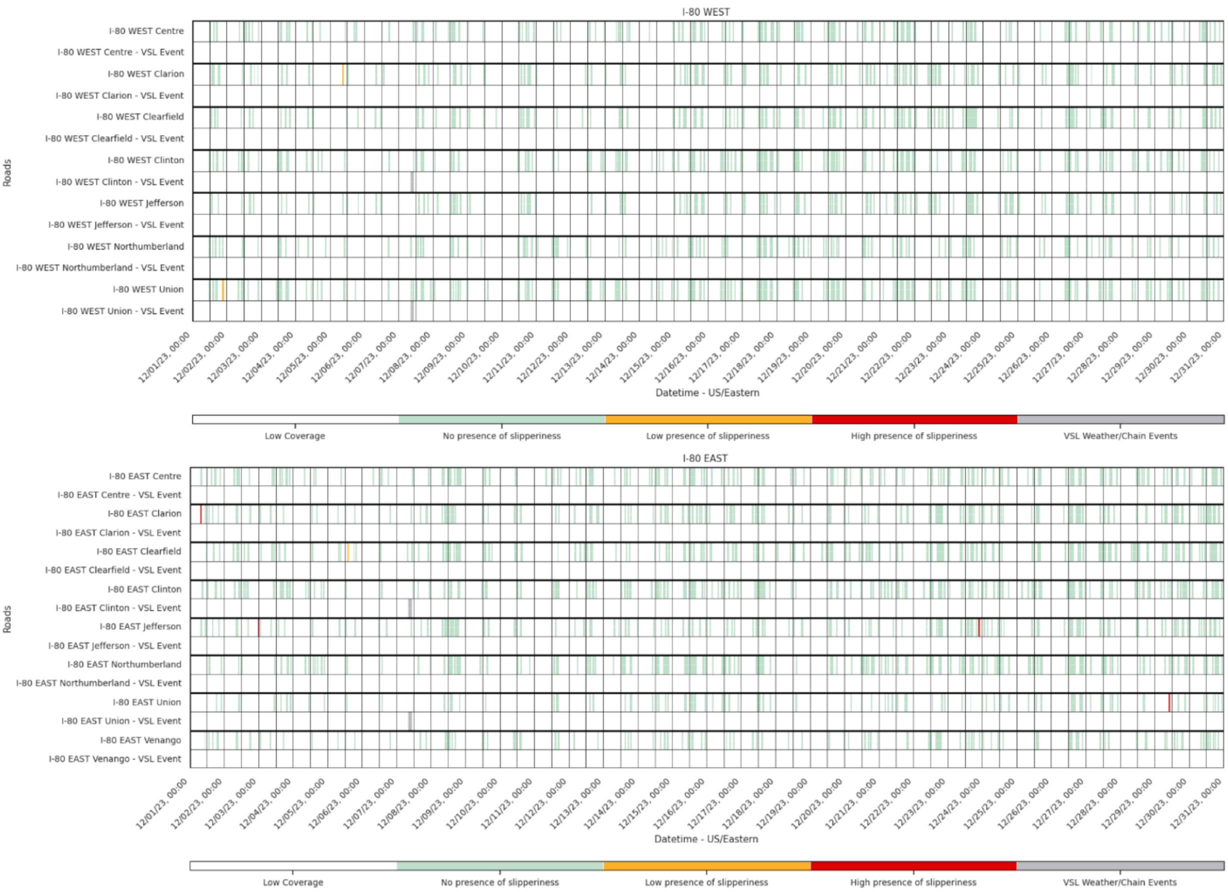
Pennsylvania I-81 December 2024 – Friction signal with DOT VSL weather events



