DEPARTMENT OF TRANSPORTATION

Pavement Marking/Colored Pavement Friction Differential and Product Durability

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Research Report
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LOCAL ROAD RESEARCH BOARD

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The frictional characteristics of pavement surfaces is a major component of safety. Pavement markings play a very important role in traffic flow and safety, but they also have different friction characteristics than pavement due largely to the spherical glass media needed to improve retroreflectivity for night visibility and the marking material itself. The sudden change in frictional characteristics — friction differential — can create a safety hazard for pedestrians, motorcyclists, and bicyclists, especially under wet conditions. In this research effort, this issue was addressed first by performing a literature review, including a comprehensive review of the NordicCert certification process used in Scandinavian countries for selecting pavement marking products and conducting a survey to evaluate how users are affected by the friction differential between pavement markings and normal pavement surface. Then, based on recommendations from members of the Technical Advisory Panel, the research team developed and performed in situ experiments at MnROAD to determine the friction properties of various pavement markings, using a dynamic friction tester (DFT) and British pendulum test (BPT). A Sideway-force Coefficient Routine Investigation Machine (SCRIM) was also used to provide continuous friction measurement data. The data analysis showed that all three test methods (DFT, BPT, and SCRIM) produced comparable results and identified a similar range of friction differentials. A procedure used in the United Kingdom was recommended at the end, as an initial step in providing guidelines for selecting the friction coefficient of pavement markings.

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FINAL REPORT

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Correction

- **Section 5.1.1:** In Section 5.1.1, pavement markings were installed at ten positions, but **positions 8 and 9 were not used**. To maintain consistent numbering in the data analysis and tables, the final three markings listed in that section (formerly positions 8–10) have been renumbered to reflect the correct positions (10-12) and are referred to as **marking codes 10–12** throughout the report.

Clarification

- Additionally, please note that **material references for marking codes 10 and 11 are mislabeled in some tables and figures**. The correct materials, as installed and described in Section 5.1.1, are:
    - **Code 10**: MMA with Beads & Corundum
    - **Code 11**: MMA with Beads & Taconite
- Readers should refer to Section 5.1.1 for the authoritative material descriptions.

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EXECUTIVE SUMMARY

The frictional characteristics of pavement surfaces is a major component of safety. Pavement markings play a very important role in traffic flow and safety, but they also have different friction characteristics than pavement due to the glass media needed to improve retroreflectivity for night visibility. The sudden change in frictional characteristics can create a safety hazard for pedestrians, motorcyclists, and bicyclists, especially under wet conditions. In this research effort, this important issue was addressed as follows.

The research started with a literature review that summarized several studies and information about commercial products with the aim of gathering relevant findings in the area of pavement markings and colored pavements. Particular emphasis was placed on friction properties of different products and product durability, including resistance from weathering and traffic wear.

Different pavement marking materials come with various pros and cons. Thermoplastics are durable and cost-effective but are moisture-sensitive. Preformed tapes have great longevity but are pricey. They also have less resistance to shear and are not a good option for messages and colored pavement. Paints are cheap but don't last long, while epoxy markings last up to four years but fade over time. Methyl methacrylate (MMA) markings are durable and weather-resistant but need special equipment.

In Minnesota, Latex paint is the most commonly used material. High-traffic areas warrant longer-lasting materials like tape and epoxy. For pavement markings, visibility, not skid resistance, is the main criterion for durability assessment.

Studies highlight significant friction differences among marking materials, impacting safety, particularly for motorcyclists. Colored pavement surfaces, like green bike lanes in New York, enhance safety. A Vermont study found that Color-Safe™ performed the best among green bike lane materials, while a Florida study found green bike lane materials generally safe but recommended long-term monitoring. Another study found aging of colored paving asphalt reduces performance, introducing the Gastel Index (Ic) for evaluating aging resistance.

Next, the research team performed an investigation to evaluate how users, in particular bicyclists, were affected by the friction differential between pavement markings and normal pavement surface. Three different sources of information were used.

The first one was historical motorcycle crash data from the Federal Highway Administration. The analysis of FHWA motorcycle crash data revealed a strong association between the type of pavement markings and the incidence of motorcycle crashes. The study examined 351 police-reported motorcycle-involved injury crashes and evaluated variables such as pavement marking materials, surface conditions, and weather. Cramér’s V test showed strong correlations between pavement marking types and surface conditions, particularly under adverse weather.

The second was the recently released report *Addressing the Motorcyclist Advisory Council Recommendations: Synthesis on Roadway Geometry, Pavement Design, and Pavement Construction and Maintenance Practices* from FHWA. This FHWA report highlights significant gaps in motorcycle-specific safety related to roadway and pavement construction. Key findings indicate that European agencies have specifications addressing friction differentials, while U.S. guidance is limited and non-specific. The *AASHTO Product Evaluation and Audit Solutions* includes laboratory friction testing for tape markings, but it lacks comprehensive requirements for other materials. State practices, such as those used by Florida DOT, show more rigorous testing and requirements. The report underscores the need for improved guidelines and testing for pavement marking materials to enhance motorcycle safety.

The third source consisted of the results of a survey that the research team distributed to a number of organizations. The survey conducted by the research team assessed the impact of pavement markings and colored pavements on cyclists, motorcyclists, and pedestrians, with 223 individual responses. Bicyclists reported no changes in friction while cruising, accelerating, or riding on colored lanes, but significant changes during braking in wet conditions, suggesting the need for improvements such as increased roughness of markings and enhanced signage. Motorcyclists experienced friction changes during various maneuvers, particularly in wet conditions, with slip incidents common on lane and intersection markings, recommending textured materials for pavement markings. Pedestrians noted slip incidents in icy or wet conditions on crosswalk markings, advocating for improved pavement markings for better safety.

This task was followed by preliminary experiments performed to determine the friction properties of pavement surfaces and pavement marking products and colored pavement. Three different types of equipment were used, with the goal of comparing the results to determine if a less expensive piece of equipment could be used for routine investigations. The preliminary testing emphasized the critical importance of skid resistance for user safety, influenced by the surface's macro- and micro-texture. Three devices were used: British pendulum tester (BPT), dynamic friction tester (DFT), and T2Go. The BPT was cost-effective and suitable for low-speed measurements, while the DFT, although more expensive, allowed for controlled speed testing, and the T2Go, although initially promising, showed inconsistencies. Initial tests at the University of Minnesota revealed higher friction in dry conditions for concrete surfaces and epoxy markings, with DFT and BPT results consistent at low speeds but differing in wet conditions. Further testing in Duluth validated the reliability of the DFT and BPT for measuring pavement friction properties.

In addition, a comprehensive review of the current approach, used in Scandinavian countries for selecting pavement marking products, was performed and focused on the Nordic certification process of road marking materials called NordicCert. It is expected that this information could provide preliminary guidelines for developing a similar program in Minnesota.

Based on recommendations from members of the Technical Advisory Panel (TAP), the research team developed and performed in situ pavement marking friction experiments at MnROAD. A matrix composed of combinations of products and pavement surfaces was developed, based on product availability and pavement sections available on the low-volume loop at MnROAD. On October 5, 2023, pavement markings were installed within concrete Cell 46 and asphalt Cell 339 at MnROAD's low-volume loop road. Ten markings were installed per cell, measuring 2 feet in width by 24 feet in length, and spaced 8 feet apart. Marking types included latex with Type 1 beads, various epoxy formulations, preformed thermo, and MMA with different additives, such as beads, corundum, taconite, and crushed glass.

Initial baseline friction measurements were made in November 2023 using a DFT and BPT. Follow-up measurements in June 2024 assessed the impact of traffic and winter conditions. A Sideway-force Coefficient Routine Investigation Machine (SCRIM) was also demonstrated, providing continuous friction measurement data. The SCRIM tests, conducted at three speeds, offered valuable comparative data to the DFT and BPT results. However, the mild winter of 2023-2024 resulted in minimal snow plowing and limited impact assessment.

The data collected was then statistically analyzed. The DFT provided data across speeds from 0 to 80 km/h, focusing on non-vehicular modes of transportation. Measurements in November 2023 and June 2024 showed the highest friction values at low speeds, decreasing between 5-20 km/h and remaining constant up to 70 km/h. The control pavements maintained higher and more consistent friction values. Initial friction values for markings were higher and then decreased due to exposure to traffic.

The BPT measures friction at ~10 km/h. Average friction values, obtained in 2023 and 2024, showed decreasing friction for most markings, especially in wheel paths, due to wear and exposure of markings to traffic and weather. The DFT and BPT results were correlated, showing similar friction characteristics for both pavement markings and control pavements.

The SCRIM testing, conducted in July 2024, provided continuous friction measurement data at 10-cm intervals, identifying friction differentials between pavement markings and unmarked intervals. The analysis of the experimental results indicated that:

- Both DFT and BPT methods produced comparable results.
- SCRIM testing, conducted at three speeds (15 mph, 30 mph, and 40 mph), showed consistently similar friction values for control portions and identified friction variability.
- SCRIM data correlated well with DFT data, especially for measurements in the traffic lane where markings experienced wear. The friction differentials increased with testing speed, while the control pavement values remained largely unchanged.
- Epoxy-based markings generally had a significantly higher friction differential from the control pavements compared to MMA-based markings.
- The effect of wear and environmental exposure of the markings were observed by a change in friction characteristics from 2023 to 2024.

The research team concluded that the DFT, BPT, and SCRIM testing methods provide reliable and consistent measurements for assessing pavement friction properties and can be used to evaluate and select pavement marking products.

The research team was not able to provide numerical recommendations regarding the friction coefficient of pavement markings, based on the limited data obtained in this study. However, the research team identified a procedure used in the United Kingdom (2021) that could be adapted to Minnesota conditions and implemented in the future.

Chapter 1: Introduction

Safety of all modes of travel represents one of MnDOT's core values. The frictional characteristics of pavement surfaces is a major component of safety; good skid resistance allows users to move and stop safely under various weather and moisture conditions. While pavement markings play a very important role in traffic flow and safety, they also tend to have different friction characteristics than the pavement and can be more slippery, since most contain glass media needed to improve retroreflectivity for night visibility. The sudden change in frictional characteristics, when transitioning from normal pavement surfaces to pavement markings and, in some cases, to colored pavement lanes, can create a safety hazard for pedestrians (including those with disabilities), motorcyclists, and bicyclists, especially under wet conditions, including frozen components of the marking in cold weather.

In recent years, a number of pavement markings and colored pavement products that provide improved friction properties and, in some cases, show promise from a durability standpoint have become available. A number have been used on MnDOT projects; however, there has been no rigorous scientific investigation to measure and analyze the friction differential between pavement markings/colored pavement and the surrounding pavement.

This task provided an initial assessment of research benefits, a proposed methodology, and potential implementation steps.

1.1 Methodology

In this project, we addressed this issue by performing skid resistance testing on a number of products, using different testing devices and providing guidelines for evaluating the frictional characteristics of pavement markings and colored pavements. In addition, a comprehensive literature review was performed to better understand what is being done nationally and internationally, to address the issue of friction differential.

The research started with a literature review that summarized several studies and information about commercial products with the aim of gathering relevant findings in the area of pavement markings and colored pavements. Particular emphasis was placed on friction properties of different products and product durability, including resistance from weathering.

Next, the research team performed an investigation to evaluate how users, in particular bicyclists, were affected by the friction differential between pavement markings and normal pavement surfaces. Three different sources of information were used. The first was historical motorcycle crash data from the Federal Highway Administration. The second was the recently released report *Addressing the Motorcyclist Advisory Council Recommendations: Synthesis on Roadway Geometry, Pavement Design, and Pavement Construction and Maintenance Practices* from FHWA. The third source consisted of the results of a survey distributed to a number of organizations by the research team.

This task was followed by preliminary experiments performed to determine the friction properties of pavement surfaces and pavement marking products and colored pavement. Three different types of equipment were used, with the goal of comparing the results to determine if a less expensive piece of equipment could be used for routine investigations. In addition, a comprehensive review of the current approach used in Scandinavian countries for selecting pavement marking products was performed, focused on the Nordic certification process of road marking materials called NordicCert. It was expected that this information could provide preliminary guidelines for developing a similar program in Minnesota.

Based on recommendations from TAP members, the research team developed and performed in situ experiments at MnROAD to determine the friction properties of various pavement marking and colored pavement products. A matrix composed of combinations of products and pavement surfaces was developed, based on product availability and pavement sections available on the low-volume loop at MnROAD.

The data collected was statistically analyzed to determine which products have good friction properties and which need improvement. A number of conclusions and recommendations were made for developing a standard procedure to determine the frictional characteristics of pavement markings and colored pavements.

Chapter 2: Literature Review

2.1 Introduction

Pavement markings that are present on pavement surfaces have been proven to increase traffic safety by guiding and informing drivers, particularly during night hours, when visibility is limited (Nassiri, 2018). However, the friction variation from the pavement markings to the adjacent pavement may be detrimental to skid resistance and create a hazard to bicyclist, motorcyclists, and pedestrians (Harlow, 2005). Large pavement markings, such as crosswalks, school zone markings, large arrows, and symbols on bicycle lanes, can cause riders to slip when wet, especially when they are located in the approach of intersections and roundabouts, where drivers tend to brake more often and more abruptly (Nassiri, 2018; Austroads, 2005). Selecting pavement markings with material properties that minimize the differential in friction properties, while keeping the retroreflective properties unchanged, becomes an important priority in keeping pavement users safe.

This task summarizes several studies and information about commercial products with the aim of gathering relevant findings in the area of pavement markings and colored pavements. Particular emphasis is placed on friction properties of different products and product durability, including resistance from weathering.

2.2 Pavement marking materials

Some of the most commonly used pavement marking materials are described below (Nassiri, 2018; Asdrubali, 2013; Montebello & Schroeder, 2000).

2.2.1 Thermoplastics

Thermoplastics are durable marking material that consist of four components: binder (plastics and resins), pigment, glass beads, and filler (usually calcium carbonate, sand, or both). The mixture of plasticizer and resins is solid at ambient temperature, so it must be heated at least at 200ºC for the application. There are two types of thermoplastics: hydrocarbon (easier to apply, but sensitive to oil drippings and other automobile byproducts) and alkyd (generally more durable and has better retro reflectivity properties) (Nassiri, 2018; Asdrubali, 2013; Montebello & Schroeder, 2000)

Most thermoplastics have low cost, good retro reflectivity, can be applied over older thermoplastic marking, and perform very well on all types of asphalt surfaces. Their expected service life varies from 2 to 7 years and is strongly affected by installation, environmental condition, and snow-removal operations, except for Preformed Fused Thermoplastic markings that are melted into the surface and are resistant to snowplows. Thermoplastic materials are not recommended for regions with high humidity or susceptibility to dew formation during striping operations because they are highly susceptible to moisture-associated bonding failures. (Nassiri, 2018; Asdrubali, 2013; Montebello & Schroeder, 2000)

2.2.2 Preformed tapes

Tapes are available in several types and performance levels. They can be permanent (usually made of a plastic binder material with glass beads embedded into the surface) or temporary (used in construction zones and maintenance jobs that require altered travel lanes or temporary delineation). Tapes have longer service life when compared to most marking materials. However, the initial costs tend to be 5 to 10 times higher than thermoplastics. They can also be used for precut symbols and legends. (Nassiri, 2018; Asdrubali, 2013). An example of a commercial polymer tape is shown in Figure 1.

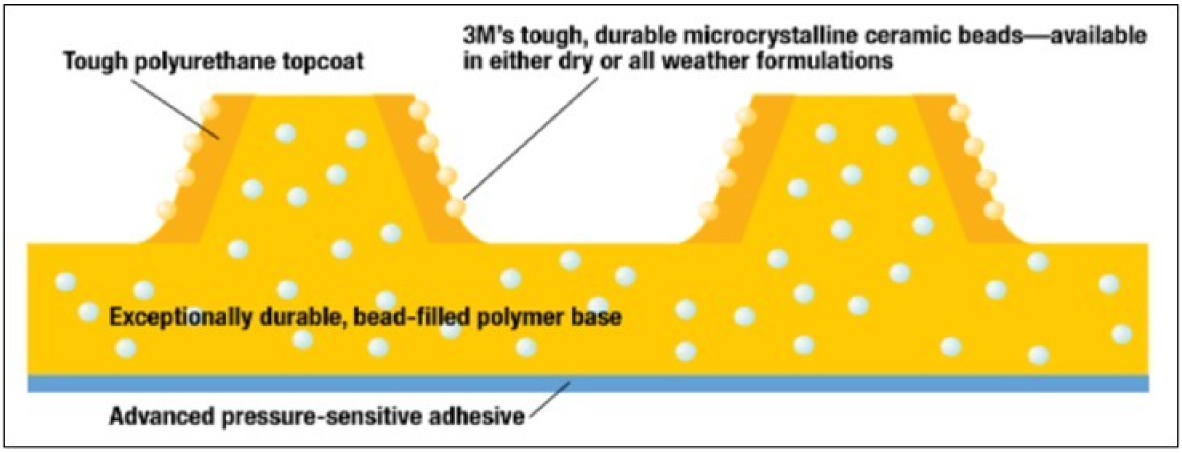


Figure 2.1 Cross-section of a commercial polymer tape from 3M™ (Nassiri, 2018)

Tapes are a cost-effective choice for high traffic volume roads because their service lives are superior to most marking materials. Their service lives are most affected by snow removal and ice control techniques, heavy trucks, unpaved shoulders, narrow lane width, and excessive encroachment (crossover) on high AADT roadways. The material loss from snowplow operations is mitigated when the tape is inlaid into freshly placed bituminous or when using grooving. The first process consists of applying the tape marking immediately after the asphalt compaction is complete and rolling it into the surface with the use of a finishing roller. (Nassiri, 2018; Montebello & Schroeder, 2000)

2.2.3 Paints

Paints represent the most inexpensive and widely used road marking material. Pavement marking paints contain pigments and binders and can be mixed with water (waterborne paints) or solvents (solvent-borne paints). The pigments may contain other additives such as fillers, UV stabilizers, and retroreflective glass beads. Solvent-borne paints are more durable, while waterborne paints are more environmentally friendly and easier to work with. Paints are expected to last from 6 months to 3 years, depending on pavement surface, traffic volume, paint thickness and weather conditions. Material can be lost from snow-removal operations. It is mostly recommended for low-volume roads under normal conditions. (Nassiri, 2018; Asdrubali, 2013)

2.2.4 Epoxy-based marking materials

Epoxy-based marking materials contain two parts: a pigmented resin base, and a catalyst used to accelerate the setting time. The materials are heated and then sprayed onto the pavement surface. They usually take several minutes to dry and should not be applied over markings made from other materials. Epoxies have a service life up to 4 years, but they fade and lose color with age, especially under ultraviolet lighting. (Nassiri, 2018; Asdrubali ,2013)

2.2.5 Methyl methacrylate (MMA) marking materials

Methyl methacrylate (MMA) is a two-component mixture of MMA and a catalyst. MMA is environmentally friendly, durable, and can be sprayed or extruded onto the pavement. It does not require heat to cure and is resistant to antifreeze chemicals, and is a great option for places with cold weather. MMA has a long service life (it can last for several years), but its appearance can fade over time, making it appear less bright than its actual retro numbers. Its application might require special equipment. (Nassiri, 2018; Asdrubali, 2013)

2.3 Pavement marking materials used in Minnesota

According to surveys performed by the Minnesota Department of Transportation, the most common pavement marking material type used in Minnesota is Latex (waterborne paint), followed by Epoxy paint (Smadi et al., 2017, Smadi & Hawkins, 2010). Table 2.1 shows the distribution of material used by local agencies, as they responded to five survey question. The five questions were as follows:

1. Please select all of the pavement marking products used by your agency for long lines on new construction or pavement rehab (skips and edge lines).
2. Please select all of the pavement marking products used by your agency for legends on new construction or pavement rehab (symbols, arrows, crosswalks).
3. Please select all of the pavement marking products used by your agency for long lines for regular maintenance (skips and edge lines).
4. Please select all of the pavement marking products used by your agency for legends for regular maintenance (symbols, arrows, crosswalks).
5. Please tell us if you apply any of these products in a groove or recess in the pavement.

From table 2.1, it is possible to see that Thermoplastic (Extruded) and MMA markings were not used by any of the agencies that responded to these questions. For the fifth question of the survey, 40 (46.51%) agencies out of 86 indicated that they do not apply any of the products in a groove or recess in the pavement.

Table 2.1 Responses to questions on the use of different marking types (Smadi, et al. 2017)

Answer Choices	Q.1 Long Lines (new)		Q.2 Legends (new)		Q.3 Long Lines (maint.)		Q.4 Legends (maint.)		Q.5 Grooving	
Latex (Waterborne Paint)	80.46%	70	64.37%	56	95.35%	82	84.88%	73	16.28%	14
Highbuild Waterborne	11.49%	10	4.60%	4	8.14%	7	2.33%	2	9.30%	8
Epoxy	64.37%	56	48.28%	42	31.40%	27	27.91%	24	37.21%	32
Sprayed Thermo	0.00%	0	1.16%	1	0.00%	0	0.00%	0	0.00%	0
Extruded Thermo	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0
Preformed Thermo	11.49%	10	39.08%	34	2.33%	2	17.44%	15	17.44%	15
Tape	10.34%	9	9.20%	8	1.16%	1	4.65%	4	9.30%	8
Polyurea	0.00%	0	1.15%	1	0.00%	0	0.00%	0	2.33%	2
Urethane	1.15%	1	1.15%	1	1.16%	1	1.16%	1	0.00%	0
Methyl Methacrylate (MMA)	0.00%	0	0.00%	0	0.00%	0	0.00%	0	0.00%	0
Agencies answered	87		87		86		86		86	

The survey also identified who is usually responsible for installing the pavement markings. As shown in Figure 2.2, the majority of pavement markings are installed by contractors (64.04% of the agencies that participated on the survey). The agencies that answered "Combination" install their pavement markings using any combination of in-house crews, contractors, or MnDOT.

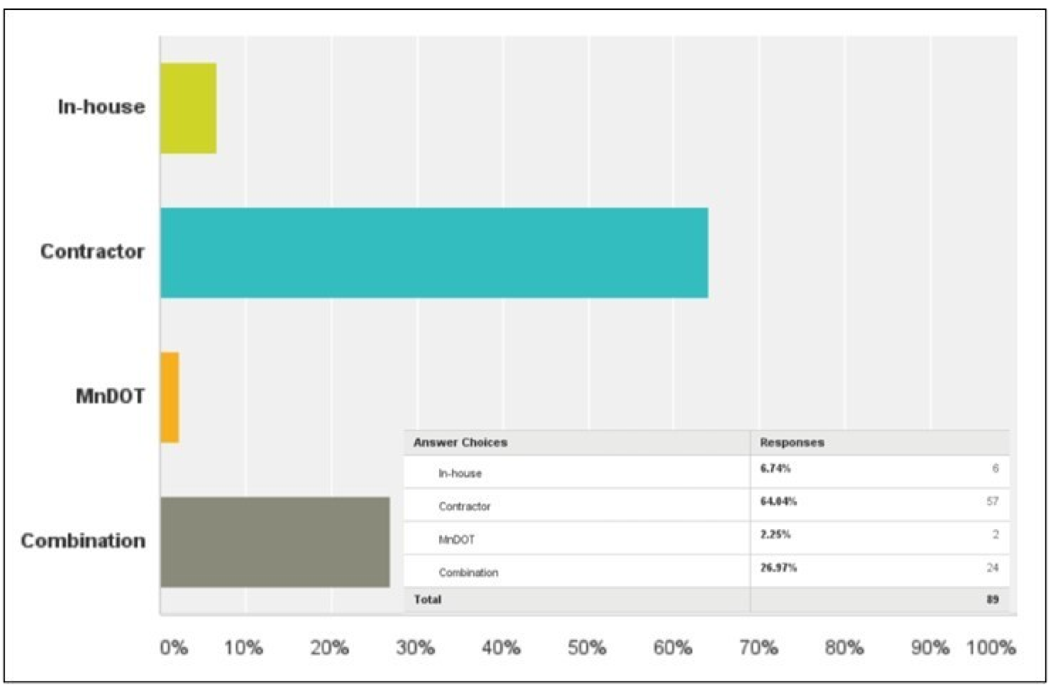


Figure 2.2 Agencies response to who installs their pavement markings (Smadi et al., 2017)

The agencies were also asked about the estimated life for each product type. Although Latex paint is the most used material, agencies had lower expectations for its durability, when compared to Epoxy. On the other hand, Thermoplastic (preformed), Tape, and Polyurea paints are expected to have longer service lives especially on the sections with higher traffic.

The same study analyzed the long-term performance of several pavement marking materials. The measures considered for the analysis were: initial average retro reflectivity, ratio between the average retro reflectivity after 1 year of service to the initial average retro reflectivity (R1/R0), ratio between the average retro reflectivity after 2 years of service to the initial average retro reflectivity (R2/R0), deterioration rate estimated from the deterioration models, and average retro reflectivity. Neither the survey, nor the data analysis addressed the skid resistance of pavement markings.

2.4 Durability of pavement marking products

An important factor that needs to be considered is the reduction in skid resistance of pavement markings as they age. However, with marking systems, the service life is usually related to visibility. As a result, the markings are believed to be in good service life for as long as its visibility remains in good condition, and the decay in skid resistance is often forgotten. (Harlow, 2005)

Asdrubali et al. (2013) led a study to develop a new methodology to evaluate the quality of pavement road markings and to optimize the budget in urban areas of Perugia, Italy. The study analyzed the available budget for their municipality and concluded that it allows maintaining in good condition only 6% of their pavement markings, a situation that can be common for smaller towns. In order to evaluate how different selections of marking materials can weigh on the annual budget, the study created several scenarios to compare the service life of different types of materials over a 12-year period. The scenarios are shown in figure 2.3, where the "Max savings" option shows the result of using the most economic material for each road signage type (solvent-based paint for stripes, and sprayed thermoplastic for other signals). The performance parameter (retroflection) and service life and of the materials were taken from studies conducted by several Departments of Transportation in the United States.

2.5 Friction properties of pavement markings

The friction differential faced by pedestrians and drivers moving from regular pavement to pavement markings and colored pavements can result in safety issues, particularly under adverse weather conditions. This concern has motivated research efforts for a long time. In 1980, Anderson and Henry published a comprehensive study that aimed to determine the skid resistance of pavement marking materials. The study considered 39 formulations of 11 different types of marking materials, which were: Conventional alkyd paint, Conventional chlorinated rubber paint, Alkyd quick-dry paint, Chlorinated rubber quick dry paint, Alkyd paint with premixed glass beads, Chlorinated rubber paint with premixed glass beads, Hot-extruded thermoplastic, Hot-sprayed thermoplastic, Cold-applied plastic, Temporary tapes, and Two-part epoxy-polyesters. The 39 different formulations were obtained by combining the marking materials to different pigment color (white or yellow), and different surfaces (beaded or unbeaded). (Anderson & Henry, 1980; Henry et al., 1980)

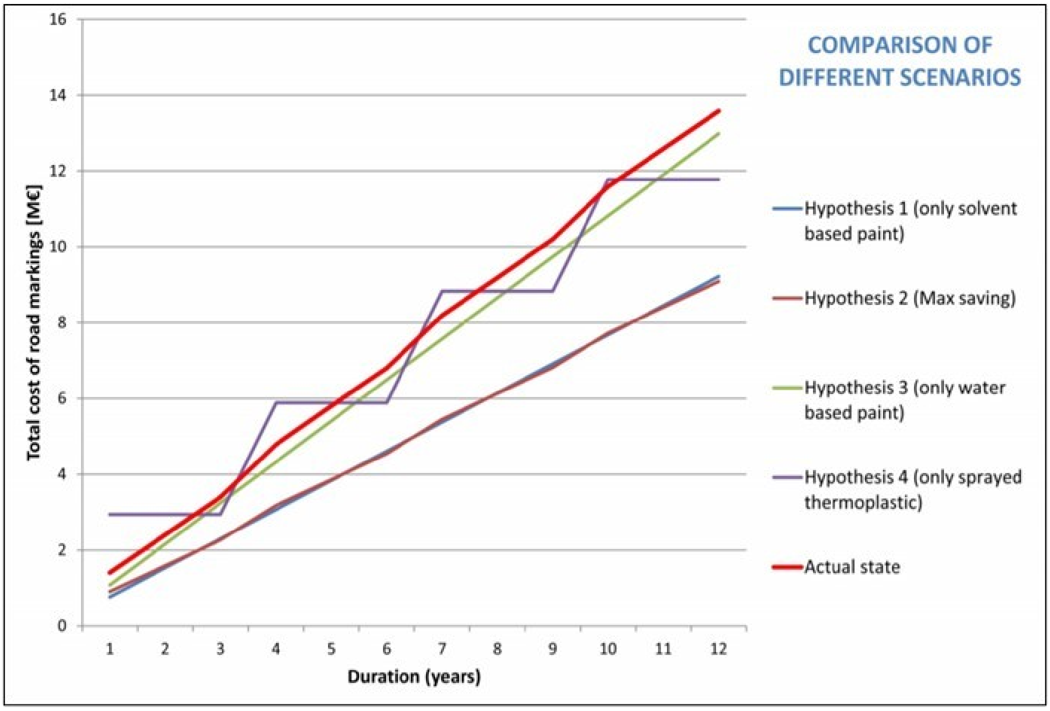


Figure 2.3 Comparison of different scenarios (Asdrubali et al., 2013)

The study evaluated each marking material in both the laboratory and in the field. The field samples were prepared by applying different marking materials in three field-test sites. Seventeen marking materials were placed in and out of the wheel tracks of a six-year-old dense graded asphalt pavement with an SN_{40} (Skid Number at 40 miles/h) of approximately 40. Eight marking materials were applied in and out of the wheel tracks of a four-year-old Portland cement concrete pavement with longitudinal brooming finishing and an SN_{40} of approximately 45. The remaining marking materials were placed in the Pennsylvania Transportation Research Facility test track, which has different surfaces including Portland cement concrete, an open-graded friction course, a dense-graded asphalt concrete, and a surface coated with Jennite. The friction of the investigated surfaces ranged from SN_{40} of 30 to 65. The paints, the two-part epoxy-polyesters, and the hot-sprayed and hot-extruded thermoplastics were applied using commercial application equipment, while the cold-applied materials and the temporary tapes were simply pressed into place. (Anderson & Henry, 1980)

The laboratory samples were prepared using four different laboratory panels designed to simulate a variety of field surface textures. The majority of the panels were 16-gauge galvanized steel plates 152 mm (6 in) long by 102 mm (4 in) wide. A smaller number of panels were made in the laboratory with (a) broomed Portland cement concrete, (b) coarse-textured asphalt concrete and, (c) fine-textured asphalt concrete. The extruded materials were extruded in the laboratory, while the paint and the hot-sprayed and two-part materials were sprayed into the panels placed on the pavement just ahead of the field test stripes. The wear in the field was simulated by polishing all the laboratory panels by using the Pennsylvania State University Reciprocating Pavement Polisher. (Anderson & Henry, 1980)

The friction resistance and texture of the marking materials were analyzed through a number of test procedures:

1. SN measurements (ASTM E274) at 30, 40, and 50 miles/h at all field sites;
2. Use of the NBS-Brungraber Portable Slip-Resistance Detector at all field sites and for all laboratory panels;
3. Microtexture and macrotexture profile measurements at selected field samples and for selected panels;
4. British Pendulum (Tester) Number or BPN (ASTM E303) at all field sites and for all laboratory panels; and
5. Atlas Twin-Arc Weatherometer exposure on selected laboratory panels followed by Brungraber, BPN, and texture measurements.

The tests revealed that there were no statistically significant differences between white and yellow materials. Therefore, their data were combined. The test results also showed that accelerated exposure testing is not helpful in specifying the friction of marking materials.

The study concluded that different marking materials have different characteristics that can affect skid resistance, and that skid resistance reductions may last over a long period of time in spite of considerable surface wear. The skid resistances of the Alkyd paint with premixed glass beads, Chlorinated rubber paint with premixed glass beads, Conventional chlorinated rubber paint, Chlorinated rubber quick-dry paint, and Hot-sprayed thermoplastic were all less than that of the control surface. None of the marking materials approached the unmarked control surface's friction, even after nine months' exposure. The lowest SN_{40} values were obtained for the Conventional chlorinated rubber paint and Chlorinated rubber quick-dry paint and, even after nine months' exposure, very little improvement in skid resistance was observed. The authors stated that the results were unexpected because of the considerable wearing away of the paint during the nine-month period. Finally, the study concluded that, due to their low skid resistance, some marking materials may result in safety hazards if applied over large areas, such as gore areas. (Henry et al., 1980; Anderson & Henry, 1980)

The study also tried to recommend limits on the differential friction caused by marking materials. The purpose of setting friction limits was to ensure the safety of cars and motorcycles by reducing the effect of emergency maneuver such as locked-wheel skid. However, the lack of experimental data and the complex and variable nature of human behavior made it very difficult to set numerical values for the parameter limits and recommendations for allowable levels of marking material skid resistance could not be established. Thus, the study concluded that further studies of the driver behavior and an analysis of accidents occurring on marked roads were required. (Henry et al., 1980; Anderson et al., 1982)

The study also resulted in a data base of full-scale locked-wheel skid resistance for paints of various formulations, temporary tapes, cold performed plastics, hot strays and extruded thermoplastics, and some two-component systems. The study concluded that motorcyclists are more affected by the friction differential than drivers of four wheel-vehicles, and thus the skid resistance of pavement markings can be directly responsible for motorcyclists' safety. (Henry et al., 1980)

In a different study, Nassiri et al. (2018) investigated the frictional properties of three different types of pavement markings materials using a British Pendulum Tester (BPT) in the laboratory and in the field. Waterborne paint, preformed fused thermoplastic, and cold applied pre-formed tape were applied to concrete slabs and tested in the laboratory under dry, wet, and icy conditions. The three pavement marking types are shown in figure 2.4.

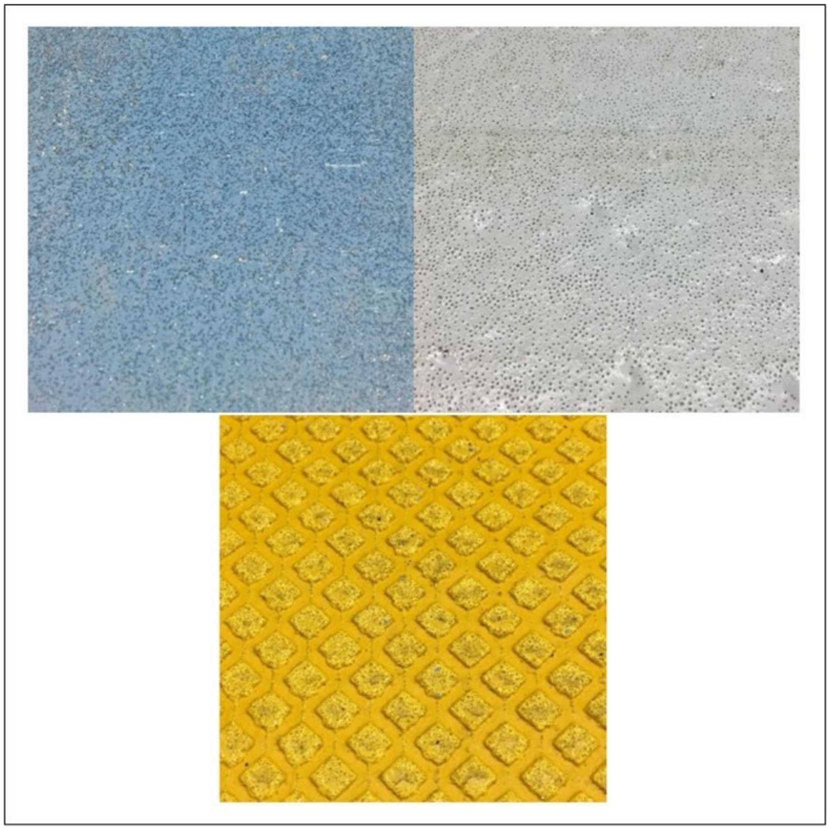


Figure 2.4 Slab surface markings for a) paint with beads, b) thermoplastic with beads, and c) cold-applied preformed tape (Nassiri, 2018)

The field testing evaluated painted markings applied at two different locations on the Washington State University (WSU) Pullman campus, under dry and wet conditions. The testing used a BPT and two bicyclists that rode over the markings in a variety of ways (figure 2.5). The riders, then, evaluated the field markings using a safety scale created by the authors. (Nassiri, 2018)

Figure 2.5 Dry testing using the mountain bike at Test Site 1 by a) the BPT, b) rider one, and c) rider two. Wet testing at Test Site 2 by d) the BPT, e) rider one, and f) rider two (Nassiri, 2018)

Laboratory test results revealed that the paint and thermoplastics resulted in lower BPN values than the control concrete surface. Results from the field testing revealed that most riders feel unsafe when turning and braking on wet pavement markings. The BPN values obtained in the laboratory tests were higher than the values obtained in the field, likely due to the fact that beads were used only in the laboratory. The authors concluded that the centerline striping showed promising frictional properties. Out of the three marking materials tested with the BPT, only cold-applied preformed tape was found suitable for difficult road sites, such as a) roundabouts, b) bends with radius less than 150m on unrestricted roads, c) gradients, 1 in 20 or steeper, of lengths greater than 100m, and d) approaches to traffic lights on unrestricted road. (Nassiri, 2018)

2.6 Improving skid resistance of pavement markings

A study by Siyahi et al (2015) investigated the enhancement of the skid resistance of pavement markings using waste glass powder, silica granules and Lika (i.e., expanded clay). The study concluded that adding 10% by weight of waste glass powder, with particle gradation No. 3, improved the skid resistance of the two-component road marking paint up to 58%. (Two-component paints are mainly comprised of two components of resin and a curing agent. The study used a two-component acrylic paint with the first component containing an acrylic resin, and the second component containing peroxide). On the other hand, while the addition of granules and Lika improved the skid resistance, it caused significant abrasion resistance reduction.

Harlow (2005) also investigated the improvement of skid resistance of pavement marking systems. The study concluded that the skid resistance of marking materials can be improved with the addition of angular materials, such as crushed high purity quartz, silica sand and corundum angular material. Harlow highlighted that if the angular material needs to be applied in conjunction with glass beads, the angular material should match the bead size and should be applied immediately before the application of the bead glass. An application rate of 1-part angular material to 2 parts glass beads is recommended.

2.7 Colored pavement lanes

Colored pavement surfaces have been widely used to mark bike lanes and bus corridors, and it has been linked to safety improvements. Reports from the City of New York concluded that green colored bike lanes limit instances of drivers driving in the bike lane (NYCDOT, 2011).

A study from the Vermont Agency of Transportation (Anderson, 2018) evaluated the constructability, durability and retroreflectivity of products used in green bike lanes. The research effort considered three green pavement marking materials: Transpo Industries Color-Safe, Ennis-Flint PreMark, and Ennis-Flint CycleGripMMAX.

The commercial product Color-Safe™ (figure 2.6), from Transpo Industries of New York, is sold as an acrylic based resin system used for area markings and anti-skid surfacing for asphalt and concrete pavements. The product is advertised as a pavement coloring material and as a surface coat to enhance skid-resistance on hazardous turns and other high accident areas. It is expected to have a life cycle of 6 to 10 years, requires a curing time of 20 to 40 minutes, and the application does not need specialized equipment. (Grossman, 2017; Coral Sale Co., n.d)

Figure 2.6 Green bike lane in NYC colored with Color-Safe™ Methyl methacrylate (MMA) (Grossman, 2017)

PreMark (figure 2.7) is a preformed thermoplastic manufactured by Ennis-Flint of North Carolina, sold as a heavy-duty, durable intersection grade pavement marking material. The product is advertised as a material engineered for use in high-traffic areas subjected to vehicular traffic that lasts 6 to 8 times longer than paint. (Ennis-Flint, n.d)

Figure 2.7 Green bike lane colored with Ennis-Flint PreMark (Ennis-Flint n.d)

CycleGripMMAX combines Methyl Methacrylate (MMA) resin with hardwearing aggregate and premium pigment and is also manufactured by Ennis-Flint in North Carolina. The product is designed for long lane areas with low to high vehicle traffic including crossover points such as parking lot entries/exits along the corridor. It is advertised to offer long-lasting color retention, friction, and extreme durability. (Anderson, 2018)

The authors used visual observations of the bike lane markings and categorized each marking on a Good/Fair/Poor/Missing scale. Examples of the classification can be seen in Figure 2.8 for Good Condition, in Figure 2.9 for PreMark in Fair Condition, and in Figure 2.10 for Poor preforming markings. Observations after 2 years of service revealed that the Color-Safe MMA was performing the best in both of its applications, followed by the CycleGripMMAX, and PreMark having the worst performance. Color-Safe had more texture remaining and retained a greater depth/thickness of material. Based on the results, the study suggested that MMA green bike material should be explored for future bike lane markings, when cost, time to use, and environmental factors permit. (Anderson, 2018)

Figure 2.8 Location 1 PreMark in good condition

Figure 2.9 Location 1 PreMark in fair condition

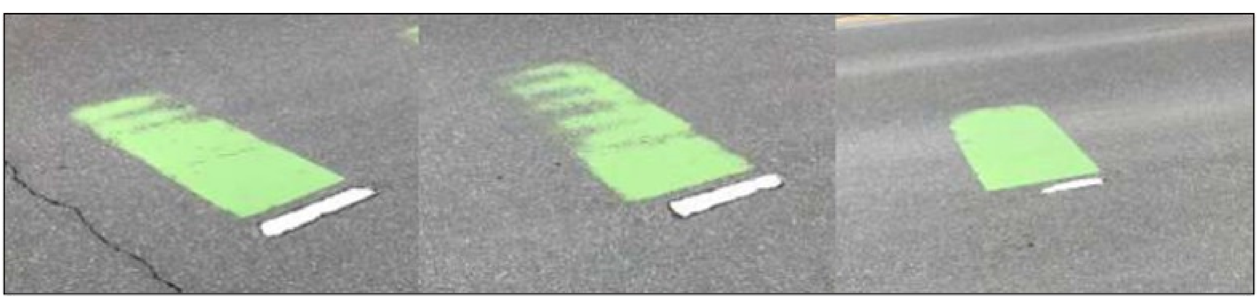


Figure 2.10 Location 1 PreMark in poor condition

A study by Gao et al. (2006) analyzed the aging process of colored paving asphalt using the rotate thin film oven (RTFO) test at three different temperatures (150ºC, 163ºC, and 180ºC). The study concluded that the aging caused resins, aromatics, and saturated content to decreased, while asphaltene increased. Consequently, the original colloidal structure of the colored paving asphalt was destroyed, which deteriorated the performance of the colored paving asphalt. The study also revealed that the Gastel index (Ic) can be used to evaluate the aging resistance of the colored paving asphalt. The Gastel index is calculated as shown in equation 1, and the greater it is, the lower its colloidal stability, and the worse its aging resistance.

$$Ic = \frac{(Asp + Sa)}{(Ar + Re)} \qquad (1)$$

where Ic is the Gastel Index; Asp is the content of asphaltene in asphalt (%); Sa is the content of saturate in asphalt (%); Ar is the content of aromatics in asphalt (%); and Re is the content of resin in asphalt.

Another study from the Florida Department of Transportation (Offei et al., 2017), aimed to evaluate the materials used in green colored bike lanes to determine whether they create any issues with pavement friction. The study was motivated by concerns that some materials could increase safety issues, in particular, thermoplastics, which have been noted by cyclists to be very slippery when wet.

The study considered five different green colored bike lanes that have been in operation for more than a year and has one of three types of material: Epoxy Modified, Thermoplastic, and High Friction Surface treatment. The materials were applied to three types of existing pavement surfaces: concrete, open and dense graded asphalt pavements. Circular Texture Meter (CTM) and Dynamic Friction Tester (DFT) were used to obtain the texture and friction values, respectively. (Offei et al., 2017)

The study concluded that “the use of the green bike lane materials does not create a hazard in themselves”, and that all green bike lane sites met the initial friction number requirements established by the Florida’s Patterned Textured Pavement Specification, and minor friction loss was observed at the keyhole sections. The authors acknowledged the need to monitor the long term frictional and surface texture characteristics of the green colored bike lanes. (Offei et al., 2017)

Chapter 3: Impacts to cyclists from pavement marking types and colored lanes

3.1 Introduction

In this chapter, the research team performed an investigation to evaluate how users, in particular bicyclists, are affected by the friction differential between pavement markings and normal pavement surface. Three different sources of information were used. The first one is historical motorcycle crash data from the Federal Highway Administration. The second is the recently released report on "Addressing the Motorcyclist Advisory Council Recommendations: Synthesis on Roadway Geometry, Pavement Design, and Pavement Construction and Maintenance Practices" from FHWA. The third source represents the results of a survey distributed to a number of organizations by the research team.

3.2 FHWA motorcycle crash data

Historical crash data from the Federal Highway Administration were used to analyze the correlation between motorcycle crashes and pavement markings. The database contains records of 351 police-reported, motorcycle-involved, injury-producing crashes. The variables analyzed were:

- Fatality (yes or no)
- Pavement Markings Material (left and right side)
  - no markings
  - paint
  - thermoplastic
  - raised markers
  - tape
  - not applicable, no adjacent lane
  - other (specify)
  - unknown
- Longitudinal Pavement Markings at Edge of Lane Traveled by Vehicle (left and right side)
  - no markings
  - centerline, skip-dash, yellow
  - centerline, solid, yellow
  - centerline, solid double, yellow
  - lane line, skip-dash, white
  - lane line, solid, white
  - edge line, left, yellow
  - edge line, right, white
  - left-turn lane lines, combination of solid and skip-dash, yellow
  - turn arrow symbols, thru, left, or combination of the two
  - not applicable, no adjacent lane
  - other (specify)

    - unknown
- Surface Condition
    - none
    - dry
    - wet
    - snow
    - slush
    - ice/frost
    - water (standing, moving)
    - mud, dirt
    - sand
    - gravel
    - oil
    - debris (tire tread, construction materials, tree limbs, etc.)
    - loads dropped from another vehicle
    - other (specify)
    - unknown
- Ambient Temperature
- Weather Description
    - clear
    - cloudy, partly cloudy
    - overcast
    - drizzle, light rain
    - moderate or heavy rain
    - snow
    - sleet, freezing rain
    - hail
    - other (specify)
    - unknown

The data allows the analysis of pavement marking materials and the severity of the crashes. Figures 3.1 and 3.2 show the number of crashes observed at each pavement marking material and whether they were fatalities. However, the absence of a control variable makes it difficult to determine whether the higher incidence of crashes occurred because certain materials are more dangerous, or because they are just more commonly used.