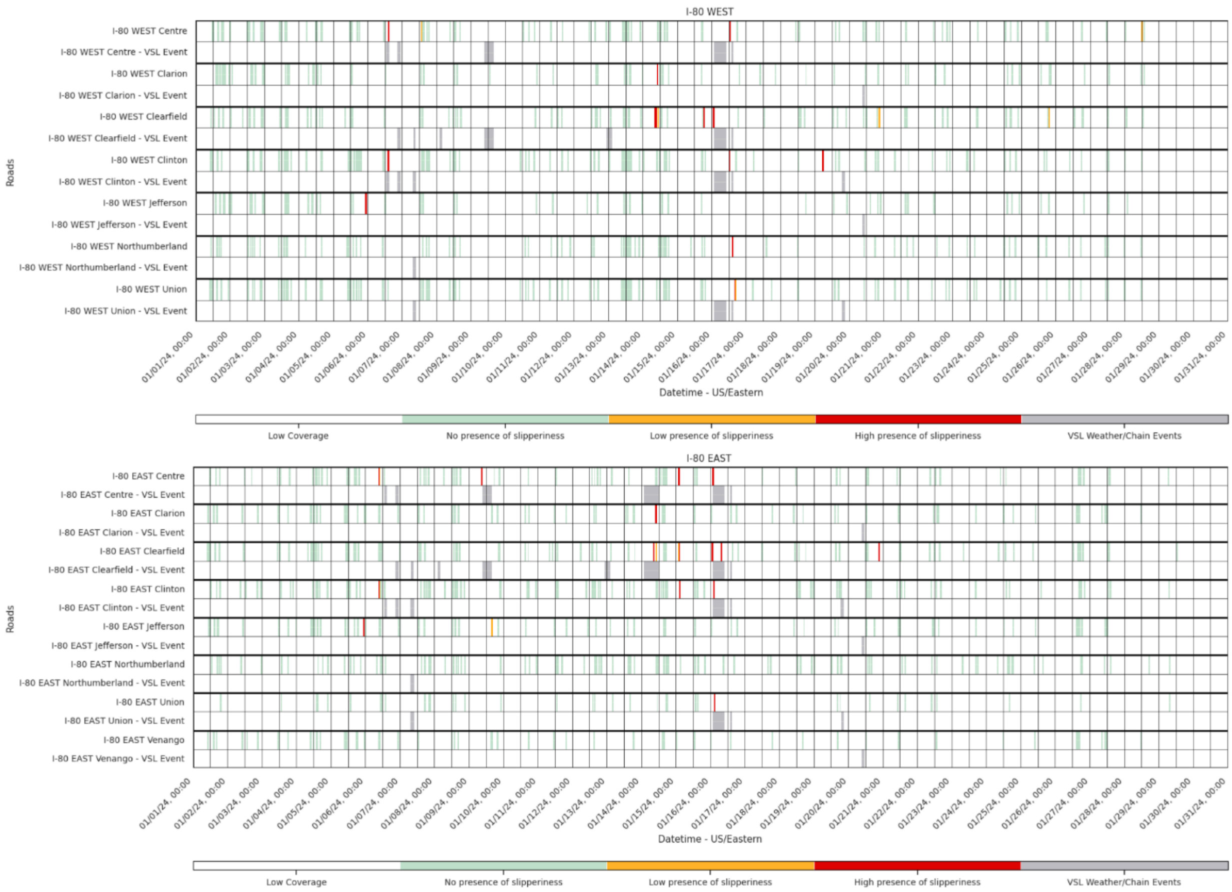
Pennsylvania I-81 January 2024 – Friction signal with DOT VSL weather events

Pennsylvania I-81 February 2024 – Friction signal without DOT VSL weather events

A.2. Pennsylvania I-80



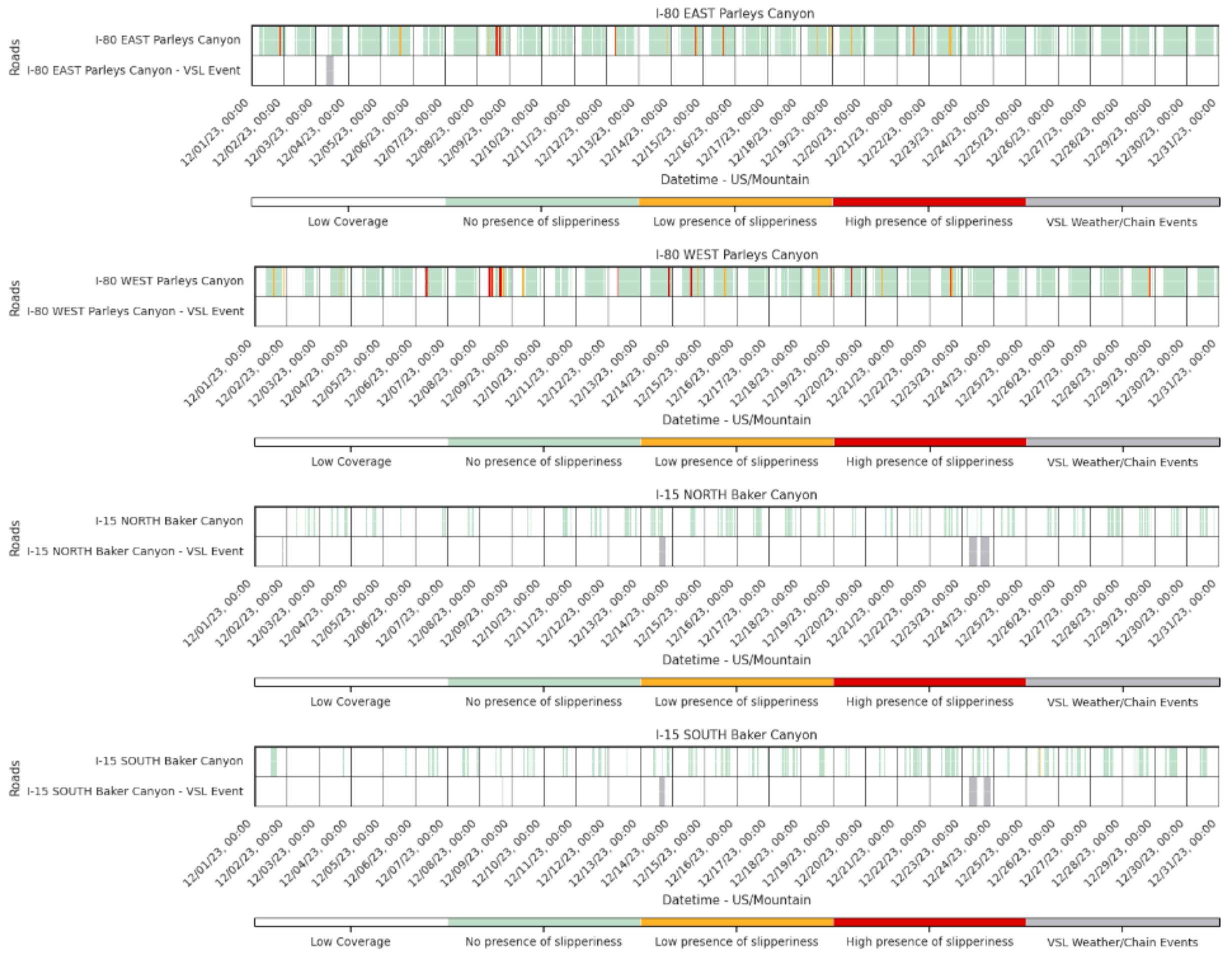
Pennsylvania I-80 December 2023 – Friction signal with DOT VSL weather events