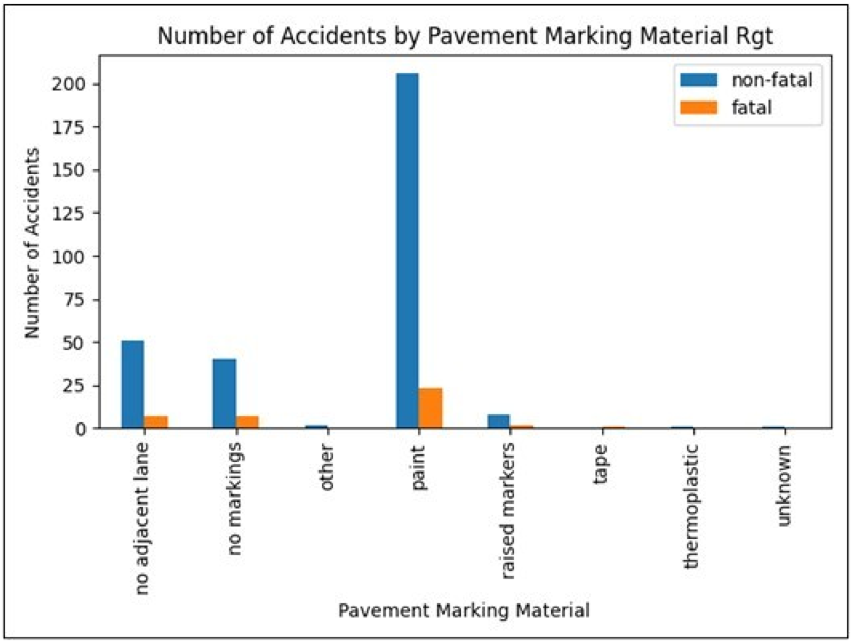


Figure 3.1 Number of accidents by pavement marking material observed on the right side

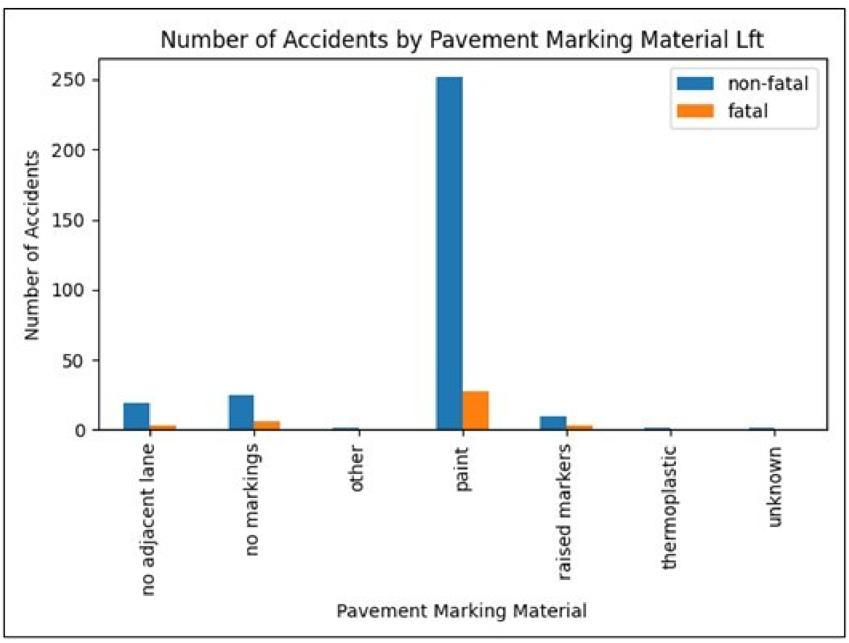


Figure 3.2 Number of accidents by pavement marking material observed on the left side

The measure of association between the categorical variables was analyzed using the Cramér's V test, a nominal variation of the Pearson's Chi-Squared Test. Finding the association between the variables can help summarize the data and find possible patterns. For instance, is fatality associated with the weather condition? The Cramér's V test can reveal if there is any statistically significant evidence of variable association.

Cramér's V is computed by taking the square root of the chi-squared statistic divided by the sample size and the minimum dimension minus 1, as shown in equation 2.

Equation 1 Cramer's V

$$V = \sqrt{\frac{X^2/n}{\min(k-1, r-1)}}$$

Where X^2 is the chi-squared statistic, *n* is the number of total observations, *k* is the number of columns in the dataset, and *r* is the number of rows.

The results of the Cramér's V coefficients are displayed in the heatmap shown in figure 3.3.

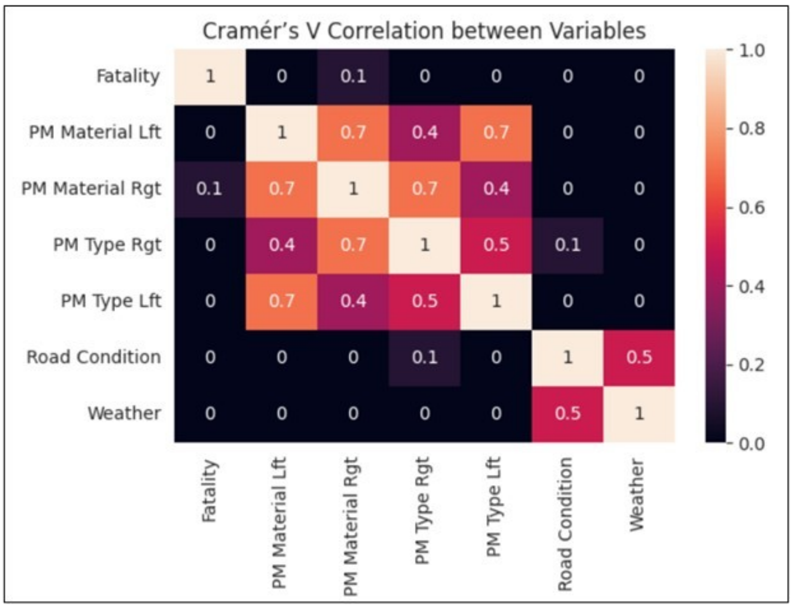


Figure 3.3 Cramér's V Correlation Matrix

The Cramér's V coefficients can be interpreted using a rule of thumb created by Rea and Parker (2014), shown in Table 3-1.

Table 3.1 Rule of Thumb for interpreting the strength of Cramér's V coefficients

Cramér's V	Interpretation
0.00 < 0.10	Negligible
0.10 < 0.20	Weak
0.20 < 0.40	Moderate
0.40 < 0.60	Relatively strong
0.60 < 0.80	Strong
0.80 <= 1.00	Very strong

In conclusion, strong association was found between the Pavement Markings Material (PM Material) and the Longitudinal Pavement Markings at Edge of Lane Traveled by Vehicle (PM Type), and relatively strong association was found between Weather and Road Condition.

3.3 FHWA-SA-21-090 Report

In a recently released report funded by Federal Highway Administration Office of Safety (Geary et al., 2021), a synthesis of recent history of motorcycle-specific safety research was performed. The study found significant gaps in design, friction needs, and motorcycle-specific concerns related to roadway and pavement construction and maintenance. A summary of the most relevant information is presented next.

An international scan performed in 2011 found that some European agencies have specifications addressing friction differentials due to different pavement types, such as High Friction Surface Treatment (HFST) and pavement markings. In some countries, pavement markings placed in intersections leave a gap for motorcycles and bicycles.

The current EU standard for pavement marking materials, EN 1436:2018, includes several different skid-resistance classes, S1 to S5, that are differentiated by minimum friction values in terms of Skid Resistance Tester (SRT), which is the European designation for the British Pendulum Test value. The specification notes that "in general, high classes of retroreflection and slip/skid resistance cannot be obtained together" (European Committee for Standardization, 2018). While there are standards and testing for retroreflectivity, the current U.S. guidance on pavement marking materials and friction simply states, "Consideration should be given to selecting pavement marking materials that will minimize tripping or loss of traction for road users, including pedestrians, bicyclists, and motorcyclists" (FHWA, 2012).

The AASHTO National Transportation Product Evaluation Program (NTPEP) Project Work Plan for Pavement Marking Materials (PMM) includes a laboratory friction requirement (British Pendulum Test, ASTM E303/AASHTO T 274) for tape markings, but does not include friction testing for the more frequently used paint or thermoplastic materials (NTPEP, 2019). This requirement is only for initial testing for tape, and does not address long-term friction durability. The NTPEP Standard Work Plan for Field Evaluation of Pavement Markings Materials (NTPEP, 2019b) and the AASHTO Standard for Thermoplastic Traffic Line Material (AASHTO T 250) do not include any requirements for friction testing. The field evaluation portion of the NTPEP program includes retroreflectivity and a visible durability component, but not friction.

The Florida Department of Transportation's (FDOT's) standard specifications and design manual require a minimum friction value for patterned pavement pedestrian crosswalks (FDOT, 2021). The patterned pavement (Specification Section 523) uses special materials for overlaying decorative crosswalks and is primarily used or requested by local governments. FDOT requires the use of a locked-wheel skid tester or of the dynamic friction tester (DFT, ASTM E1911) to test the friction of the surface overlay, both as part of installation and regularly afterward, using Florida Test Method FM 5-592. Prior to 2008, Florida used the British Pendulum Test (BPT) value in the test method but discontinued the use of the BPT in 2007 due to issues found with the test in the field. Florida switched to the Dynamic Friction Tester (DFT) to test skid resistance for in-service applications after performing research and finding comparable results for the DFT and the Locked Wheel Test (LWT) test (Holzschuher et al., 2010).

FDOT also has skid-resistance requirements for preformed thermoplastic (Section 971-6) that requires an initial lab test of 55 British Pendulum Number (BPN) for bicycle and pedestrian crosswalk markings and a 35 BPN for other tape-type markings. The Florida specifications for standard hot-placed thermoplastic materials do not have the same friction testing requirements, but they do require the addition of sharp silica sand in bicycle and pedestrian crosswalk markings, which should improve the friction resistance (FDOT, 2019).

Oregon Department of Transportation has a standard detail for pavement markings for crosswalks designed to avoid the wheel paths. This detail, similar to Figure 3-4, is also used in roundabouts (Oregon DOT, 2021). Minnesota Department of Transportation has something somewhat similar in their Pavement Marking Typical Detail for Crosswalks.

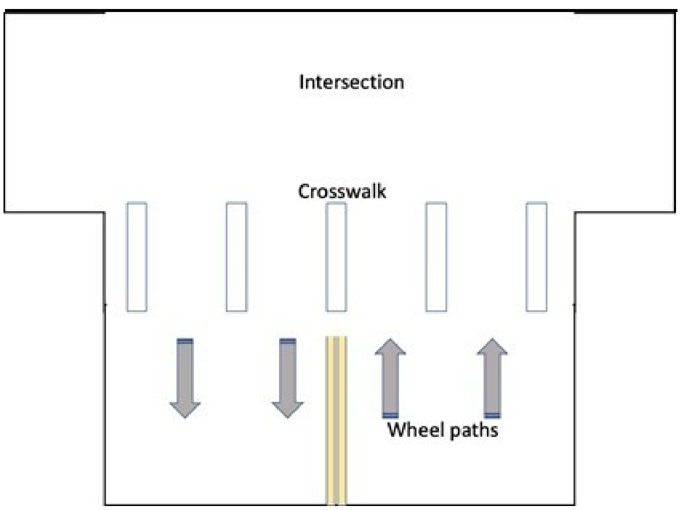


Figure 3.4 Staggered crosswalk detail

The current *AASHTO Guide for Pavement Friction* does not address friction differentials, or any other motorcycle considerations (AASHTO, 2008), but the current task force revising the manual is considering additional language to specifically address motorcycles.

3.4 Survey Results

In this task, the research group also conducted a survey on the impact of pavement markings and colored pavements on the safety of cyclists, motorcyclists, and joggers/pedestrians. The survey consisted of three sets of questions, one for each category of users. The questions were designed to collect information on user experience of the difference in friction between pavement markings/colored pavements and regular pavement in various weather conditions. The survey was sent out in March 2022 to the University of Minnesota's Civil, Environmental, and Geo-Engineering (CEGE) students and faculty, various local bicyclist and motorcyclist groups, and various transportation and engineering organizations. Google Forms was used to collect and analyze the information received. The software was chosen because it was accessible and user friendly and provided the proper tools for question creation and response analysis. The survey questions are shown in Appendix A. Overall, 223 individual responses were collected. Detailed summaries of the responses for each question set are presented in the following section.

3.4.1 Demographics

Information was collected from the following groups:

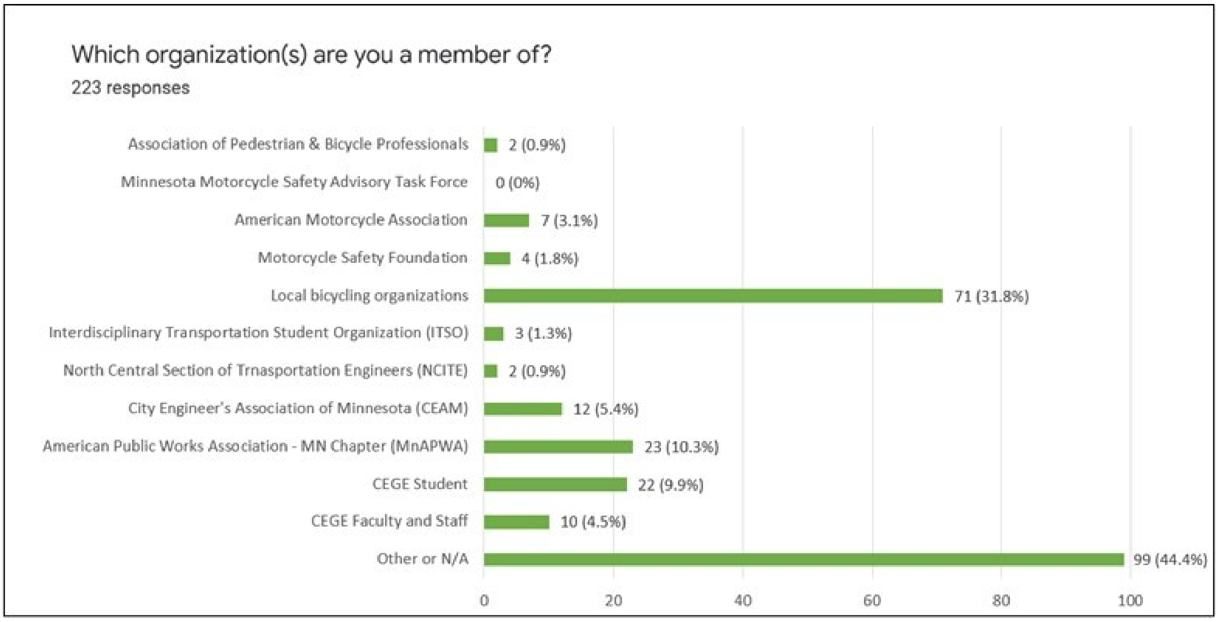


Figure 3.5 Organization distribution of survey responses

There were 173 respondents to the bicyclist question set of the 223 total responses. The distribution is as shown:

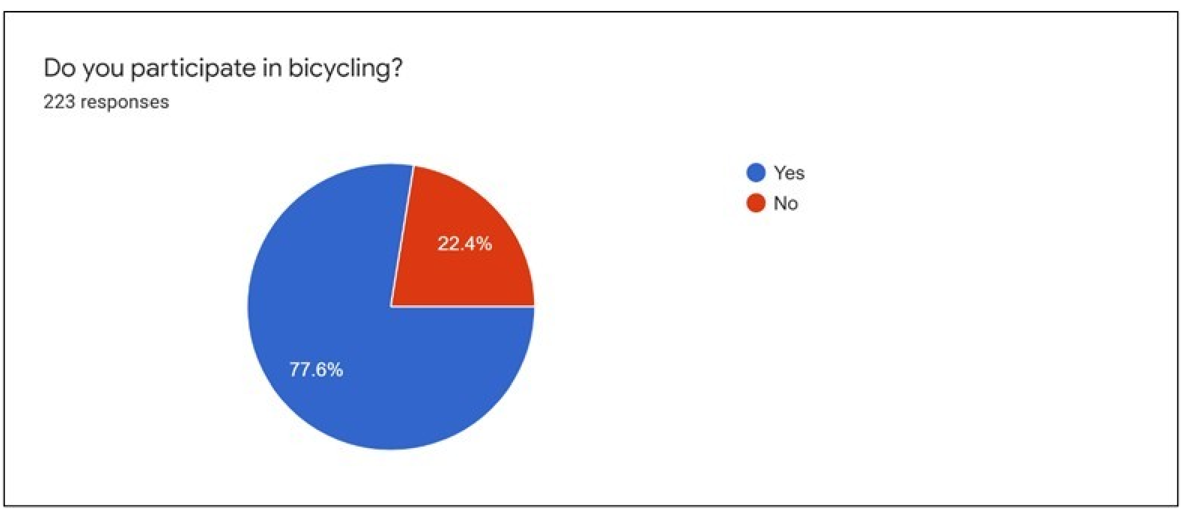


Figure 3.6 Response distribution for the bicyclist question set

There were 57 respondents to the motorcyclist question set of the 223 total responses. The distribution is as shown:

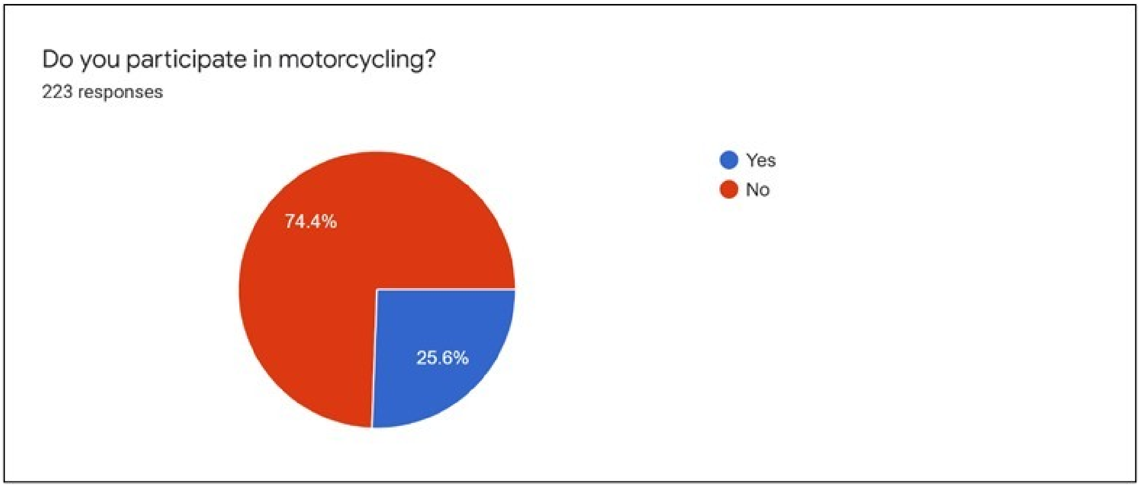


Figure 3.7 Response distribution for motorcycling question set.

There were 135 respondents to the pedestrian question set of the 223 total responses. The distribution is as shown:

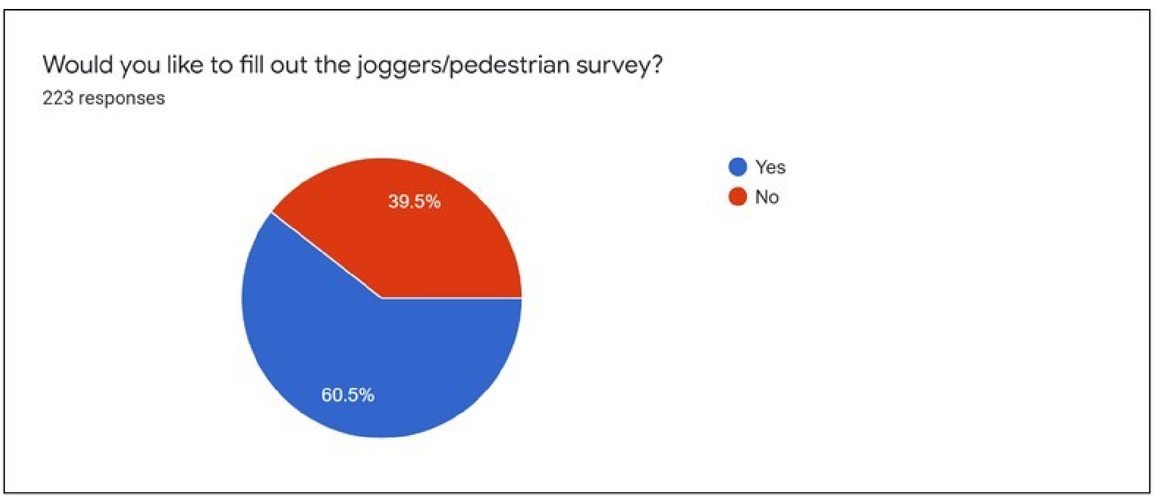


Figure 3.8 Response distribution for the pedestrian question set

3.4.2 Bicyclist Question Set

It was important to obtain the information on frequency and weather conditions that the users participated in biking. It was also important to establish the road surface conditions and road types that the bicyclists used. The biking frequency distribution can be shown in the following figure:

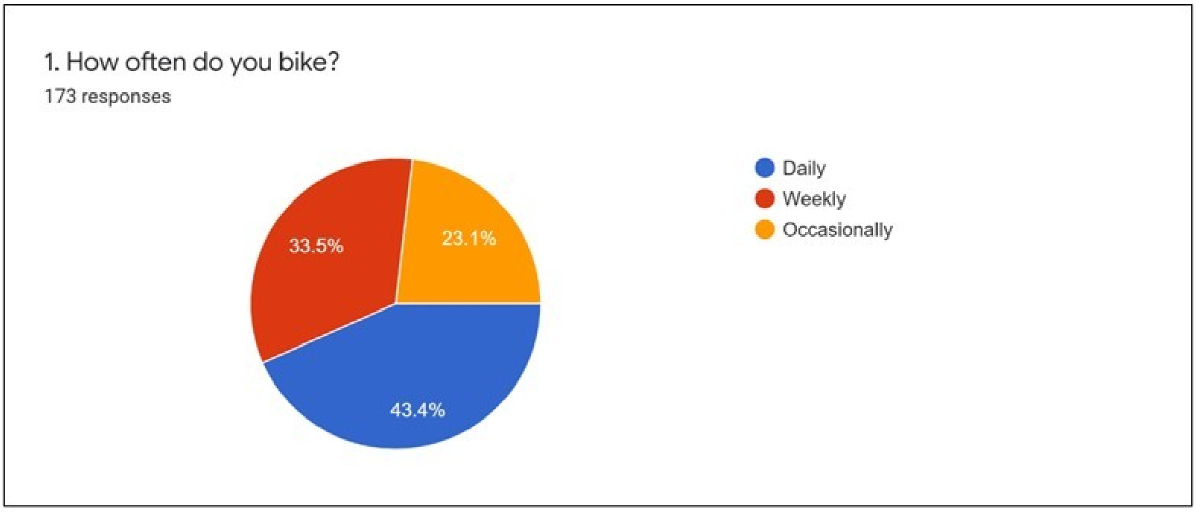


Figure 3.9 Responses results for frequency of biking

The distribution of responses for temperature conditions is shown below:

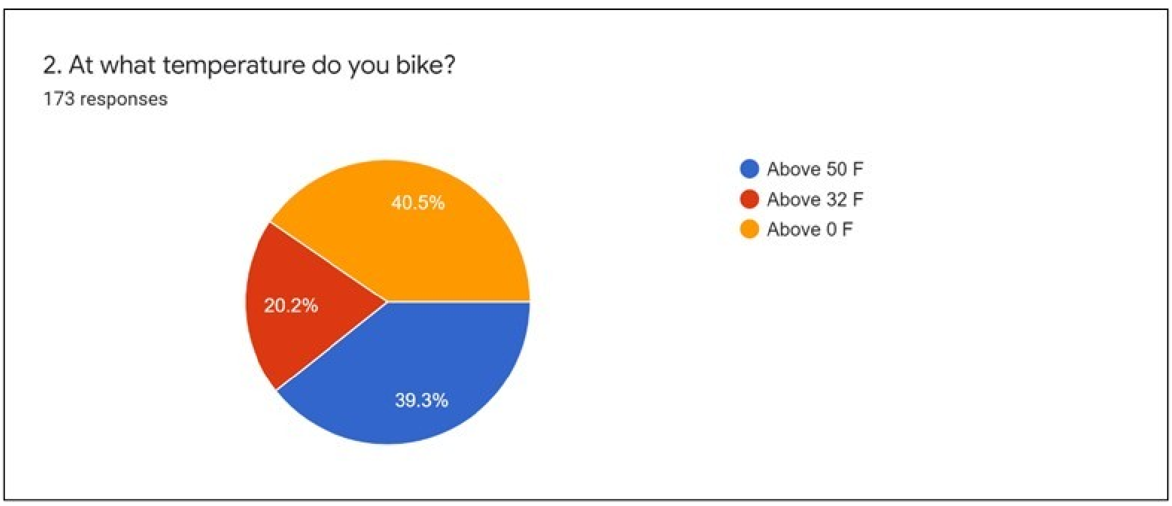


Figure 3.10 Response results for temperature at which users participate in biking

The distribution of responses of what surface conditions bicyclists use is shown below:

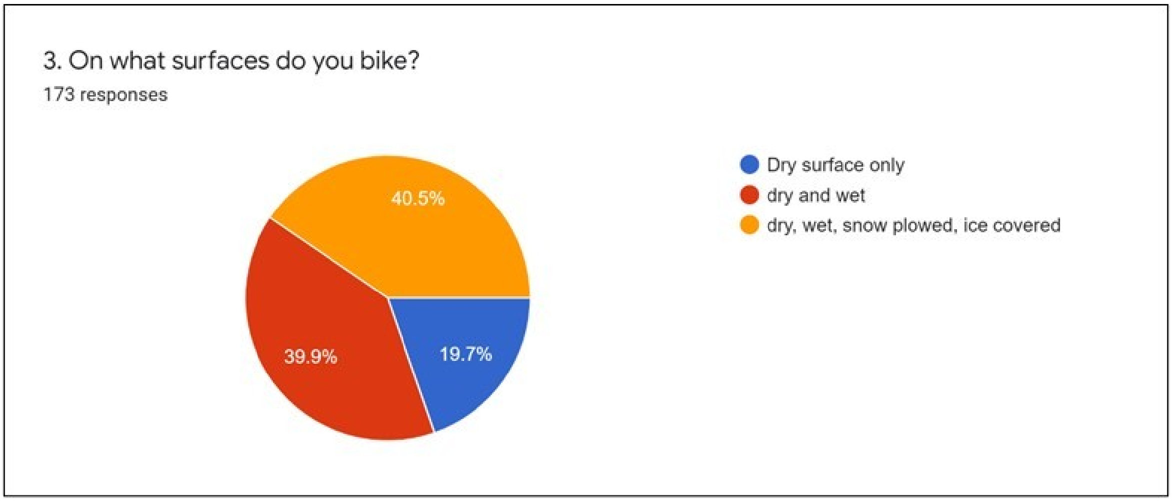


Figure 3.11 Response results for surface conditions that users bike on

The results for road types used by bicyclists are shown below. There was a lower number of users using colored lanes, compared to other road types which could relate to the lack of colored lanes in some areas.