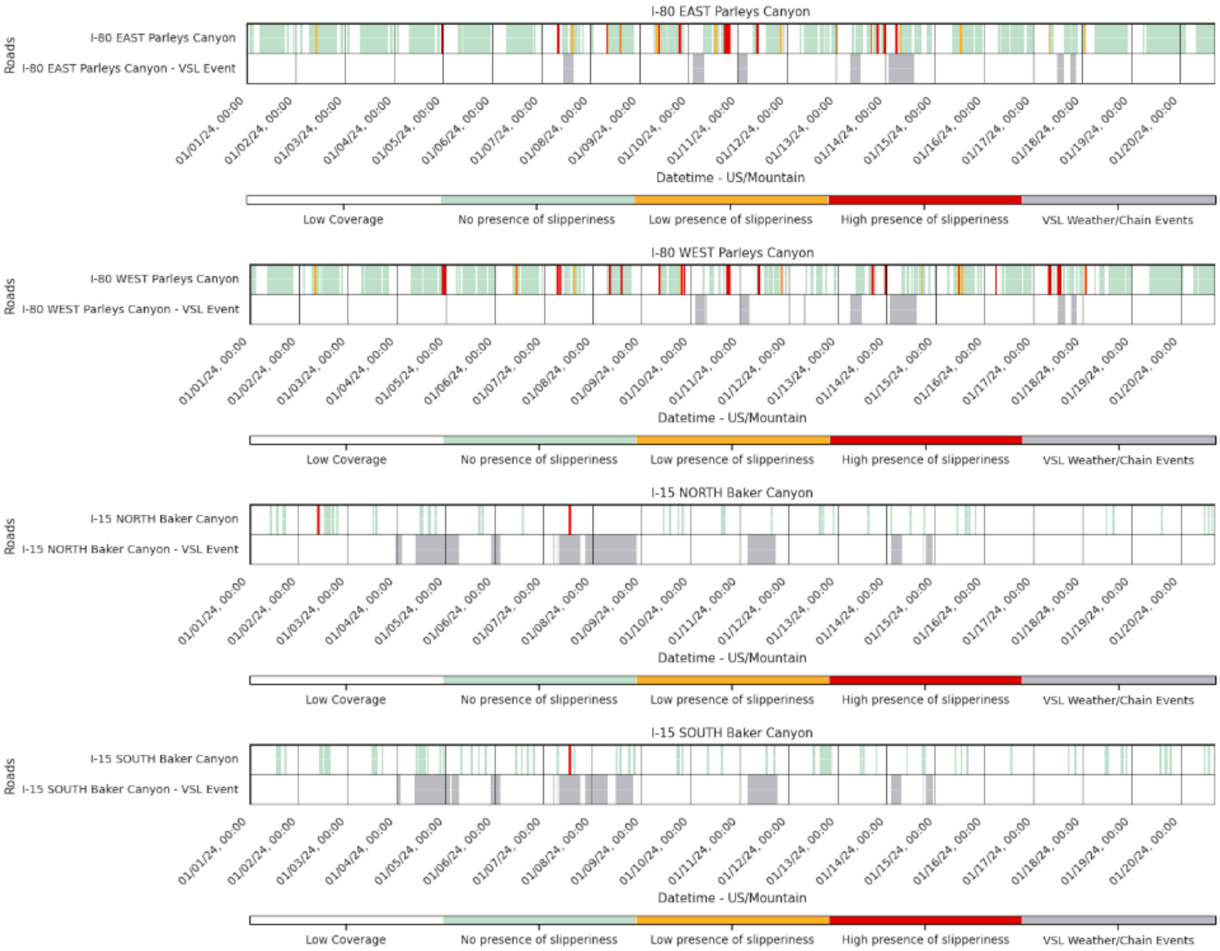
Pennsylvania I-80 January 2024 – Friction signal with DOT VSL weather events

Pennsylvania I-80 February 2024 – Friction signal without DOT VSL weather events

A.3. Utah I-80 and I-15



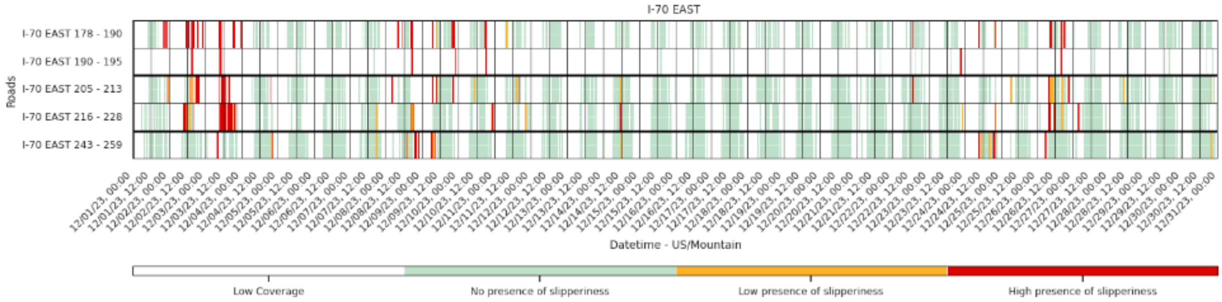
Utah I-80 and I-15 December 2023 – Friction signal with DOT VSL weather events

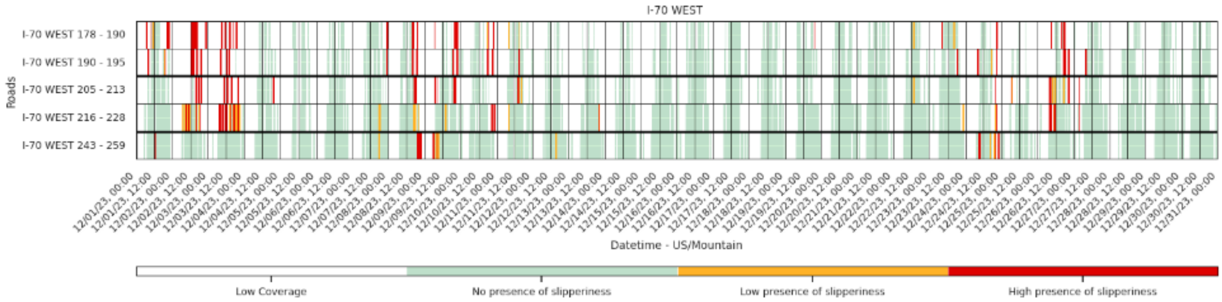


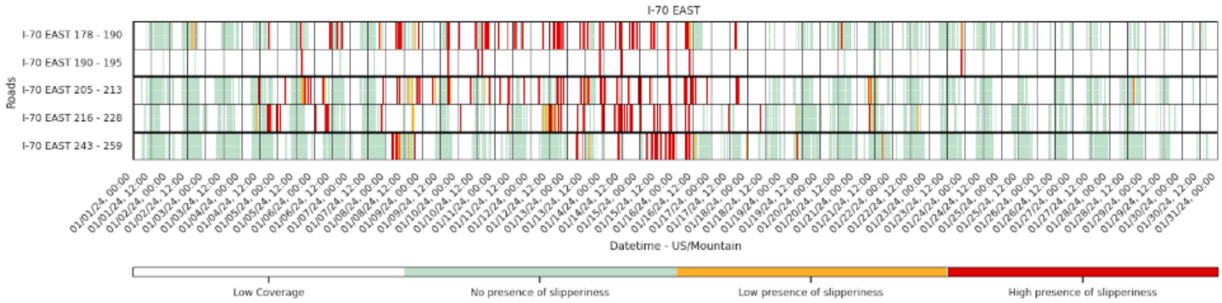
Utah I-80 and I-15 January 2024 – Friction signal with DOT VSL weather events