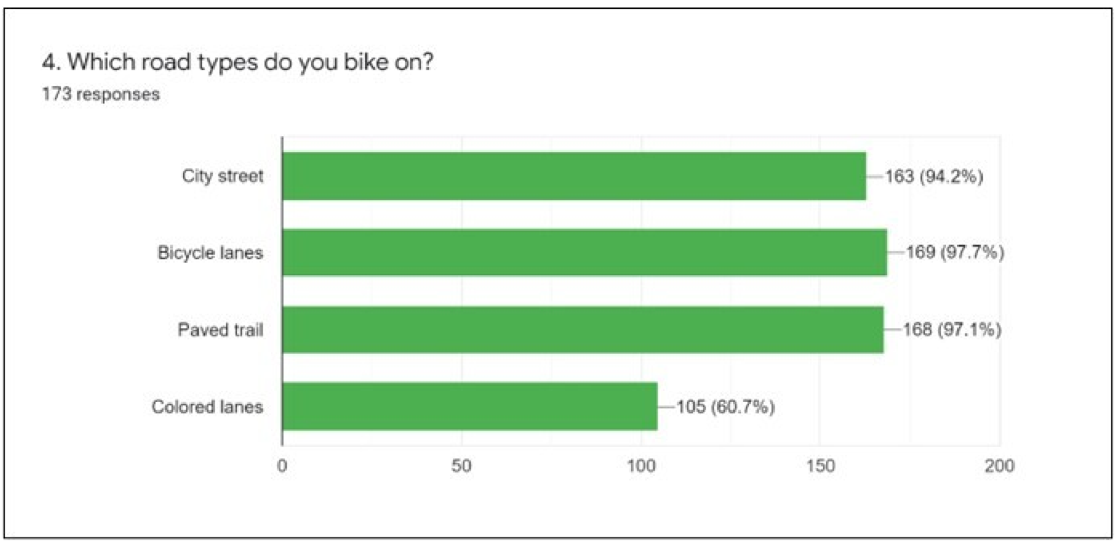


Figure 3.12 Response results for road types that the users bike on

The users were also asked to comment on any changes they noticed when transitioning from bare pavement surface to pavement markings or colored lanes. Users were asked to comment on changes during cruising, accelerating, braking, and while riding on colored lanes. While cruising, accelerating, and riding on colored lanes, most users said that there were no changes in friction. While braking, there was a considerable number of users that said there were changes in friction in wet conditions. The results are shown in the following figure:

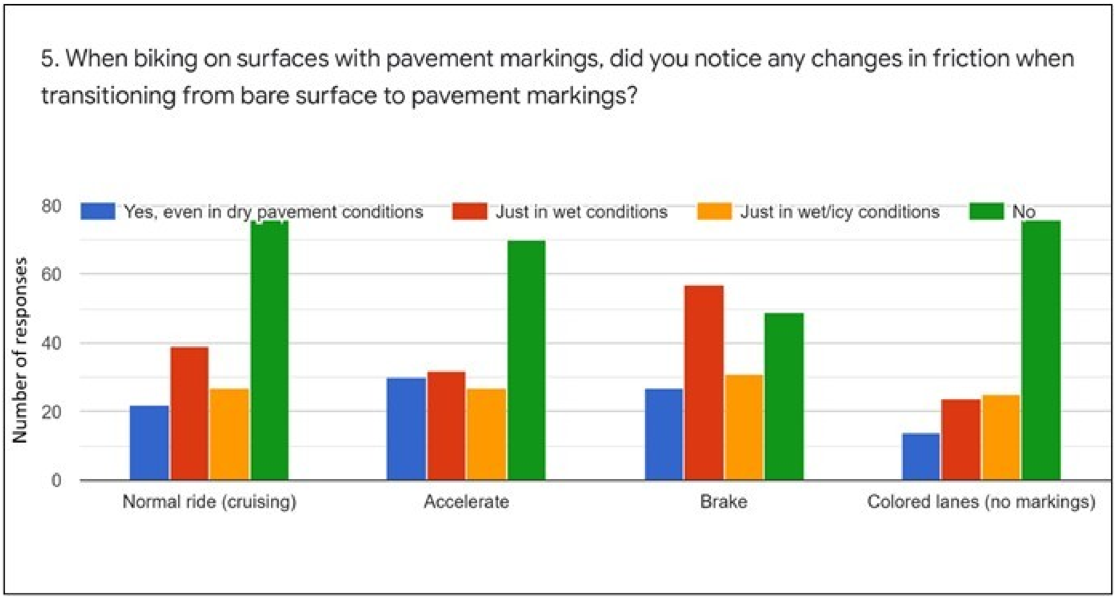


Figure 3.13 Response results on whether users noticed any changes in friction of pavement markings while cruising, accelerating, braking, and riding on colored lanes

The users were also asked to whether they or someone else they saw slipped on surfaces with pavement markings. Responses primarily mentioned painted markings during icy or wet conditions, especially while turning or braking. The individual responses to the question can be found in Appendix B.

The users were asked to provide any feedback on how to improve biking safety related to pavement markings or colored lanes. Most responses mentioned increasing roughness of the markings and increasing signage and separate infrastructure for pedestrians and bicyclists separate from other vehicles. The individual responses to the question can be found in Appendix B.

3.4.3 Motorcyclist question set

It was also important to obtain the information on frequency and weather conditions that the users participated in motorcycling. It was also important to establish the road surface conditions and road types that the motorcyclists used. For more information, the users were also asked what type of motorcycle they used most often. The motorcycling frequency distribution can be shown in the following figure:

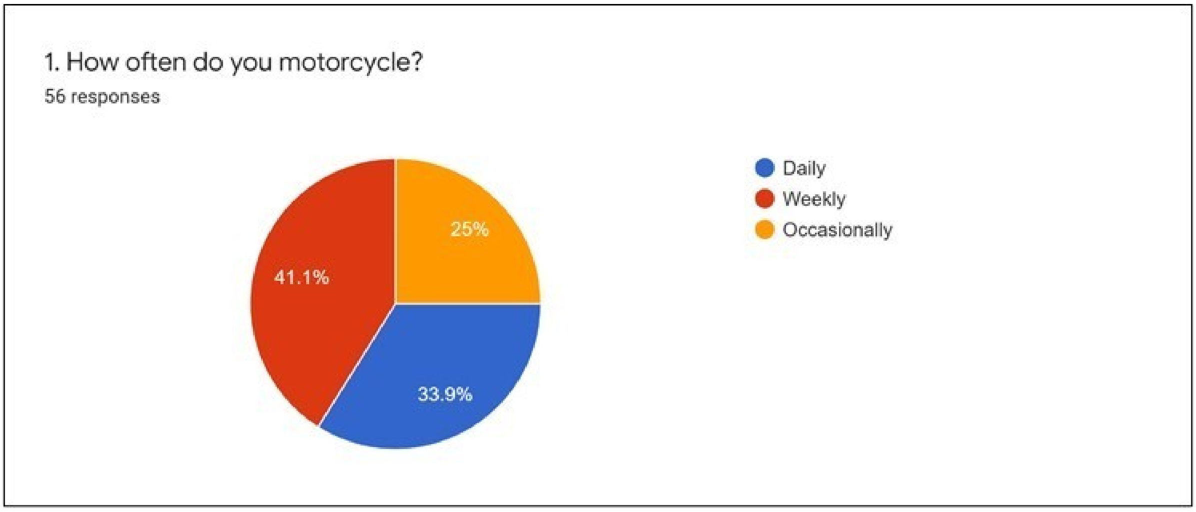


Figure 3.14 Response results on frequency of motorcycling

Temperature ranges surveyed for motorcyclists were higher than for bicyclists based on feedback from local motorcycling groups. The distribution of responses for temperature conditions is shown below:

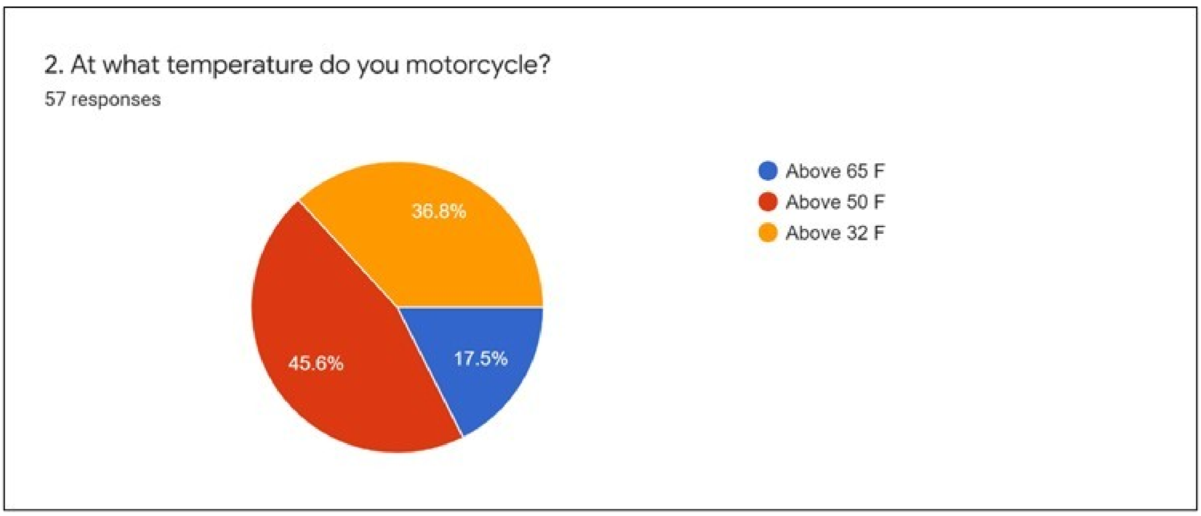


Figure 3.15 Response results on temperature at which the users motorcycle

The distribution of responses of what surface conditions motorcyclists use is shown below:

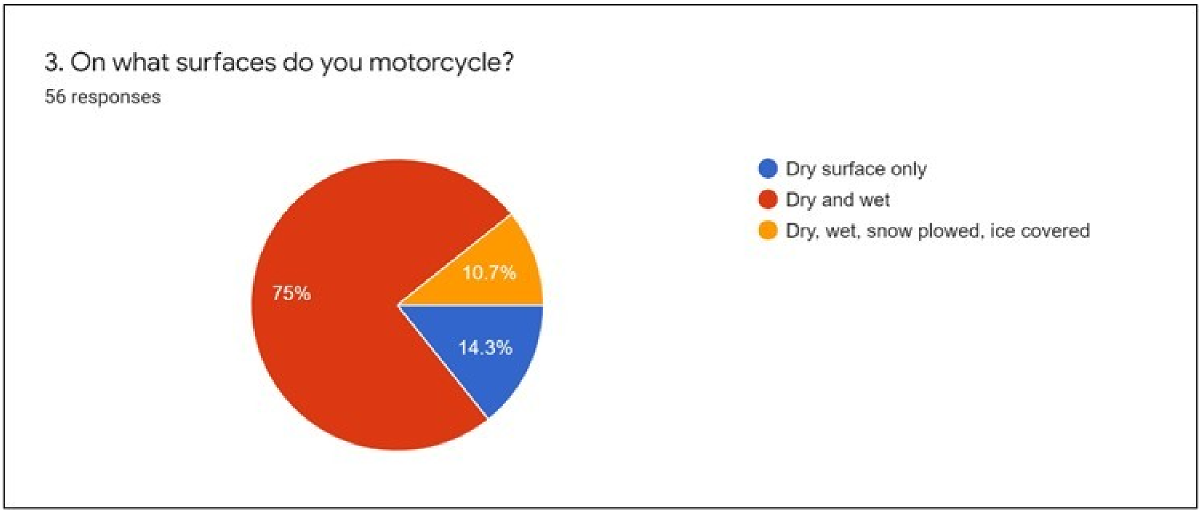


Figure 3.16 Response results, on what surfaces do motorcyclists drive?

The results for road types used by motorcyclists are shown below:

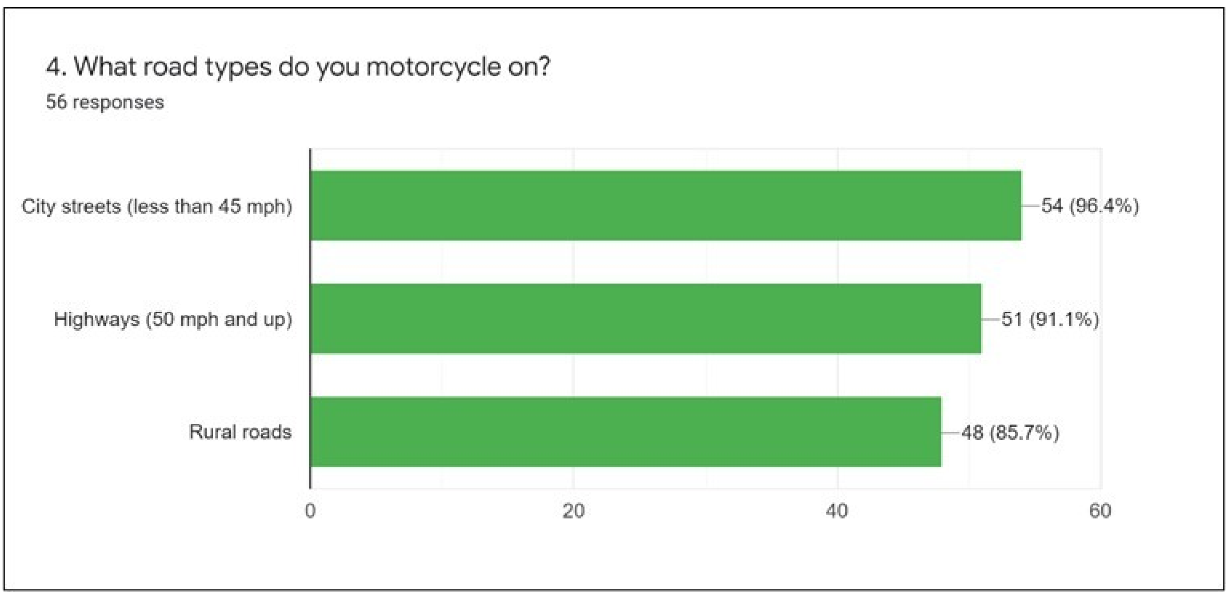


Figure 3.17 Response results for what road types motorcyclists use

The types of motorcycles used by users is shown in the figure below. Please note that multiple choices were accepted as answer.:

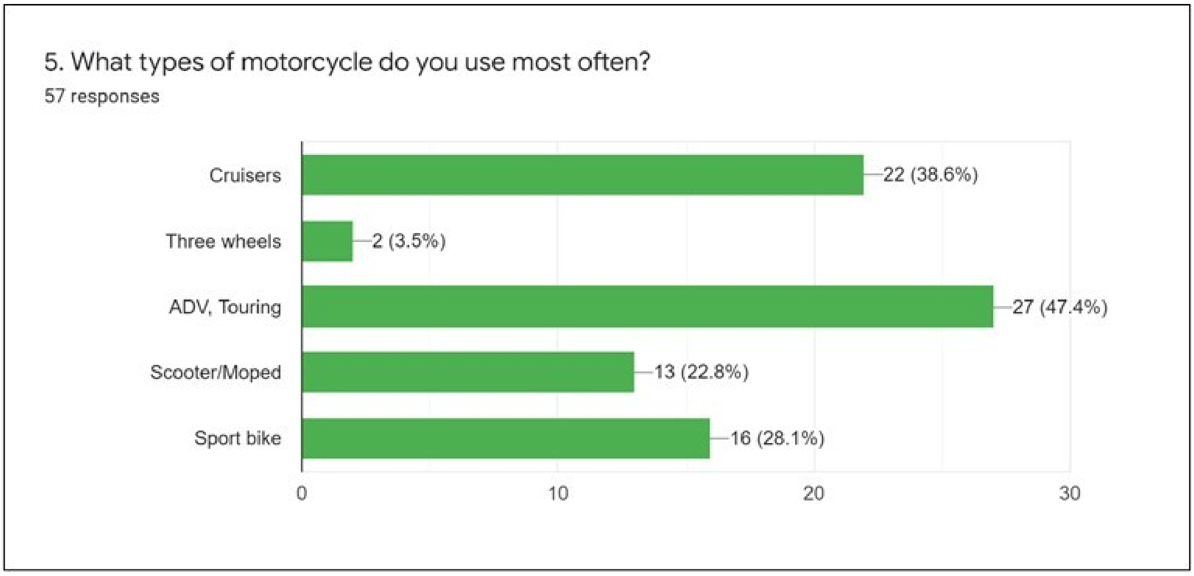


Figure 3.18 Response results for the types of motorcycles that users most commonly use

The users were also asked to comment on any changes they noticed when transitioning from bare pavement surface to pavement markings during cruising, accelerating, braking, and in a roundabout. The results are shown in the following figure:

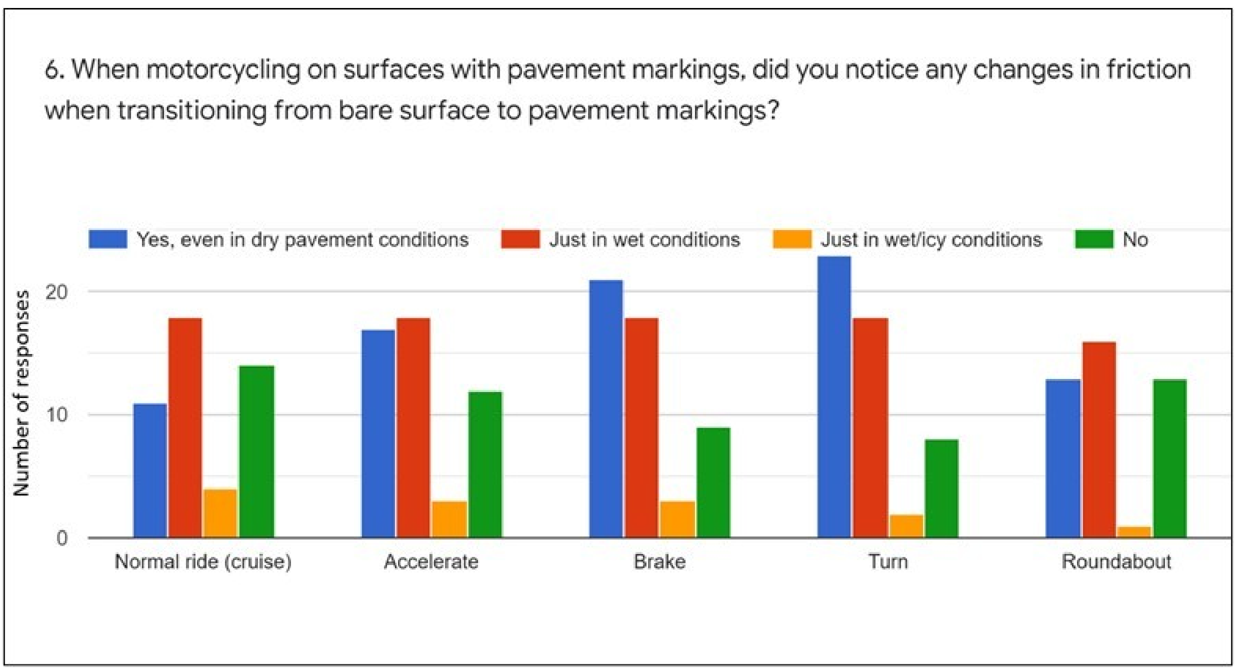


Figure 3.19 Response results on whether users noticed any changes in friction of pavement markings while cruising, accelerating, braking, turning, or driving in a roundabout

The users were also asked to comment on whether they themselves have slipped or seen someone else slipped on surfaces with pavement markings, and comment on the types of pavement markings that had changes in friction. Most users mentioned that lane markings, markings at intersections, and crosswalk markings were the most prone to cause slipping. Specific types that caused the most slipping were smooth and painted markings. The results are shown in the following figures:

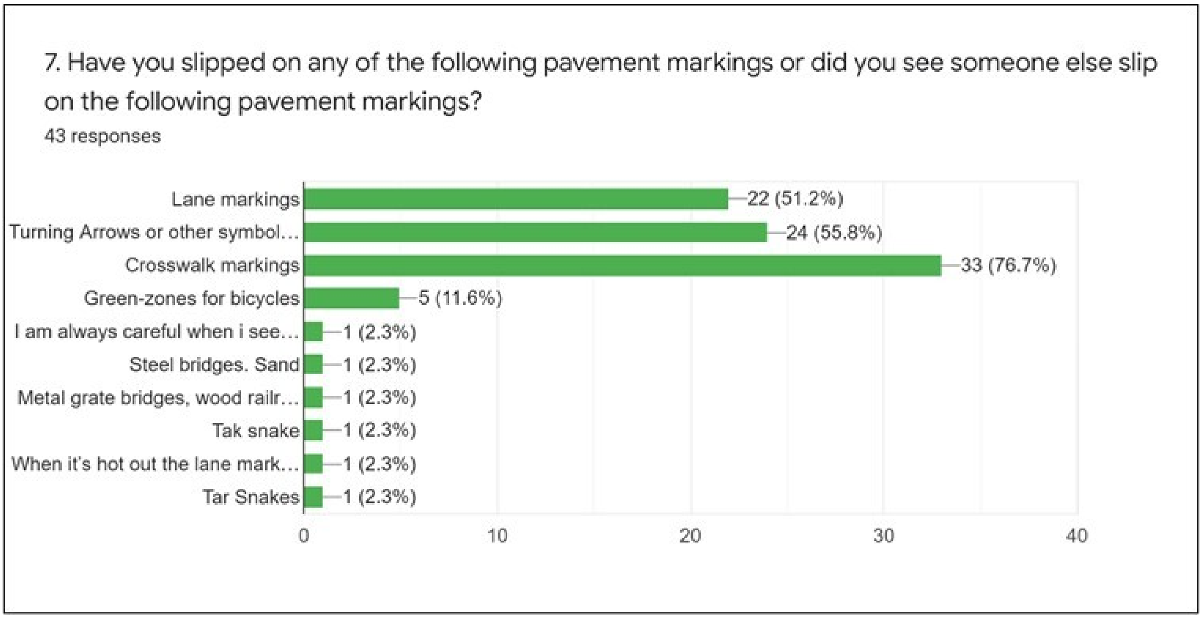


Figure 3.20 Response results on whether users slipped on any pavement markings or whether they saw someone else slip on any pavement markings

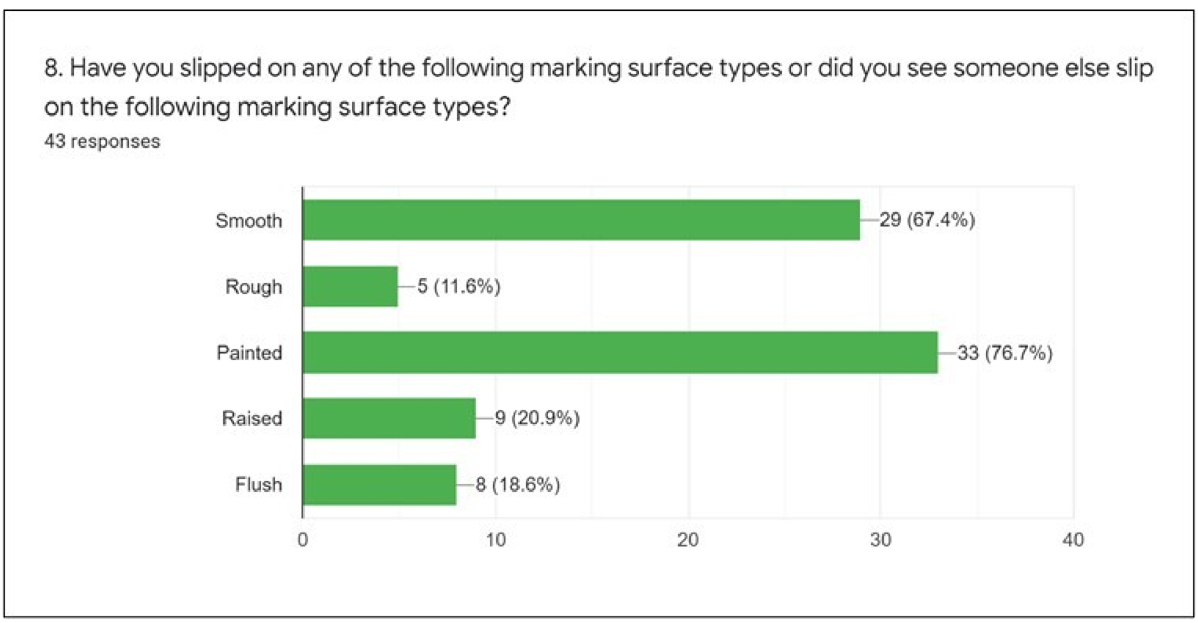


Figure 3.21 Response results on the types of marking surfaces that users slipped on or saw someone else slip on

The users were asked to provide any feedback on how to improve motorcycling safety related to pavement. Many responses mentioned using some sort of textured material for pavement markings. The individual responses to the question can be found in Appendix B.

3.4.4 Pedestrian question set

Like biking and motorcycling, the survey asked for information regarding weather and road conditions that pedestrians most walked or jogged on. The frequency of pedestrians walking/jogging is shown below:

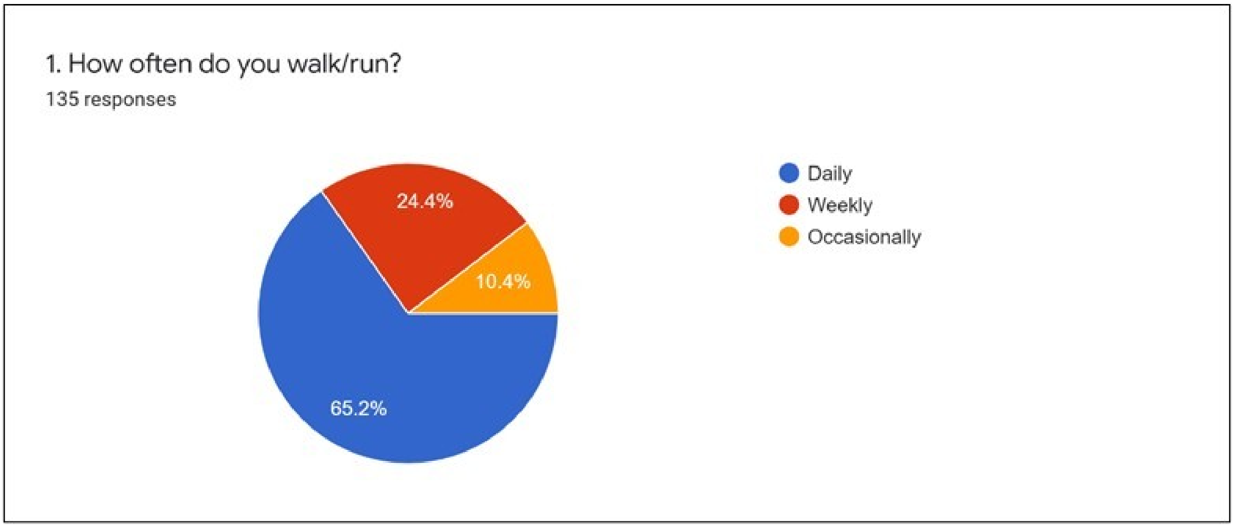


Figure 3.22 Response results on the frequency of pedestrians walking/jogging

The temperature distribution at which pedestrians walked/jogged is shown below:

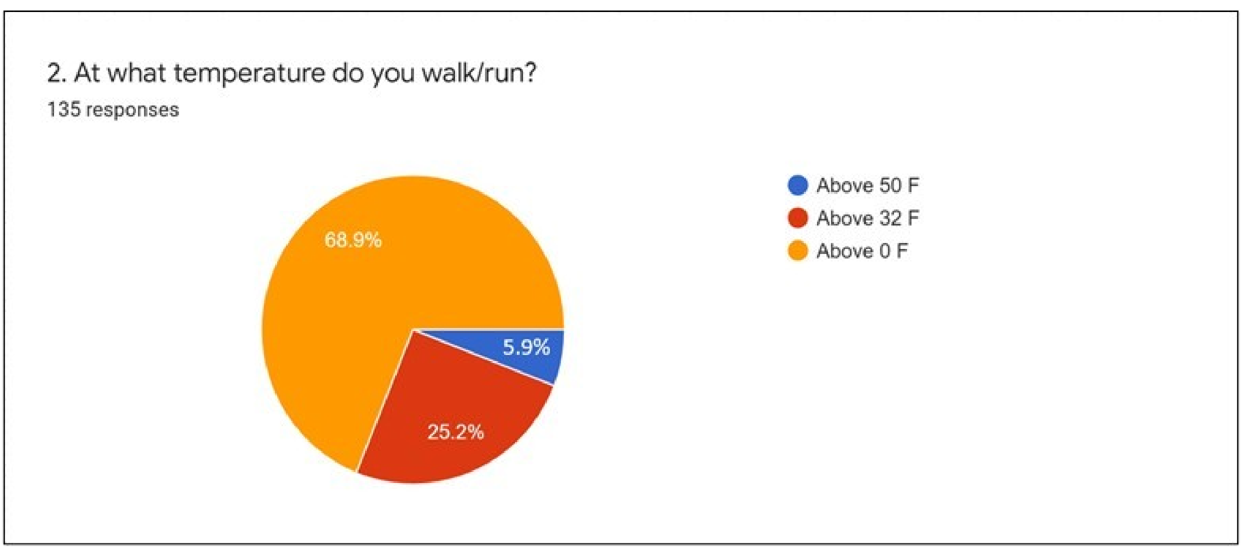


Figure 3.23 Response results of temperatures at which pedestrians walk/run

The road conditions at which pedestrians walked/jogged is shown below:

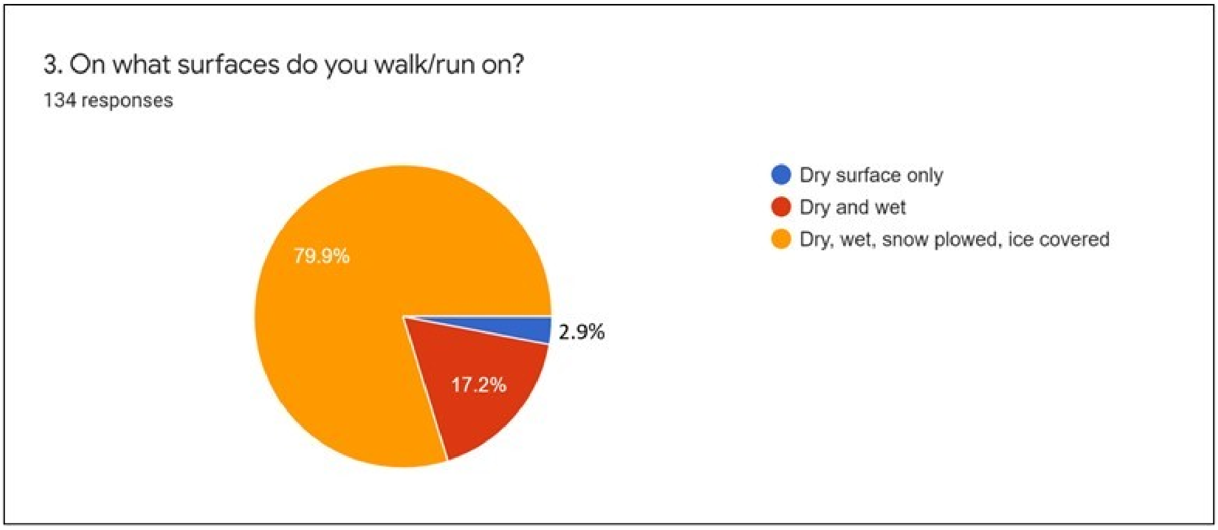


Figure 3.24 Response results of what surfaces pedestrians use

The pedestrians were also asked to comment on whether they themselves or someone else they saw slipped on any pavement markings and any feedback they have for improving pedestrian safety regarding pavement markings. Many users mentioned that crosswalk markings and bare pavement surfaces were slippery in icy or wet conditions. Individual responses to both questions can be found in Appendix B.

Chapter 4: Preliminary testing of pavement markings and colored lanes products and review of current certification standards in Scandinavian countries

4.1 Introduction

In this task, preliminary experiments were performed to determine the friction properties of pavement surfaces and pavement marking products and colored pavement. Three different types of equipment were used, with the goal of comparing the results to determine if a less expensive piece of equipment can be used for routine investigations.

In addition, a comprehensive review of the current approach used in Scandinavian countries for selecting pavement marking products was performed, including a description of the Nordic certification of road marking materials program called NordicCert. This information could provide preliminary guidelines for developing a similar program in Minnesota.

4.2 Preliminary testing

Adequate skid resistance of pavement surfaces is a requirement for the safety of users. The mechanisms involved in tire-pavement friction are hysteresis and adhesion. Pavement friction is affected by macro- and micro-texture of the surface, and it plays direct roles in dry and wet condition crash risks (Merritt 2015). Pavement friction is a complex problem that has been investigated using empirical relationships and field data.

Many different types of friction testing devices are currently used to measure surface friction (Fwa 2021). In this preliminary work, the research team used three types of equipment, ranging from the more expensive dynamic friction tester, for which the speed the test is performed can be controlled, to the less expensive British pendulum tester, which allows testing only at one very low speed. The goal is to compare the results to determine if a less expensive piece of equipment can be used for routine investigations.

4.3 Testing equipment

The research team performed friction tests using three commonly used devices that are portable and require minimal traffic control.

The British Pendulum device is the least expensive, and it is performed at a very low speed, which is more representative of the skid resistance experienced by pedestrians and bicycles.

The Dynamic Friction Tester (DFT) has been used for many decades to determine the skid resistance of pavement surfaces. It allows measurements at different speeds, similar to the standard method that uses a locked wheel mechanism to determine the skid number (SN).

A newer device, the Sarsys-ASFT T2Go friction tester, was also used since it was advertised as a device that can measure friction on both dry and contaminated surfaces and has been used to investigate the friction properties on sidewalks and road markings (EN1436).

Figure 4.1 British pendulum tester

Figure 4.2 Dynamic friction tester

Figure 4.3 Sarsys-ASFT T2Go friction tester

4.3.1 British pendulum tester

The British Pendulum Tester (BPT) (ASTM E303-33, "Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester") is the most widely used low-speed skid resistance testing device. The BPT is used for spot measurements of low-speed skid resistance and can be used to measure surface frictional properties at a relatively low cost. It is also portable and easy to operate.

The device consists of an impact pendulum with a standard rubber slider, which is used to determine the frictional properties of the test surface. The test surface is prepared to be free of lose particles and then is flushed with water to ensure the presence of a film of water at the surface. The pendulum slider is released from a locked position and contacts a specific length of the test surface.

A pendulum test value (PTV) or British pendulum number (BPN) is obtained from the device after five swings of the pendulum. The larger the friction between the slider and the test surface, the more the swing is delayed, corresponding to a larger PTV or BPN. Studies have shown, using three-dimensional finite-element method modeling, that there is a mechanistic relationship between a coefficient of friction and the BPN (Chu et al. 2020). A table developed by Sotter (2022) can be used to convert the PTV to a coefficient of friction. It is important to record the test surface temperature, type, age, condition, texture, and location. The simplicity of this device only allows measurements of friction at very low speeds. The BPT has spatial limitations as it makes spot measurements of a small surface of about 3.5 inches by 6 inches. The test can be performed in multiple directions, both transverse and longitudinal to the traffic direction.

4.3.2 Dynamic friction tester

The Dynamic Friction Tester (ASTM E1911-09, "Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester") is a widely used spot skid resistance testing device, which measures the frictional properties of a test surface as a function of speed. The device utilizes a spinning flywheel with a user-set rotational velocity. There are three rubber sliders on the flywheel. Once the desired velocity is set, water is introduced in front of the sliders, and the spinning flywheel is lowered until the rubber sliders are in contact with the test surface. Torque is continuously monitored until the flywheel stops rotating. The device provides the friction value as a force on sliders divided by weight of the flywheel assembly. Three measurements are performed at various locations on the test surface. Temperature, type, age, condition, and location of the test surface are recorded, along with the measured DFT numbers. This device is portable; however, it is significantly more expensive than the BPT, and although it is portable, it is not as easy to operate. This device is also used at low speeds and measures a testing area of about 20 inches by 20 inches. According to the ASTM standard and the DFT manual, the test is performed on a wet surface. However, tests can be also performed on a dry surface, if needed.

4.3.3 T2Go

The T2Go testing device was developed by SARSYS-ASFT (https://www.sarsys-asft.com/t2go). The device is simple to use and can measure friction on both dry and contaminated surfaces. The device is a slow-moving wheeled tester that provides continuous measurements of friction coefficient for around 30 to 50 feet. This device utilizes two rubber tires connected by a belt which is in contact with a load sensor. The load sensor can measure the frictional resistance from the road on the tires. An onboard computer is able to connect to a personal digital assistant (PDA) or a laptop via Bluetooth to measure additional data including GPS position, temperature, date, time, road name, and total Mu-number. The Mu-number or value is defined as follows in the equipment manual: ""A surface should have a mean friction (Mu-value) on any section of minimum 0.5." This device is very portable and able to be used in areas that are difficult to access with larger equipment or vehicle type friction testers. A study by Yun et al. (2020) used the T2GO to measure the skid resistance of asphalt concrete pavement and related the results to the real contact area between vehicle tire and road. A study by Kanafi et al. (2014) performed spectral analysis of the macro- and micro-scale changes in surface texture and used the T2Go device to correlate the contribution of texture and temperature to friction evolution of asphalt pavements. Hossain et al. (2014) used the T2Go device for measurements of friction in field tests to determine what factors affect snow-melting performance and de-icing performance of road salt.

4.4 Test data

Due to the limited availability of traffic control for the test section initially recommended by TAP members, only a very limited number of preliminary tests were carried out. A more comprehensive investigation will be performed as part of task 4B, in which a number of experimental test sections at MnROAD facility will be used.

4.4.1 Friction tests on campus

Friction tests were performed on an epoxy pavement marking on the University of Minnesota campus, which is located at the intersection of Church St SE and Washington Ave SE, as shown in Figure 4.4. Three types of friction tests were performed, i.e., the Dynamic Friction Tester (DFT), British Pendulum (BP), and T2Go.

Figure 4.4 Location of the pavement marking

DFT tests were performed on both the epoxy marking and the concrete pavement near the marking. The locations and the testing conditions (dry or wet) of the ten tests are shown in Figure 4.5.

Notes:

- Test 1 and 2 were in dry condition, while the others were in wet condition.
- Test 1, 4, 9 and 10 were done on concrete pavement, while the others were done on marking.
- Test 2, 3, 5, 6, 7 were done on the green marking, while Test 8 was done on white marking.

Figure 4.5 Locations and test conditions of the DFT tests

In Figure 4.6 the DFT results on dry and wet conditions are shown for both the bare pavement and the marking. As expected, for both concrete pavement and the marking, the friction coefficient of the dry condition is clearly higher than that of the wet condition.

In Figure 4.7, the DFT results of concrete pavement and pavement marking are compared. As shown in Figure 4.7(a), at dry condition, the concrete pavement has higher friction coefficient than the marking. However, for wet condition, as shown in Figure 4.7(b), the marking has higher friction coefficient than concrete pavement at low sliding speed, while at high sliding speed, the friction coefficient of marking becomes lower than that of the concrete pavement. This observation implies that there might be two different mechanisms for friction at low and high sliding speeds, and the effect of surface water on these mechanisms might differ for concrete pavement and pavement marking.

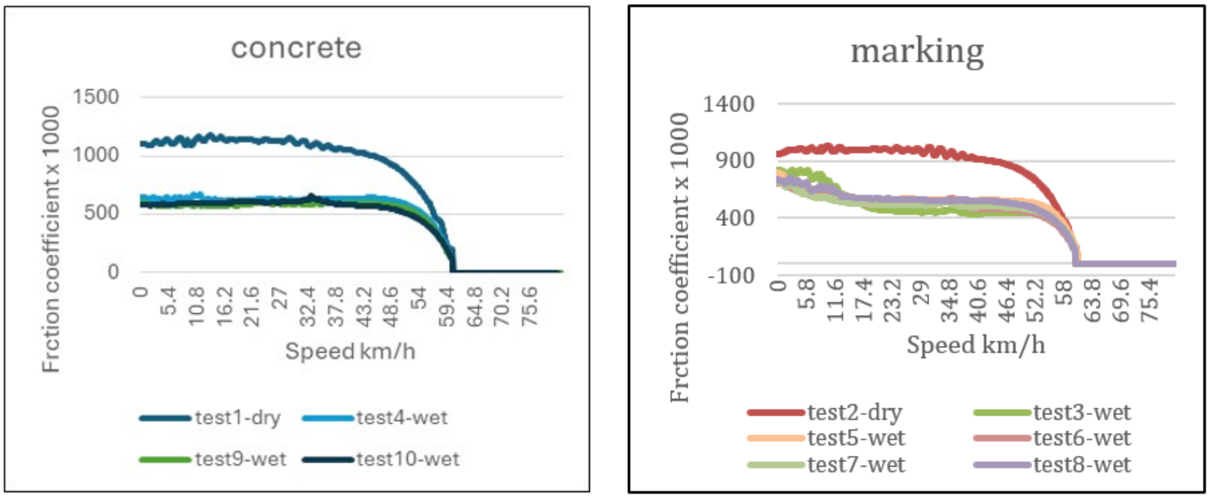


Figure 4.6 DFT results (a) concrete, (b) marking

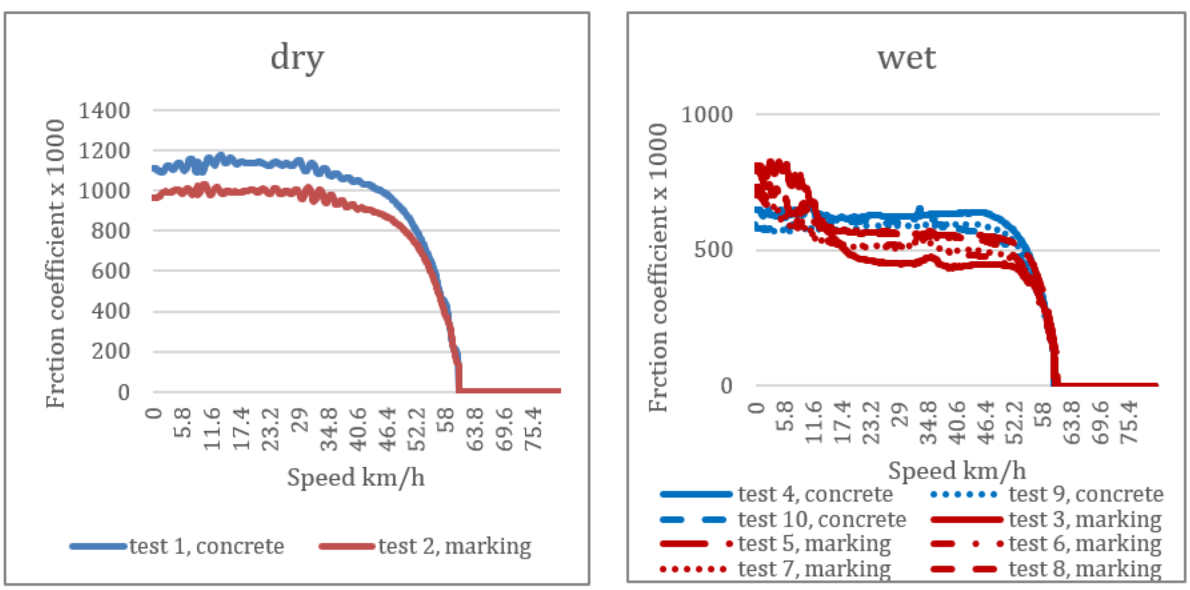


Figure 4.7 DFT test results (a) dry, (b) wet

Moreover, it is seen that the sliding speed vs. friction coefficient curves for the epoxy marking at wet condition have a unique shape compared to other curves. Specifically, there is a decrease in the friction coefficient at the beginning of these curves (low sliding speed region).

BP tests were performed at three locations, shown in Figure 4.8. One was on the concrete pavement, and two were on the marking. All tests were performed in the wet surface condition.

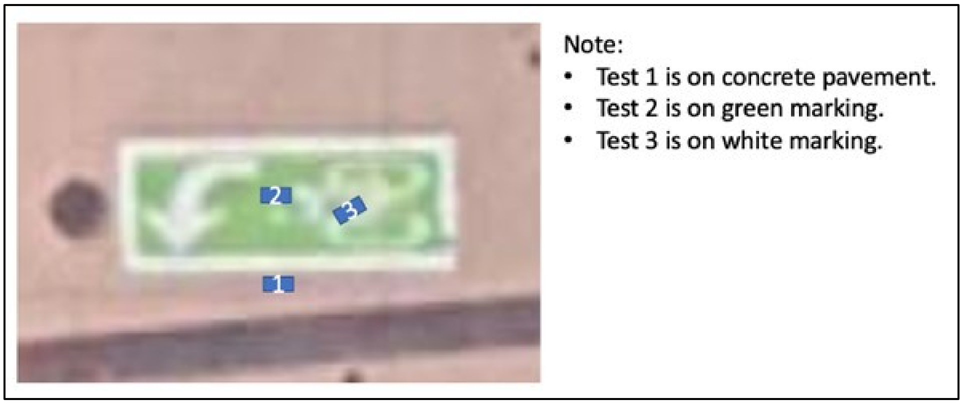


Figure 4.8 Locations of the British pendulum tests

The test results are shown in Figure 4.9. It can be seen that in wet surface condition, the friction coefficient of epoxy marking is higher than that of the concrete pavement. This result is consistent with the DFT result at low sliding speed.

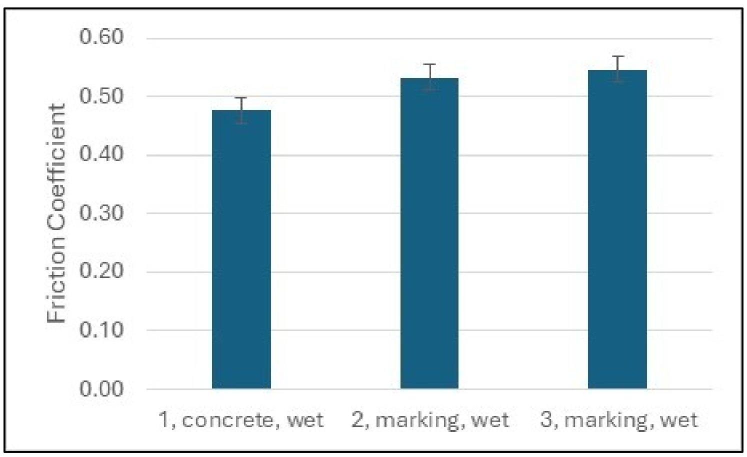


Figure 4.9 British pendulum test results

T2go tests were performed on both the concrete pavement and the epoxy marking, and in both dry and wet conditions. Figure 4.10 shows the test locations.