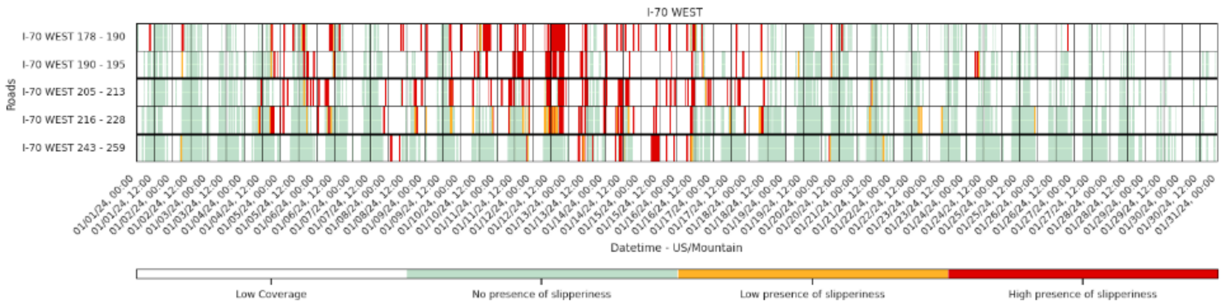
Utah I-80 and I-15 February 2024 – Friction signal without DOT VSL weather events