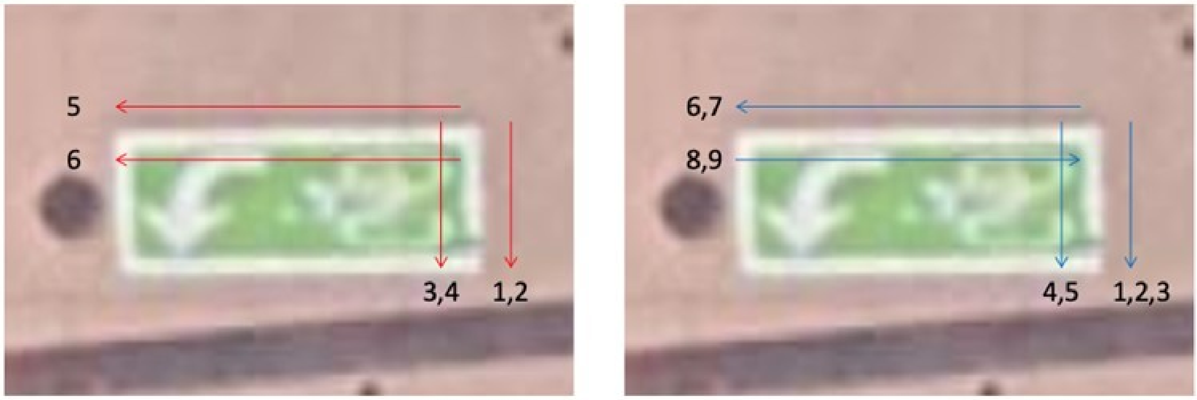


Figure 4.10 Locations of the T2Go tests (a) dry condition, (b) wet condition

The test results are plotted in Figure 4.11 and show that concrete pavement has higher friction coefficient than the epoxy marking in both dry and wet conditions. This result is consistent with the DFT results at high sliding speed, and is inconsistent with the BP results.

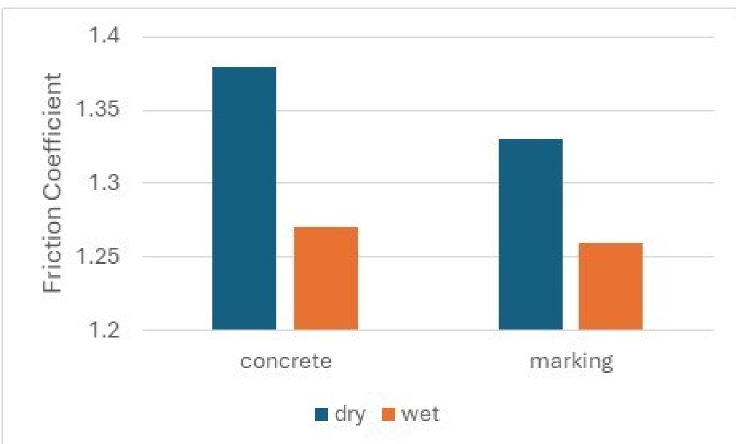


Figure 4.11 T2Go test results

The magnitude of the friction coefficients obtained from the T2Go device are unreasonably higher than that of the two other devices, which indicates that our T2Go device may have a systematic bias. Additional measurements on other surfaces indicated inconsistent values for the measurements performed with this device, and as a consequence, its further use was abandoned.

4.5 Friction tests in Duluth

In a different current research project "Taconite as a lower cost alternative High Friction Surface Treatment to Calcined Bauxite for low volume roads in Minnesota", the research team performed friction tests on six test sections near Duluth. The locations of the test sections are shown in Figure 4.12. Both the DFT and BP devices were used. In addition, the standard Locked-Wheel Pavement Friction Test (ASTM E274, 2020), used by MnDOT to determine skid resistance, was performed.

The results, presented in Figures 4.13 to 4.16, show that the three test methods are generally consistent with each other. DFT is advantageous for its convenience and the reliability of its measurements. The locked-wheel tester is less economical compared with the other two tests, while the British Pendulum is less reliable compared with the other two tests, since it gives a spot measurement that can be impacted by localized surface inconsistencies.

Figure 4.12 Locations of the test sections at Duluth

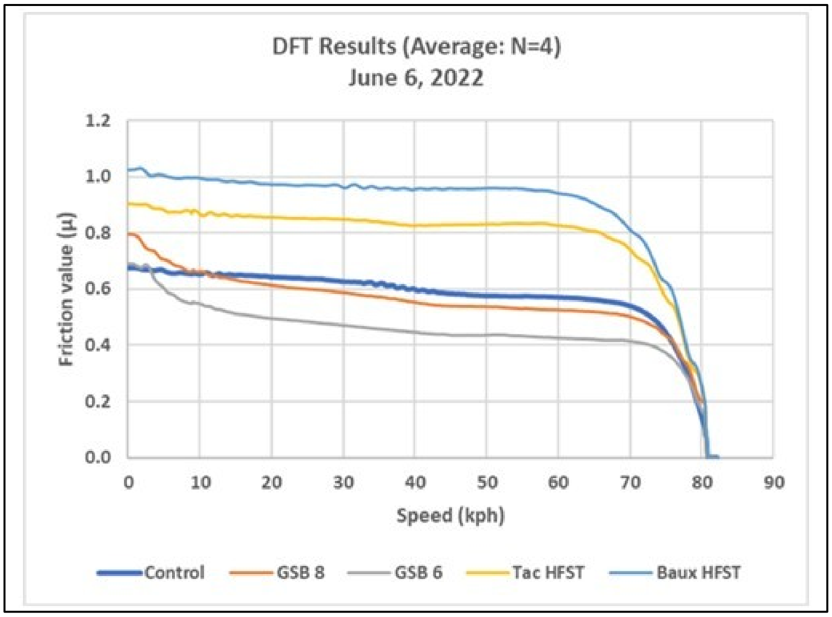


Figure 4.13 DFT test results of the six test sections

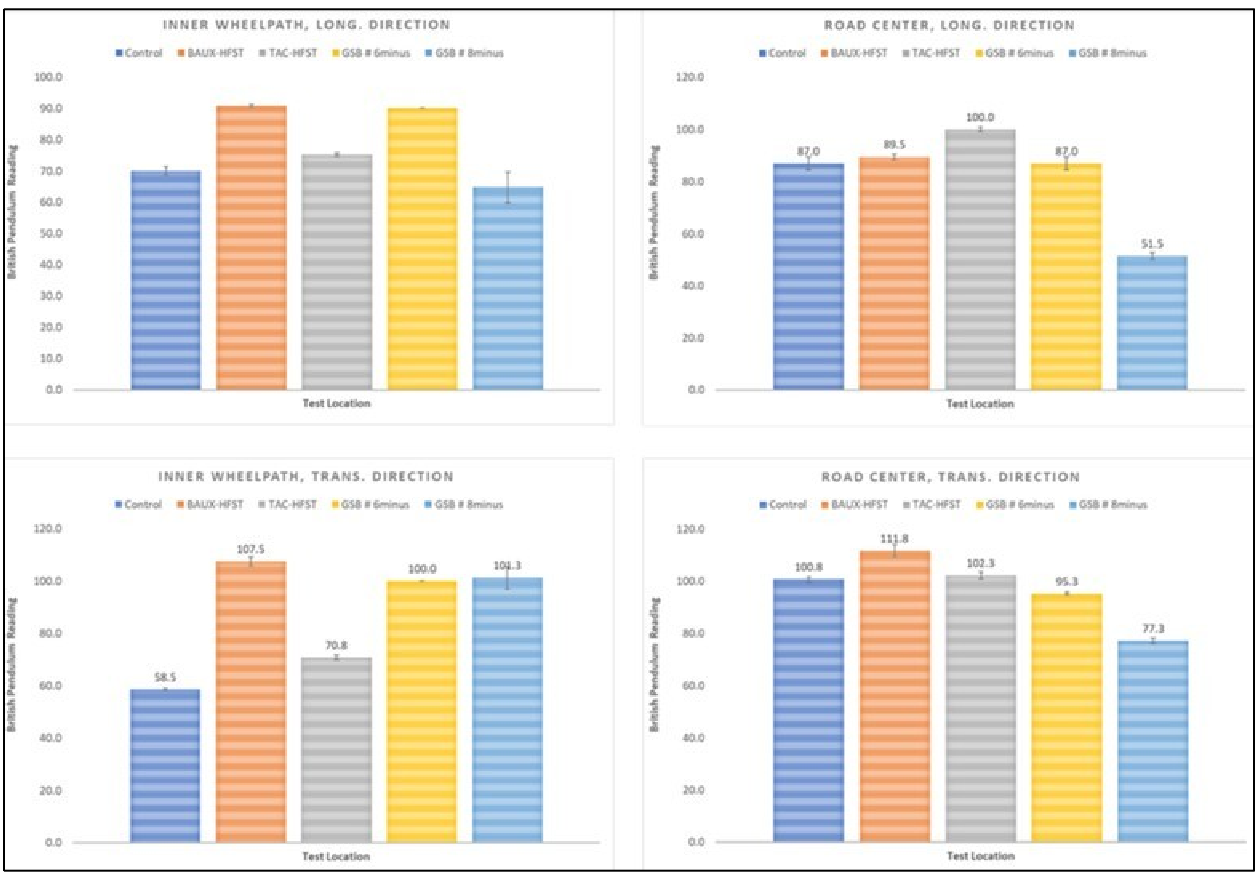


Figure 4.14 BP test results of the six test sections

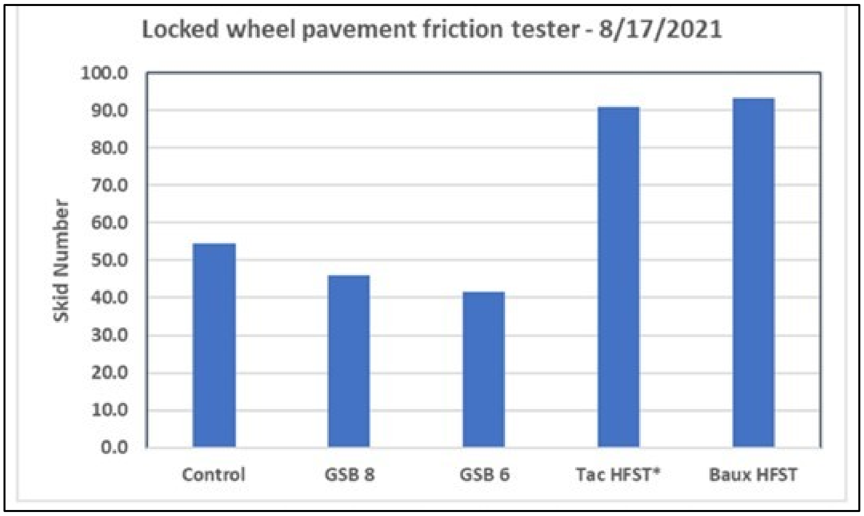


Figure 4.15 Locked-wheel tester results of the six test sections

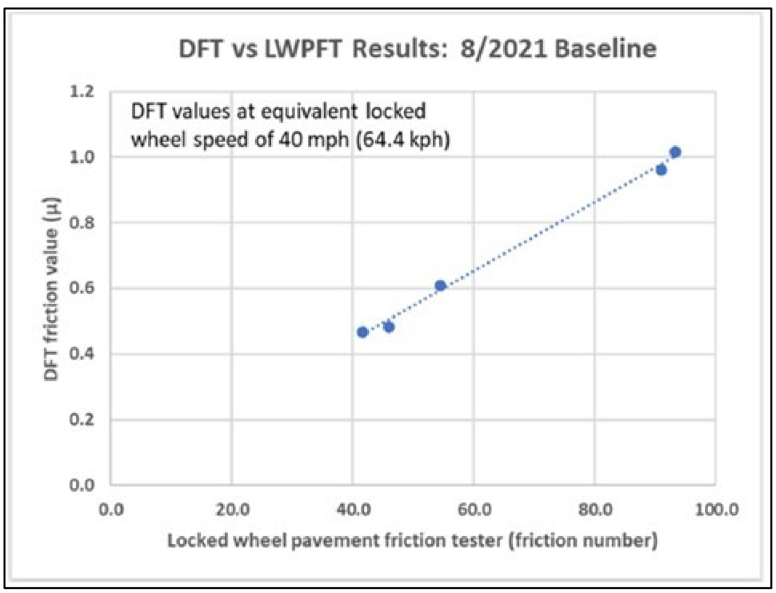


Figure 4.16 Correlation between the Locked-wheel tester results and the DFT test results

The results obtained from the limited experiments performed indicate that both the BP and the DFT devices provide consistent measurements and can be used to determine the friction properties of pavement markings.

4.6 Review of Nordic certification system for road marking materials

In this task, information related to pavement markings, including skid resistance, provided by the Danish Road Directorate were reviewed and compiled. Several documents, published by the Swedish National Road and Transport Research Institute (VTI), were also found to be useful in developing a framework for a certification system of road marking materials in Minnesota, comparable to the ones used in Scandinavian countries. Other work done by the Danish Road Authority, regarding pavement condition and skid resistance, was also included in the review.

4.6.1 Background

NordicCert is a certification system for road marking materials, that includes the countries of Denmark, Iceland, Norway and Sweden. The first test fields were established in 2015, and new rounds of material application on the test fields have been carried out yearly since then. As of January 2023, about 560 materials from 25 manufacturers have been applied at the Nordic test sites.

The certification system is meant to promote fair competition, promote development of new, better materials, increase knowledge, obtain better documentation, and improve road marking quality. The certification system imposes guidelines on materials for both longitudinal and transverse markings. Categories included in the certification are color, type I (flat) and II (markings with section properties to enhance the retroreflection in wet conditions), inlaid markings, antiskid material, materials for hand application, materials with enhanced durability, temporary markings, and alternative drop on systems. Detailed information about the certification system can be found at https://www.nordiccert.com/.

4.6.2 Location description

Two testing locations are used for testing and certification of road marking materials. The locations are intended to represent the average climate conditions in their respective locations. One location is in Denmark (for product approval in Denmark) and the second in Norway/Sweden (for product approval in Iceland, Norway and Sweden).

Location 1 is a two-lane rural road in an open landscape, with the testing site located in the southbound direction. The road is straight and flat without major junctions, with a posted speed limit of 90 km/h (56 mph). The width of the road is 9 m with 1.0 m wide shoulders. The pavement surface is type SKA 11 stone matrix asphalt (SMA) installed in 2019. Roughness grade of the surface is RG2, giving a mean texture depth between 0.6 – 0.9 mm, following EN 1824. The annual average daily traffic is approximately 3,200 vehicles per day; heavy vehicle traffic is approximately 15% of the total volume. The traffic volume is measured annually. Weather conditions at the test site are reported continuously during trials. The road at test location 1 is salted and cleared of snow using a steel blade snowplow during wintertime. Studded tires are permitted at the location following local seasonal restrictions.

Figure 4.17 NordicCert test sites, https://www.nordiccert.com/

A second location was established in 2022. The road is a two-lane rural road in an open landscape. The road is straight and flat without major junctions, with a posted speed limit of 80 km/h (50 mph). The width of the road is 8.5 m (28 ft) with 3.3 m (10.9 ft) wide lanes. There are bike lanes on the shoulders of the road. The pavement surface is a type SMA8 asphalt installed in 2021. Roughness grade of the surface is RG2. The annual average daily traffic is approximately 8,500 vehicles per day; heavy vehicle traffic is approximately 6% of the total volume. The traffic volume is measured annually. Weather conditions at the test site are reported continuously during trials. During wintertime, this location is also salted and cleared of snow by a snowplow, and studded tires are also permitted at the location following local seasonal restrictions. Measurements of the number and the transversal distribution of wheel passages are performed annually, with assessment of wheel passages conducted after application of markings. The equipment used is based on coaxial cable technique. Weather condition data includes annual average temperature, average seasonal temperature, minimum and maximum temperatures, annual precipitation, number of sun hours, number of weeks with snow, number of times a snowplow was operated, and number of times the road was salted. (Fors et al., 2022; Johansen and Fors, 2021).

4.6.3 Application of material

Each marking material is applied as longitudinal lines in the direction of traffic, with nine lines in the lane and one line in the shoulder. The dimensions of the lines are 2.5 m long by 0.15 m wide (8.2 ft × 0.5 ft). The distance between adjacent lines is 0.15 m (0.5 ft), and the distance between adjacent rows is at least 1 m (3.3 ft). The tenth line on the shoulder serves as a control without any wheel passage. Inlaid markings are markings that are installed in milled tracks with a flat bottom, with a width of 30 - 35 cm (11.8 - 13.8 in) and a depth of approximately 7 mm (0.276 in), such that the surface of the markings will stay below the pavement surface. For inlaid markings, there are two milled tracks in line positions 2, 3, 9, and 10, with line 1 corresponding to the shoulder line. Inlaid markings are applied in the milled tracks and the other positions are filled with the same marking type but are applied as non-inlaid lines and are not included in the evaluation of the material.

Application of markings are recommended to be done using self-propelled equipment of a maximum weight of 3,500 kg (7716 lb), but hand application is permitted. Five thicknesses are permitted: 0.4 mm wet (max. 0.45 mm) (0.0157 in, 0.0177 in), 0.6 mm wet (max. 0.65 mm) (0.0236 in, 0.0256 in), 1.5 mm (max. 2.0 mm) (0.0591 in, 0.0787 in), 3.0 mm (max. 3.5 mm) (0.118 in, 0.138 in), and 5.0 mm for structured/profiled type II and antiskid markings (max. 5.5 mm) (0.197 in, 0.217 in). Prefab and tape markings are applied at commercially available thickness values. Thickness is measured at application of the two lines expected to receive the highest number of wheel passages using steel plates placed at the end of the lines, and with a portable measurement tool for a random sample of lines. The material thickness is measured without any drop on glass beads or aggregates. The steel plates are weighed before and after so that the volume of material applied can be controlled. Lines exceeding maximum thickness are excluded from testing.

Rate of application of drop on materials is determined according to EN 1824, and the amount of drop on materials is recorded during application and issued in the certificate of the road marking material. Lane closures must be done during and several hours after the application is completed. Masking of road surface using suitable methods (like roofing felt or tar paper) is done during application. (Fors et al., 2022; Johansen and Fors, 2021).

4.6.4 Measurement of performance

Measurements of marking materials are carried out two weeks after application, then followed up after one year and after two years. For temporary markings, measurements are followed up after one to three months. All measurements are performed in the direction of traffic, in dry weather conditions, and on dry markings. Markings are not cleaned prior to measurements being taken. Parameters measured for certification include the coefficient of retroreflected luminance, R_L dry, coefficient of retroreflected luminance, R_L wet (type II markings only), luminance coefficient under diffuse illumination, Q_d, friction, and chromaticity coordinates. Luminance parameters are measured as an average of three points on a line. For luminance in wet conditions, 3 liters of clean water is poured 1 minute prior to measurements. Chromaticity coordinates are measured using a spectrophotometer at one point on each line. Chromaticity coordinates of yellow materials in retroreflected light is also measured using a hand-held retro reflectometer. Friction is measured on wet markings using a portable friction tester (PFT) along the center of each line. Friction measurements are taken after measurements of luminance parameters and chromaticity coordinates.

The portable friction tester currently used is manufactured by the Swedish company Coralba. The Coralba PFT was developed by VTI (the Swedish National Road and Transport Research Institute) specifically for measuring skid resistance on road markings. It has been developed over a long period of time through field work and it has been validated in numerous research projects (Wallman and Åström, 2001). The device is not available in the US, but appears to be similar to a simplified version of the T2go device. The PFT was calibrated based on friction measurements performed with the British Pendulum Tester (Walivaara, 2007).

Figure 4.18 The Coralba PFT

Two samples for identification are taken from all products applied during installation at the test site and kept in an indoor climate-controlled environment. Samples of materials that have fulfilled certification requirements are tested at an accredited laboratory and the results are compared with the manufacturer's declaration of the product constituents. To maintain validity of published product certificates, annual audits are required of the manufacturing process and the factory production control system. (Fors et al., 2022; Johansen and Fors, 2021).

4.6.5 Certification

Marking materials are certified in relation to the number of wheel passages that they will stand. Number and transverse distribution of wheel passages are used to determine the roll-over classes (P-classes defined by EN 1824) for which the materials are certified. To obtain certification for a certain P-class, all relevant performance requirements must be fulfilled for that class during follow-up measurements. Initial measurements must satisfy requirements to be approved for follow-up measurements. To be certified for a higher P-class, the material must satisfy performance requirements for all classes below that class. A certificate is issued after the material is registered, the registration fee is paid, complete product documentation is submitted, the material passes the initial and follow-up performance measurements, and identification analysis of the material matches the manufacturer's specification. Certificates can be updated with higher P-class if the material passes the performance for that class in follow-up measurements. (Fors et al., 2022; Johansen and Fors, 2021; CEN 2020).

4.6.6 Assessment

Assessment of road marking materials used in contracts is performed to determine if the materials correspond to manufacturers' declaration of constituents and as certified. Material samples are randomly selected from all contracts where certified road marking materials are used. The selections are done annually. The number of samples collected is between 1 and 10, as suggested by the assessment organization. Targeted selection is performed when a road authority has reason to believe the road marking material does not correspond to its specifications. Samples are taken directly from the application machine and stored with all relevant identification information. A selection of the collected samples is analyzed for constituent content and compared to that of the material specified in the contract. Johansen and Fors, 2019)

4.6.7 Other developments

Other work has been done by the Danish Road Authorities regarding pavement marking skid resistance and pavement condition. Geveko Markings has developed a new road marking profile to combine the benefits and performance of flat and structured type markings. These Type II markings have the high wet night visibility attributed to structured markings, and the low noise and vibration levels that are attributed to flat markings. By draining water from the markings during rain, the response time of motorists improved by up to 50%. (Geveko, 2018).

Figure 4.19 Geveko Markings new road marking profile (Geveko, 2018)

Chapter 5: Testing of pavement markings and colored lanes products on low-volume pavement sections at MnROAD

The research team conducted a series of in situ experiments at MnROAD to determine the friction properties of various pavement marking. A matrix composed of combinations of products and pavement surfaces was developed at the beginning of 2023, based on product availability and pavement sections available on the low-volume loop at MnROAD.

In early fall 2023, the products were installed over concrete and asphalt pavements, and the first set of measurements was performed to establish baseline values. Two types of equipment were used: the more expensive dynamic friction tester (DFT), in which the speed at which the test is performed can be controlled, and the less expensive British pendulum tester (BPT), which allows testing only at one very low speed. In mid-June 2024, a second set of tests was performed, using the same testing equipment.

Demonstration of a third *continuous* friction measurement technology – a Sideway-force Coefficient Routine Investigation Machine (SCRIM) – took place at MnROAD on July 25, 2024.

5.1 MnROAD pavement marking installations

All pavement markings were installed within concrete Cell 46 and asphalt Cell 339 (formerly 139) of MnROAD's Low Volume Road loop (Figs. 5.1 and 5.2) on October 5, 2023. Figure 5.3 is a MnDOT drone overflight image showing the relative locations of the installed test markings on MnROAD's Low Volume Road.