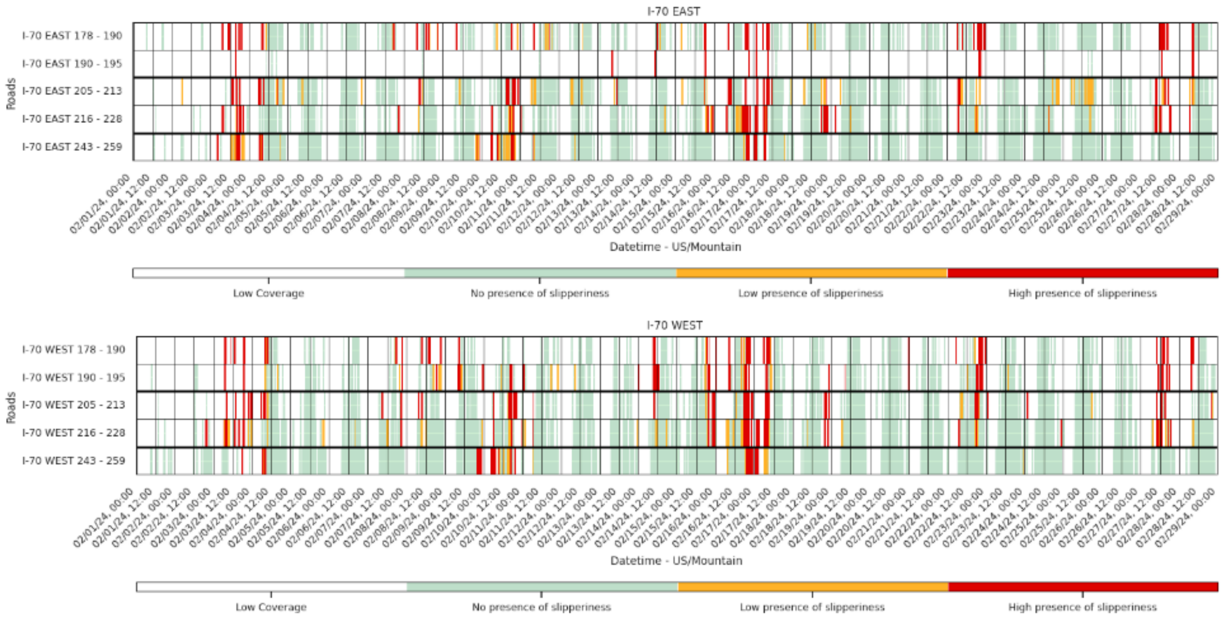
APPENDIX B. CHAIN LAW



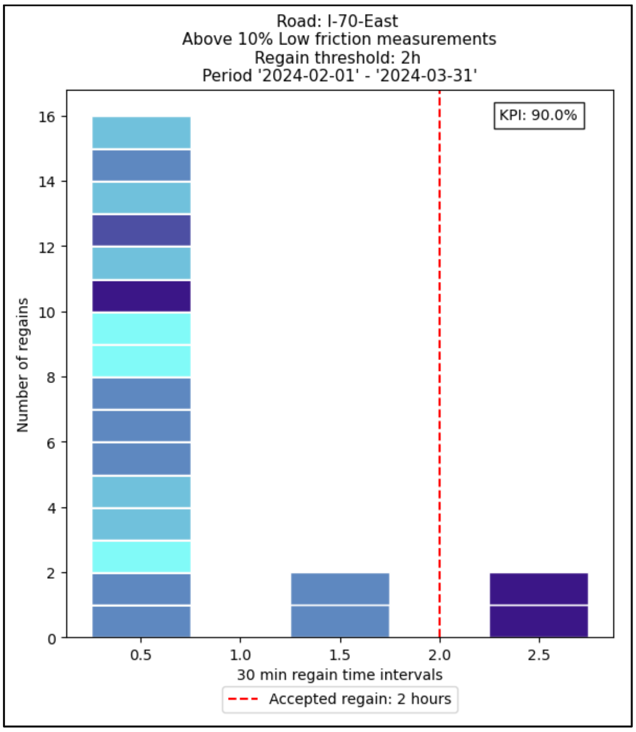


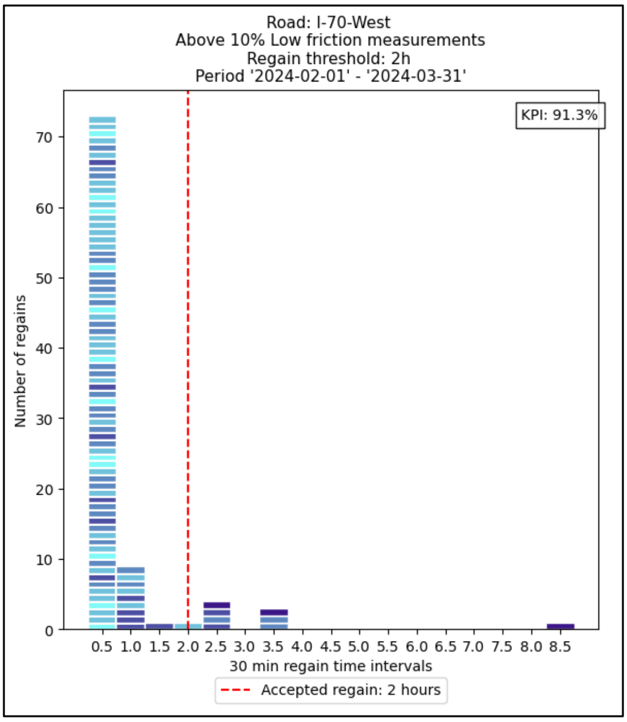


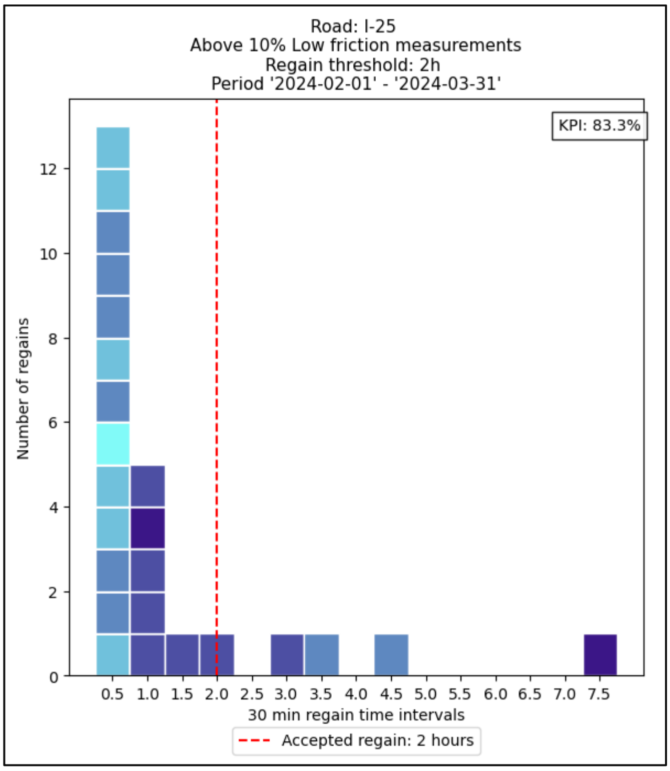


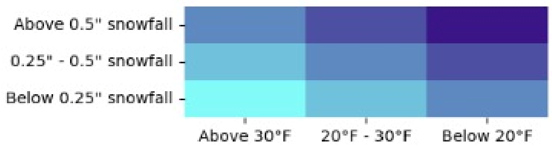

I-70 EAST
I-70 EAST 178 - 190
I-70 EAST 190 - 195
I-70 EAST 205 - 213
I-70 EAST 216 - 228
I-70 EAST 243 - 259
Roads
Datetime - US/Mountain
Low Coverage
No presence of slipperiness
Low presence of slipperiness
High presence of slipperiness
I-70 WEST
I-70 WEST 178 - 190
I-70 WEST 190 - 195
I-70 WEST 205 - 213
I-70 WEST 216 - 228
I-70 WEST 243 - 259
Roads
Datetime - US/Mountain
Low Coverage
No presence of slipperiness
Low presence of slipperiness
High presence of slipperiness