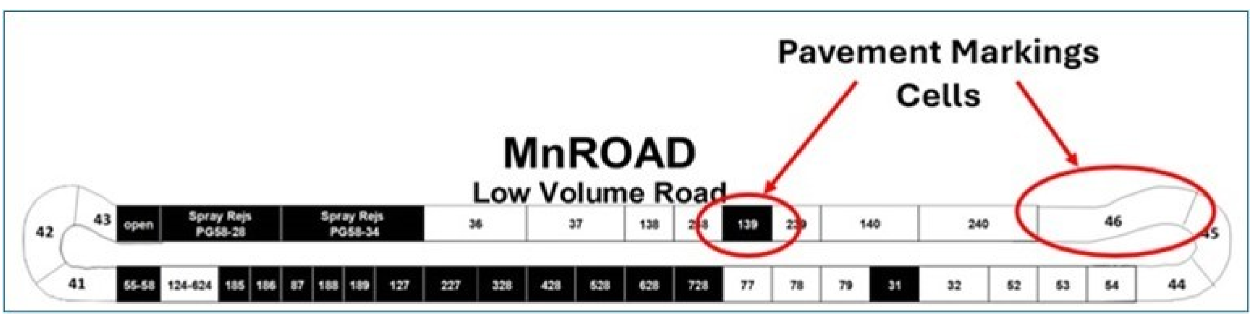


Figure 5.1 MnROAD Low Volume Road cells for pavement markings testing (Cell 46 concrete; Cell 139/339 asphalt)

Figure 5.2 Google Earth image of MnROAD Low Volume Road cells for pavement markings testing (Cell 46 concrete; Cell 139/339 asphalt)

Figure 5.3 Drone overflight view of MnROAD Low Volume Road and test marking locations

Ten markings were installed per each cell, normal (perpendicular) to traffic direction (Fig. 5.4). As installed, each marking measured 2 feet in width x 24 feet in total length, and were spaced approximately 8 feet apart, with the inside and outside lanes of both cells receiving the same marking types and materials. Section 5.1.1 lists and describes the ten markings that were tested during the project.

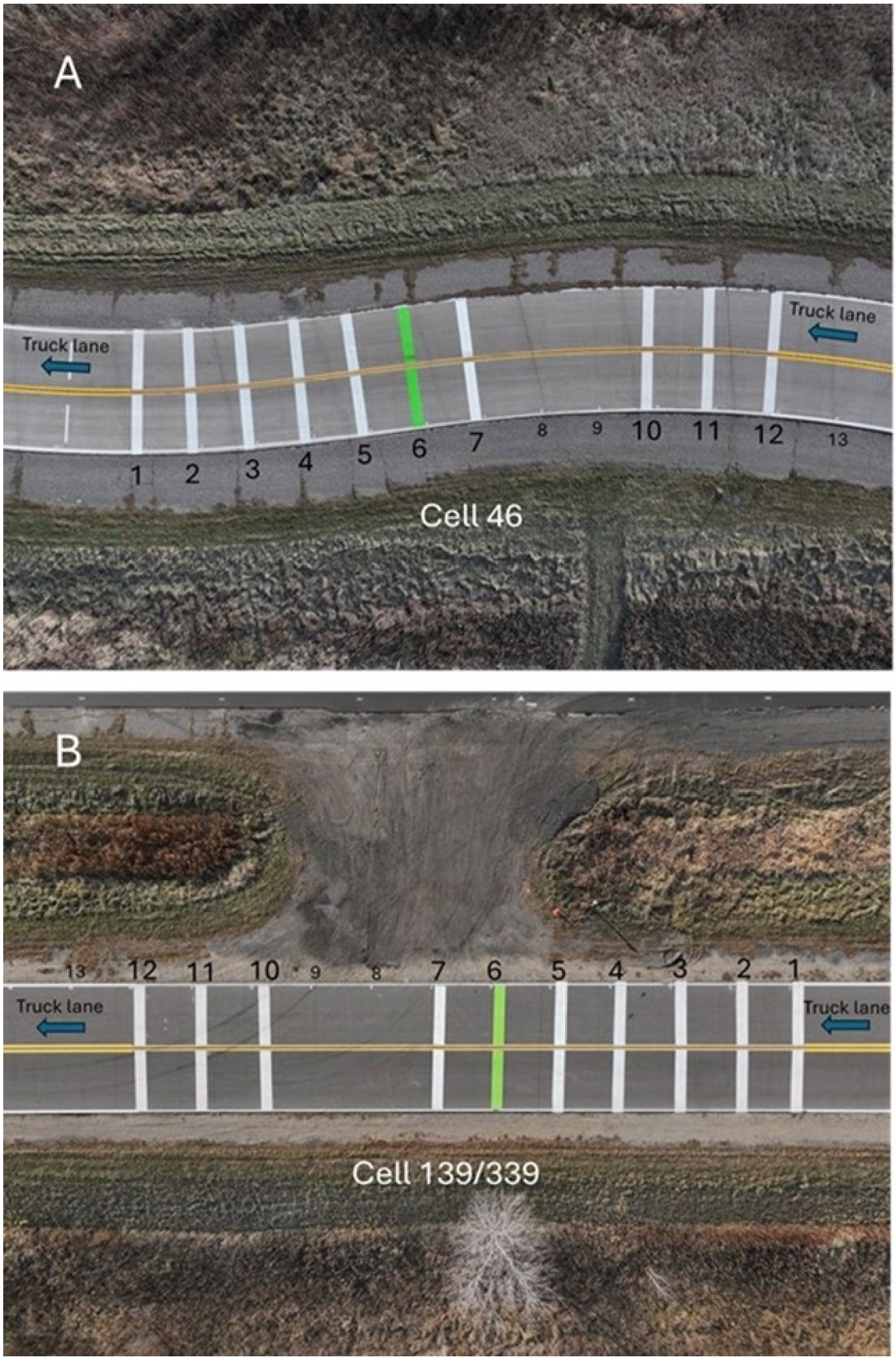


Figure 5.4 Drone view of Cell 46 (A) and Cell 139/339 (B) pavement markings

5.1.1 MnROAD pavement marking installation summary (no installation at positions 8 and 9)

1. **Latex w/Type 1 Beads– Sir Lines-a-Lot**
   a. High Solids (MN Spec PPG) spec applied at ~15 mil with AASHTO M247 Type 1 Beads.
2. **Epoxy w/Type 1 Beads– Sir Lines-a-Lot (Concrete Start)**
   a. Slow-dry epoxy (Poly-Carb Mark 55) applied at ~20 mil with AASHTO M247 Type 1 Beads sifted on.
3. **Epoxy w/Type 1 Beads & Corundum – Sir Lines-a-Lot (Concrete Start)**
   a. Slow-dry epoxy (Poly-Carb Mark 55) applied at ~20 mil for two layers, first layer had corundum sifted on, then the second layer sifted AASHTO M247 Type 1 Beads.
4. **Epoxy w/Type 1 Beads & Taconite – Sir Lines-a-Lot (Concrete Start)**
   a. Slow-dry epoxy (Poly-Carb Mark 55) applied at ~20 mil for two layers, first layer had taconite hand-casted, then the second layer sifted AASHTO M247 Type 1 Beads.
5. **Epoxy w/Potter's Crushed Glass – Sir Lines-a-Lot (Concrete Start)**
   a. Slow-dry epoxy (Poly-Carb Mark 55) applied at ~20 mil with crushed glass and Utah blend (50%/50% by weight) sifted on at 1 gal/48 SF.
6. **Preformed Thermo – Preform LLC (Asphalt Start)**
   a. 125 mil green with corundum topping.
7. **Preformed Thermo ESR – Preform LLC (Asphalt Start)**
   a. 125 mil white with corundum and proprietary bead blend (similar to something like a Utah blend) in the material.
10. **MMA w/Beads & Corundum – Swarco (Concrete Start)**
    a. Swarcoplast 5090 98:2 spray applied MMA applied at ~30 mil for two layers, first layer had corundum, then the second layer had a Colorado blend bead and corundum mix (60% beads/40% corundum). Both layers had beads/aggregate applied by pneumatic sprayer.
11. **MMA w/Beads & Taconite – Swarco (Concrete Start)**
    a. Swarcoplast 5090 98:2 spray applied MMA applied at ~30 mil for two layers, first layer had hand-cast taconite applied, then the second layer Colorado blend beads applied with a pneumatic sprayer.
12. **MMA w/Potter's Crushed Glass – Swarco (Concrete Start)**
    a. Swarcoplast 5090 98:2 spray applied MMA applied at 30 mil for one layer with crushed glass and Utah blend (50%/50% by weight) sifted on at 1 gal/48 SF.

5.2 Friction testing equipment used at MnROAD

A key project objective was to test the friction characteristics of various pavement marking products and of concrete and asphalt pavements at MnROAD to which they were applied. The results are used for quantifying the friction differential between the products and the "control" pavements. A dynamic friction tester (DFT) and British Pendulum test (BPT) were used by the research team in November of 2023, to make initial (baseline) friction measurements. Follow-up DFT and BPT measurements were made on June 11 and 12 of 2024, to assess the impact MnROAD's low-volume loop traffic (circulating truck) and winter 2023-2024 snow plowing had on the condition and wear of the markings relative to the unmarked "control" pavements. Unfortunately, winter 2023-2024 was both exceptionally mild and lacking in snowfall, and minimal snow plowing took place.

An alternative (and continuous) friction measurement technology – a Sideway-force Coefficient Routine Investigation Machine (SCRIM) – was identified by the Project's TL as a potential option worth considering. The SCRIM is a full-size over-the-road vehicle (Fig. 5.5) which can perform and provide the following tests and data (https://www.wdm-int.com/images/uploads/content/SCRIM_US_brochure_2022.pdf):

- Single-or double- wheel-path friction and texture measurement
- GPS-linked friction, texture, roughness (IRI), geometric, and video data
- Dynamic vertical load and water flow control, air and surface temperature measurement
- Continuous data collection between 15 and 55 mph (24 and 89 km/h)

Figure 5.5 SCRIM vehicle (image source: WDM)

The investigators coordinated with WDM USA (hereafter referred to as WDM) to conduct a SCRIM demonstration at MnROAD on Thursday, July 25, 2024. The demonstration was an important – and significant – addition to the project because it provided *continuous* pavement friction measurement (CPFM) information to compare and potentially correlate with the project's stationary DFT and BPT data.

Based on the project research investigators' recommendation, the SCRIM tests were performed at three speeds: 15 mph, 30 mph, and 40 mph (24 km/h, 48 km/h, and 64 km/h). Triplicate runs were made at each speed, in both the traffic and non-traffic lanes, which meant the SCRIM made 18 complete circuits of MnROAD's low-volume road during the testing. The tests were run in the same (clockwise) direction across the markings in both lanes and test cells. "Retros" (reflectors) were placed by WDM personnel at the beginning and end of each set of pavement markings which the SCRIM's on-board sensor detected for pinpointing its position. To simulate a wet pavement, a calibrated flow of water is delivered by a nozzle ahead of the SCRIM's sideway force measurement wheel.

As described by WDM's Vice President Ryland Potter (personal communication, July 29, 2024), *"The theoretical water film thickness is 0.5mm (which assumes the pavement surface is perfectly dense, smooth, and horizontal), so the flow rate is adjusted based on the speed of the vehicle to achieve the theoretical value. The actual water film thickness under the wheel will depend on the porosity, texture, and gradient of the pavement."*

Retros and the pavement-wetting water delivery nozzle's configuration are shown in Figure 5.6. Figure 5.7 shows the SCRIM approaching a retro positioned at the end of Cell 46's pavement markings, while Figure 5.8 shows the water trail left on the low volume road's pavement surface.

Figure 5.6 SCRIM vehicle components showing two types of retros.

Figure 5.7 SCRIM approaching retro on MnROAD Low-Volume Road (7/25/2024)

Figure 5.8 Water trail left by SCRIM on Cell 46 pavement

5.2.1 SCRIM testing

On August 23, 2024, WDM provided the investigators with an Excel spreadsheet and a PowerPoint summary of the SCRIM friction testing conducted by WDM at MnROAD on July 25, 2024. The PowerPoint summary also explains the spreadsheet's data content, how WDM performed its testing, and how it compiled and generated friction values for the pavement markings (Fig. 5.9). With WDM's approval, individual slides of the PowerPoint summary are included in the following text, while the entire slide deck is presented in Appendix C.

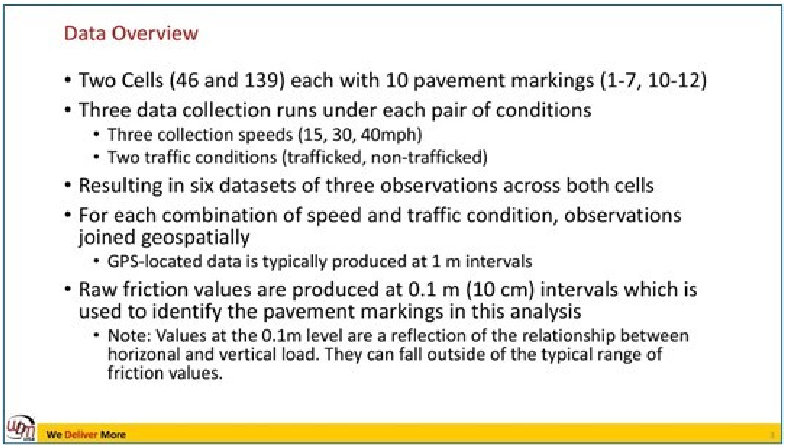


Figure 5.9: SCRIM testing data overview slide (Source: WDM)

Given that the SCRIM data was generated every 0.1 meters (10 cm, or ~4 inches) of travel by the SCRIM (i.e., the equivalent of one row of spreadsheet data), it was expected that this fine degree of resolution would make it possible to distinguish the friction differential between the 24-inch wide (~60 cm) pavement markings and the 96-inch wide (~240 cm) non-marked intervals of the MnROAD test cell pavements to which the markings were applied.

As explained by the WDM team during an August 27, 2024, virtual meeting with the project's UM investigators, each pavement marking spanned 6 to 8 rows of spreadsheet data and were identified as such in the spreadsheet (Fig. 5.10). A speed-corrected, 7-row rolling average was used by WDM to identify the approximate center (and friction value) of each pavement marking.

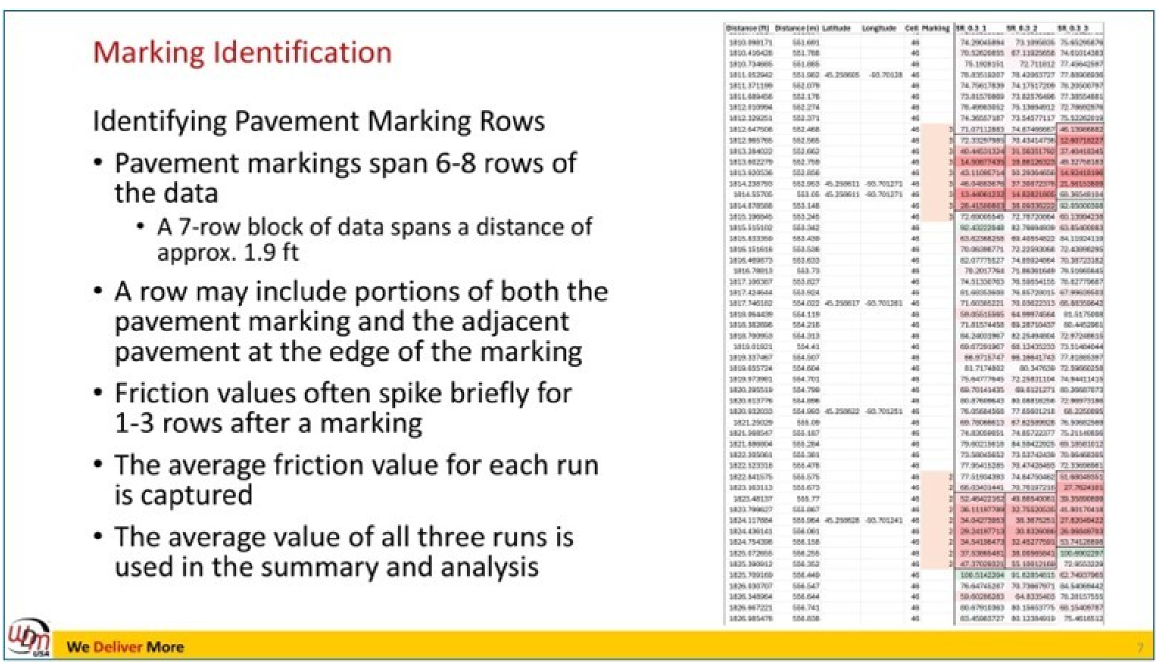


Figure 5.10: Methodology for identification of pavement markings (Source: WDM)

Figure 5.11A illustrates 10 cm (4 inch) interval friction data generated by a triplicate SCRIM run over Cell 139/339, with the wheel path markings annotated numerically at their respective positions. The 10 cm measurement resolution also meant that five to six intervals could theoretically coincide fully with an individual marking and that up to two intervals could partially overlap the unmarked pavement and leading and trailing portions of each marking.

The rolling average method (5.11B) smoothed and dampened the “noise” of the shorter 10 cm interval data while more clearly highlighting the position and magnitude of the friction differential of each pavement marking relative to the unmarked pavement. Note the dips in friction values that coincide with the markings.

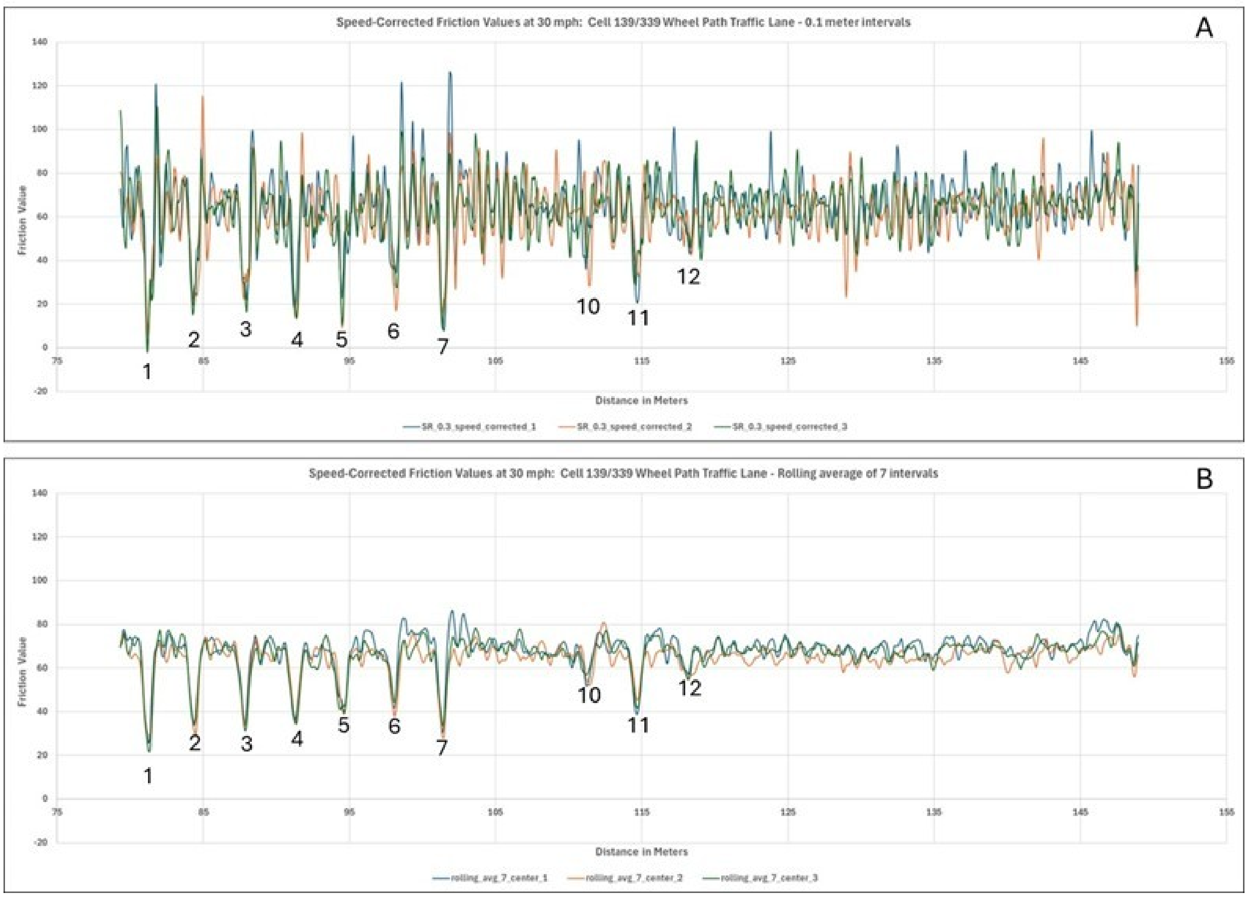


Figure 5.11: Example of SCRIM friction data generated for the wheel path Cell 139 at 30 mph test speed

This method would produce a friction value for a portion of a marking also tested by the DFT, which has a measuring diameter (footprint) of 11.2 inches (28.4 cm), or the equivalent of about three SCRIM intervals. Therefore, the 7-row rolling average made it possible for the investigators to directly compare the SCRIM results with the project’s June 2024 DFT results.

Chapter 6: Data Analysis

The data collected in the previous chapter is statistically analyzed, to investigate which products have good friction properties and which need improvement. The analyses are also used to compare the results obtained from the three pieces of equipment and determine if they produce similar results.

6.1 Overview of testing results

6.1.1 Friction Testing: Dynamic Friction Tester (DFT)

The Dynamic Friction Tester (DFT) generates data across a continuum of speed (from 0 to 80 km/h; or 0 to 50 mph) that overlaps with the three non-vehicular modes of transportation – walking, jogging/running, and cycling – most pertinent to potential safety issues associated with the friction differential between marked and unmarked pavement. Typical speeds are about 5 km/h (3 mph) for walking; 10 km/h (6 mph) for jogging; 10 to 15 km/h (6 to 9 mph) for running; and 15 to 30 km/h (9 to 19 mph) for cycling.

The increasing prevalence of e-bikes and scooters in urban environments and tourist areas (where pavement markings are frequently more widely used) make these electric-powered modes of transportation even more skid-susceptible to localized and abrupt changes in pavement friction because of their higher operating speeds of 25 to 40 km/h (15.5 to 25 mph) and much more rapid acceleration from a dead stop or slow speed compared to a bicycle. Consequently, the friction differential between pavement and pavement markings over these ranges of speed and up to a common vehicular traffic speed limit of 70 km/h (43.5 mph) is the focus of our data analysis.

Figures 6.1 to 6.4 summarize the DFT testing performed by the University of Minnesota in November of 2023 and June of 2024. The average coefficient of friction (μ) of triplicate wheel path (WP) measurements (denoted as "A") and between wheel paths (BWP) measurements (denoted as "B") are plotted for Cell 46 in Figures 6.1 and 6.2, and for Cell 139/339 in Figures 6.12 and 6.13.

The MMA markings results are shown as dashed lines, while the epoxy results are shown as double lines; the two Thermo markings results are shown as thick solid lines (two shades of green); and the latex marking results are shown as a purple triple line. The Control pavements results are represented by a thick solid red line.