APPENDIX C. ROAD REGAIN

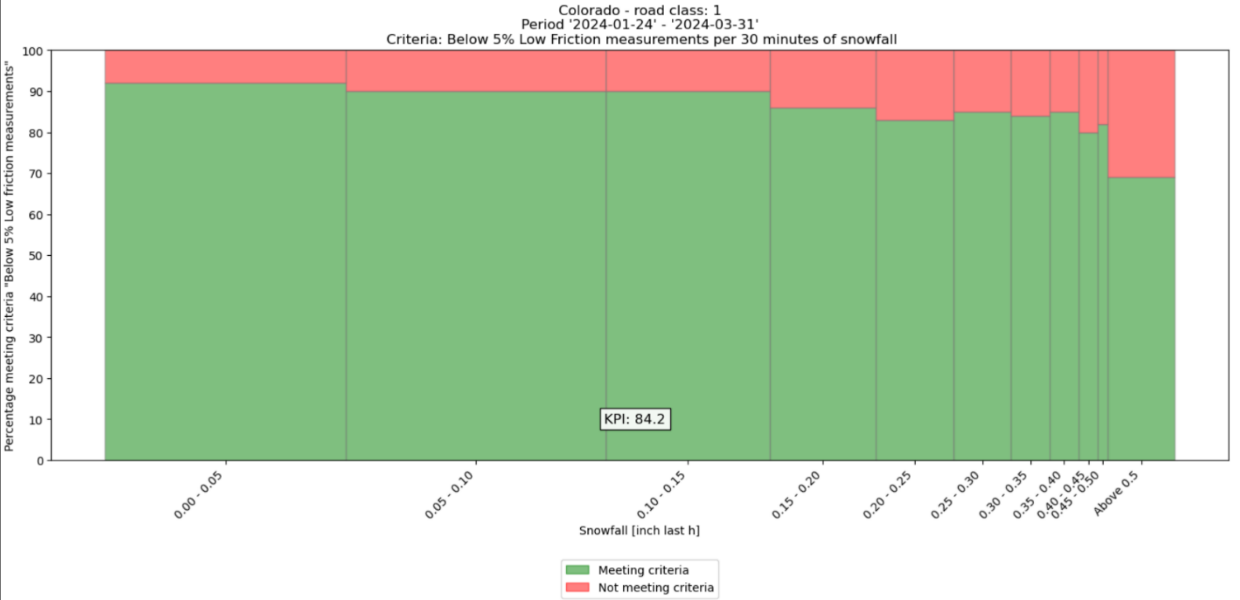


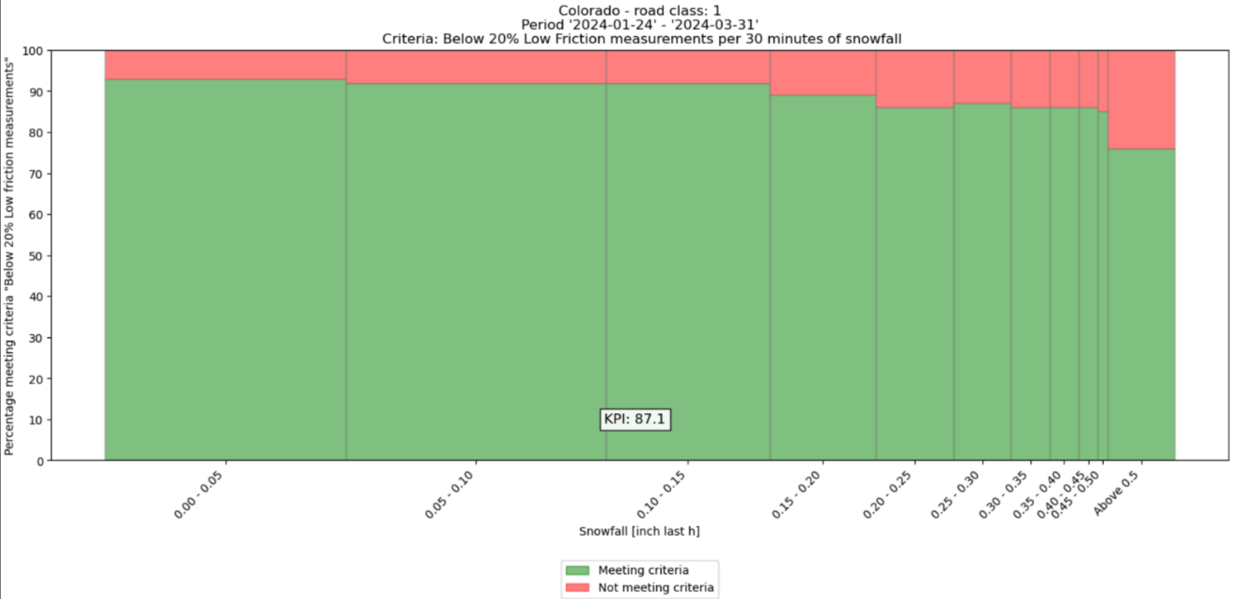


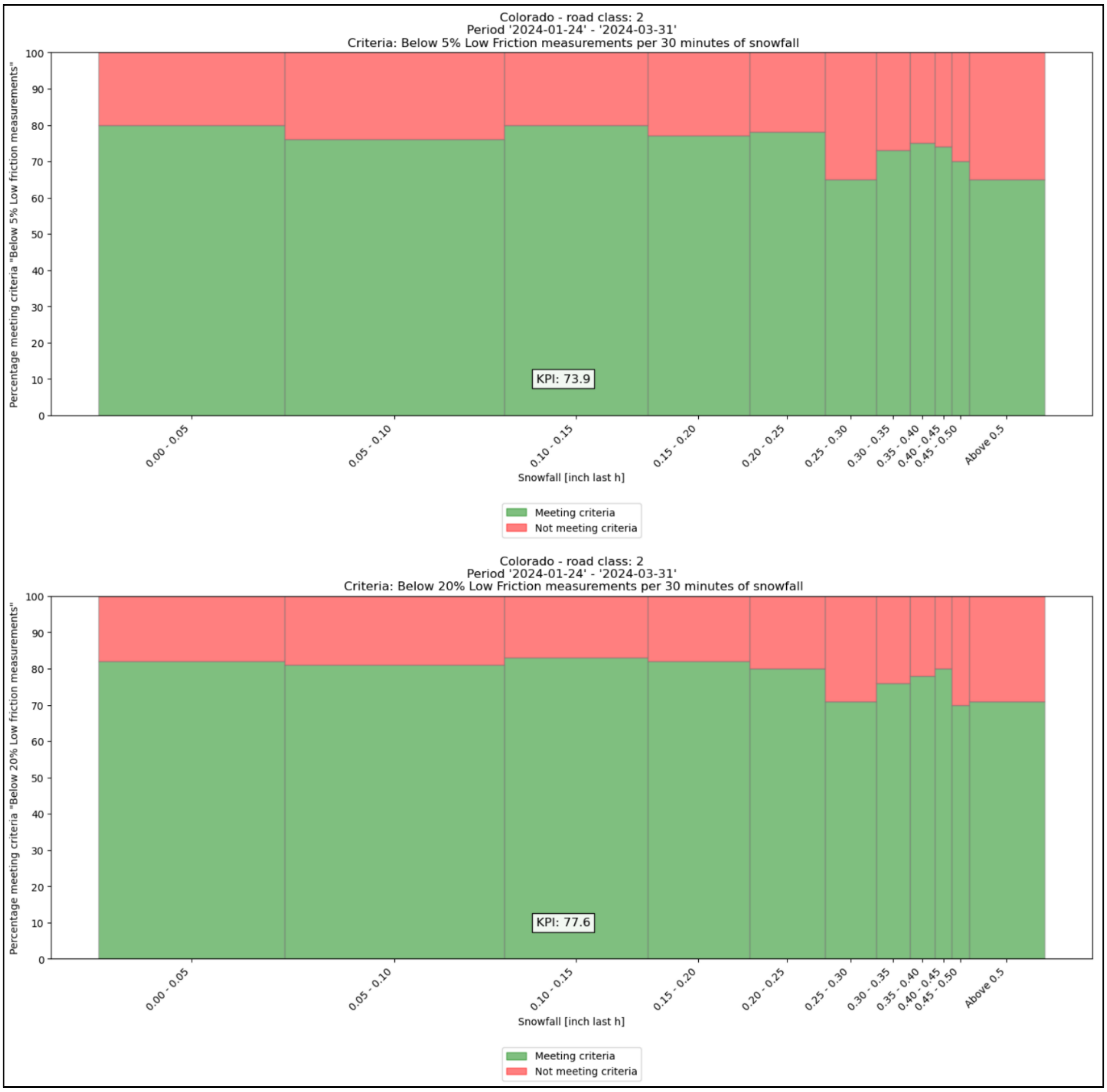

Road: I-25
Above 10% Low friction measurements
Regain threshold: 2h
Period '2024-02-01' - '2024-03-31'
KPI: 83.3%
Number of regains
0
2
4
6
8
10
12
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5
30 min regain time intervals
Accepted regain: 2 hours


Above 0.5" snowfall
0.25" - 0.5" snowfall
Below 0.25" snowfall
Above 30°F
20°F - 30°F
Below 20°F

APPENDIX D. WINTER SEASON MAINTENANCE KPI






Colorado - road class: 2
Period '2024-01-24' - '2024-03-31'
Criteria: Below 5% Low Friction measurements per 30 minutes of snowfall
Percentage meeting criteria "Below 5% Low friction measurements"
KPI: 73.9
0.00 - 0.05
0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.35
0.35 - 0.40
0.40 - 0.45
0.45 - 0.50
Above 0.5
Snowfall [inch last h]
Meeting criteria
Not meeting criteria
Colorado - road class: 2
Period '2024-01-24' - '2024-03-31'
Criteria: Below 20% Low Friction measurements per 30 minutes of snowfall
Percentage meeting criteria "Below 20% Low friction measurements"
KPI: 77.6
Snowfall [inch last h]
Meeting criteria
Not meeting criteria

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