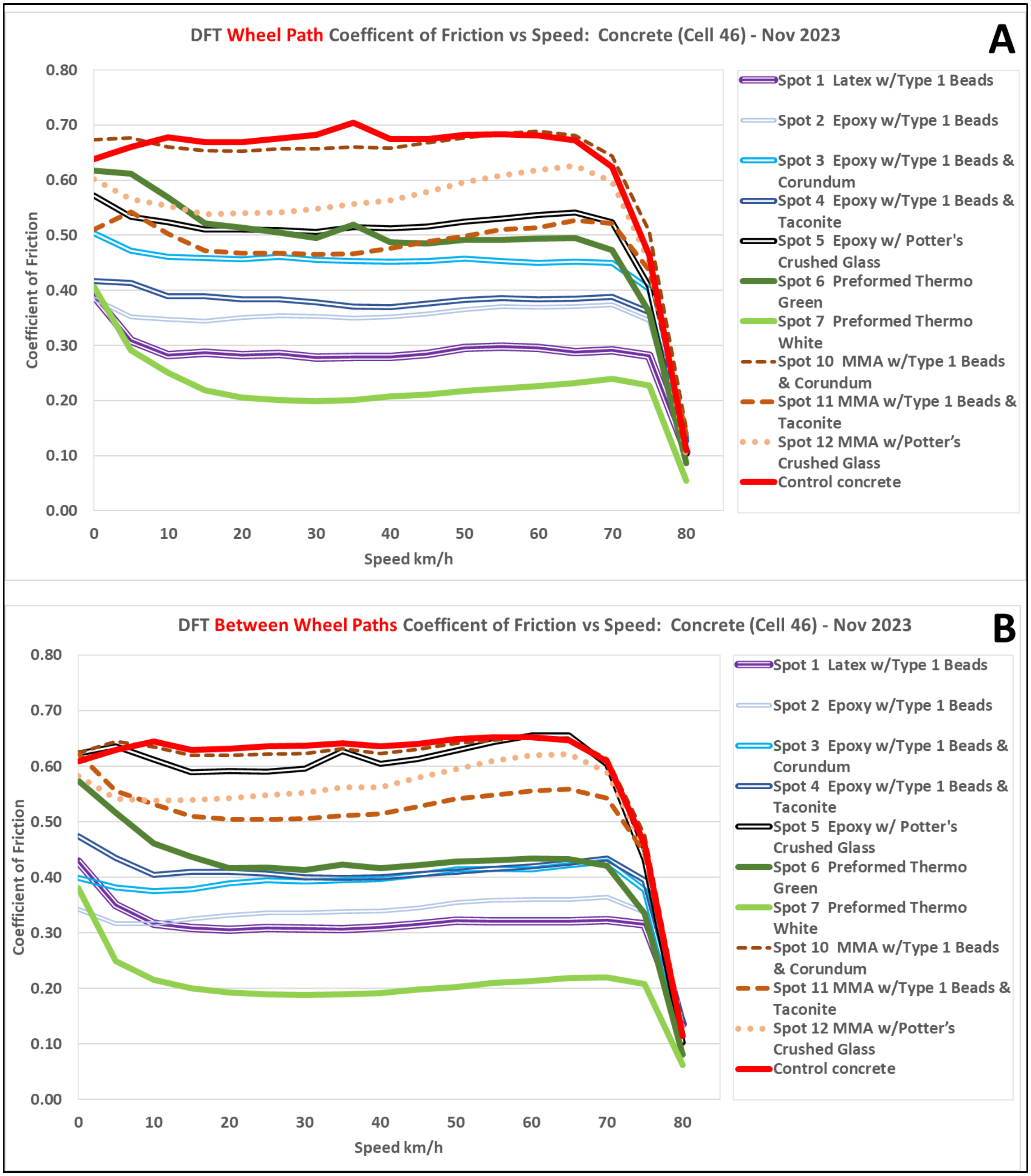


Figure 6.1 November 2023 DFT results for markings applied to MnROAD concrete Cell 46: WP (A) and BWP (B)

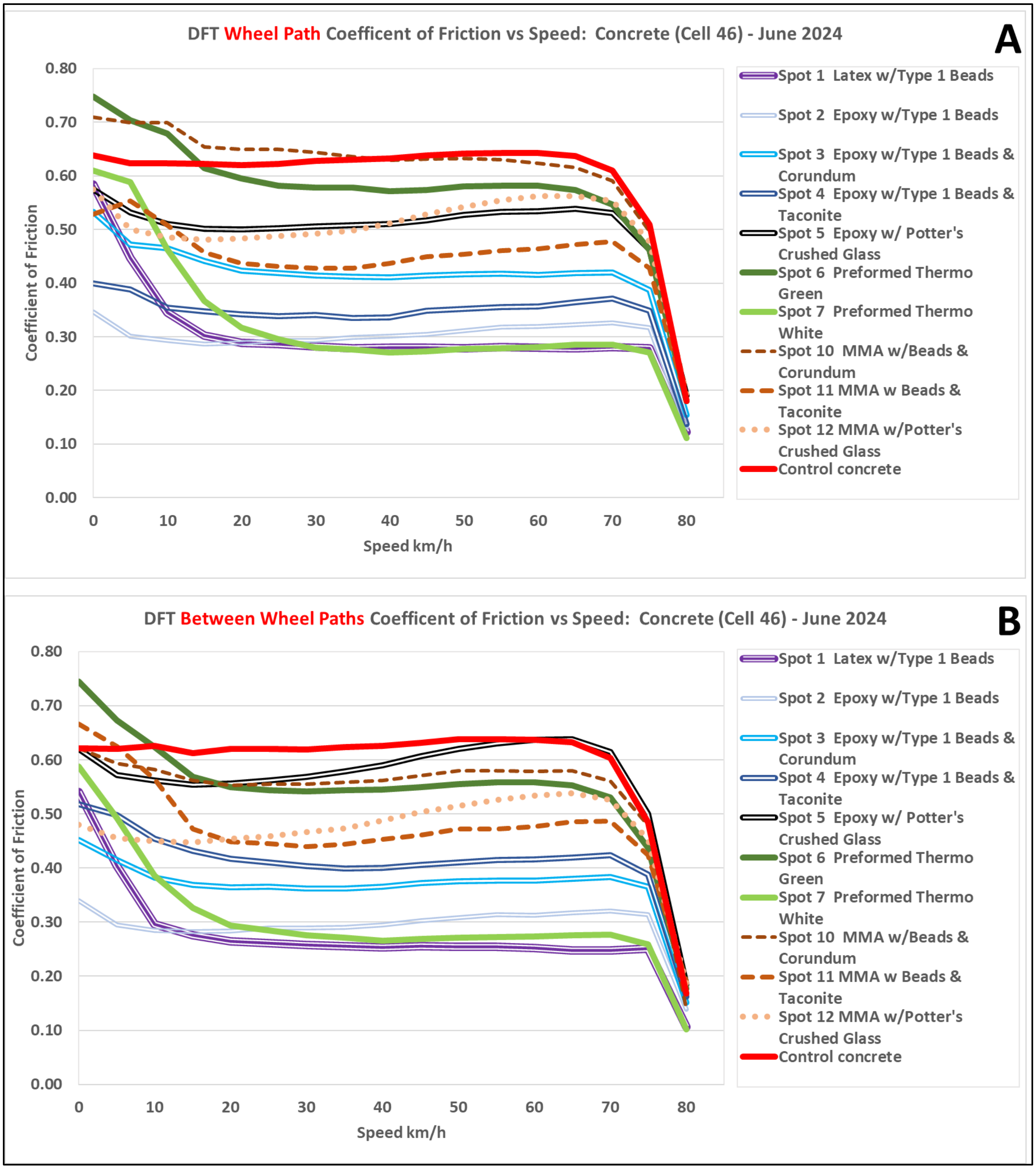


Figure 6.2 June 2024 DFT results for markings applied to MnROAD concrete Cell 46: WP (A) and BWP (B)

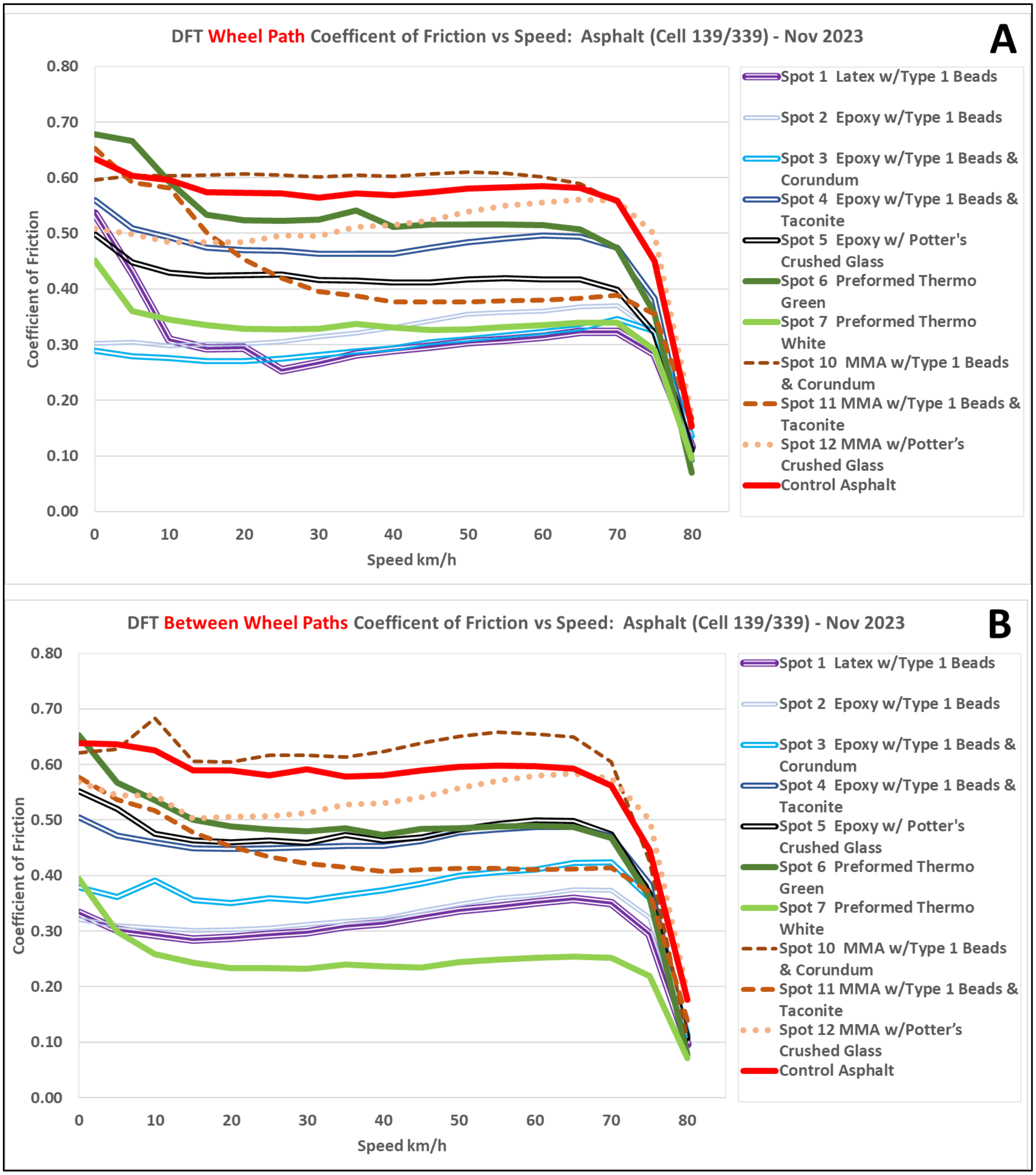


Figure 6.3 November 2023 DFT results for markings applied to MnROAD asphalt Cell 139: WP (A) and BWP (B)

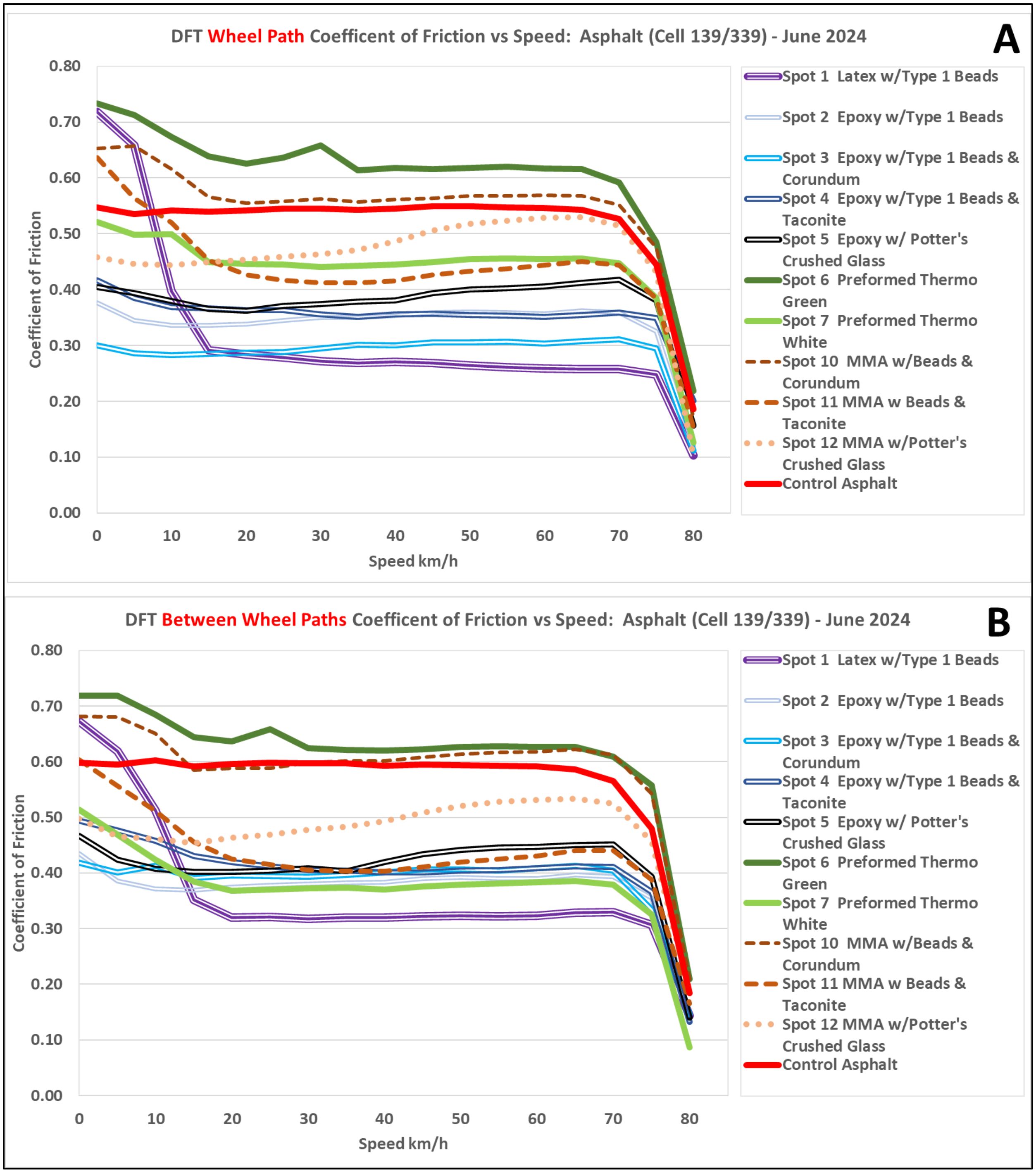


Figure 6.4 June DFT results for markings applied to MnROAD asphalt Cell 139: WP (A) and BWP (B)

The DFT coefficient of friction of most markings is generally highest from 0 to 5 km/h (0 to 3 mph), decreases from 5 to 20 km/h (3 to 12.4 mph), flattens out and remains relatively constant for speeds above 20 km/h (12.4 mph) through 70 km/h (43.5 mph), and drops at speeds above 70 km/h. This relationship applies to most of the pavement marking types, but to a much lesser degree to the unmarked control pavements, for which friction values are generally higher and remain relatively constant from 0 to

70 km/h. For example, DFT testing performed on a test section of CSAH 15 (chip sealed asphalt pavement) near Duluth has returned an average coefficient of friction value of 0.57 at a speed of 64.4 km/h (40 mph) (Marasteanu et al., in prep), similar to the Cell 139 Control.

Given that both control pavements have been in place for several years (versus 10 months for the markings) it is not surprising that the control pavement's friction characteristics exhibited little change during the project test period. Some of the markings' higher friction values at low-speed might be related to microtexture-like properties, imparted by the retro-reflective beads and/or the fine friction material embedded in the markings, as microtexture is known to contribute to skid resistance at low traffic speed (Pranjić et al., 2020).

Histogram plots of the average DFT coefficient of friction are presented in Figures 6.5 and 6.6 for cells 46 and 139/339, respectively, with measurements made in the wheel path (denoted by A) and between wheel paths (denoted by B) of the traffic lane. This average represents a composite value for speeds from 10 km/h to 70 km/h (6 to 43.5 mph); a range of speed over which the coefficient of friction stays relatively constant and coincidental with the modes of transportation described previously.

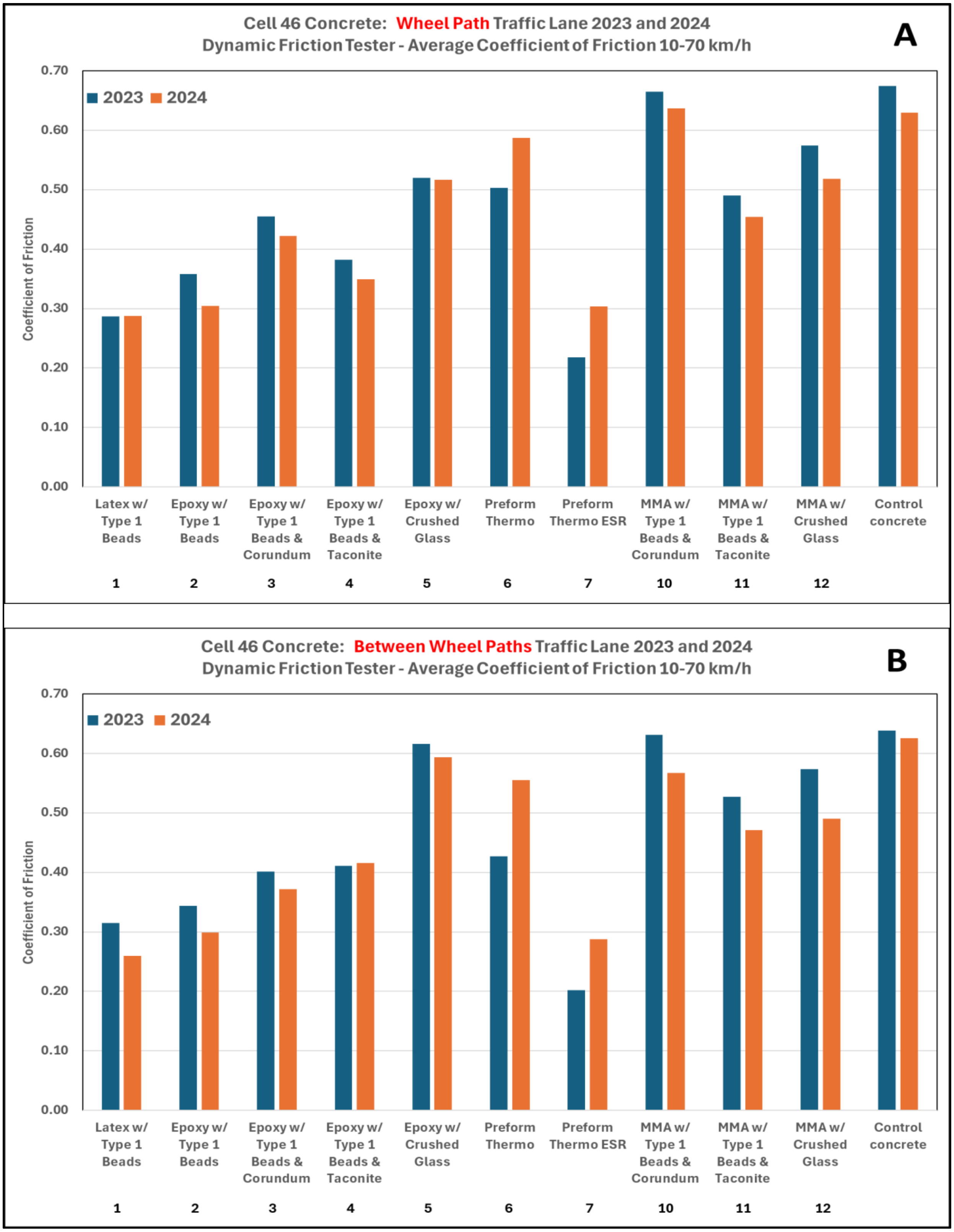


Figure 6.5 Average coefficient of friction measured by the DFT for Cell 46 markings: WP (A) and BWP (B)

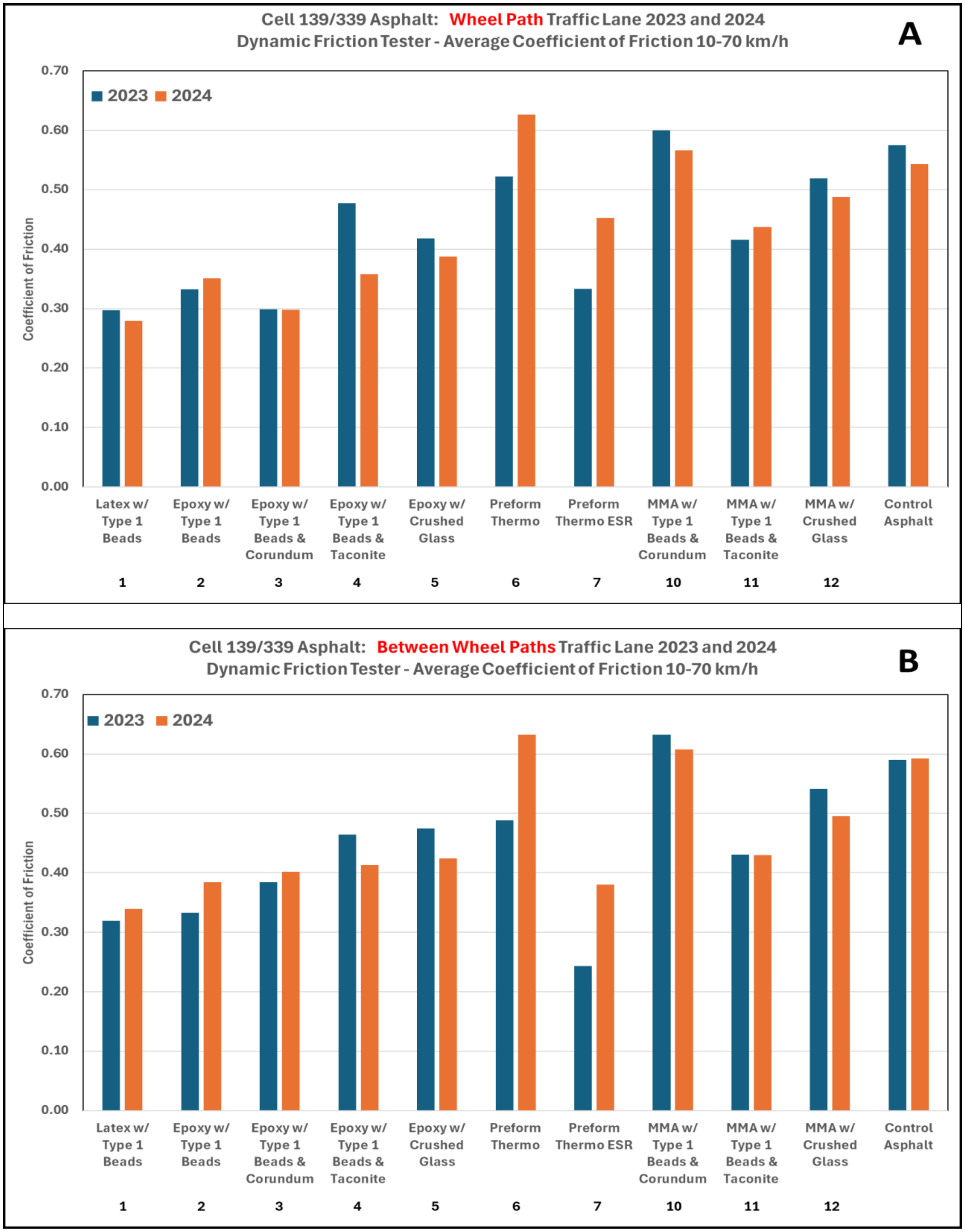


Figure 6.6 Average coefficient of friction measured by the DFT for Cell 139 markings: WP (A) and BWP (B)

6.1.2 Friction Testing: British Pendulum Tester (BPT)

The British Pendulum Tester (ASTM E303) has an effective testing speed of ~10 km/h (~6 mph) (i.e., the speed of the pendulum at the bottom of its swing as its rubber slider contacts the pavement surface). Five BPT coefficient of friction measurements (n=5) were made per pavement marking and for both Control pavements, and averaged. Histograms of the BPT averages for 2023 and 2024 are presented in Figures 6.7 and 6.8 for Cell 46 and Cell 139/339, respectively. As was the case with the DFT, measurements were made in the wheel path (denoted by A) and between wheel paths (denoted by B) of the traffic lane.

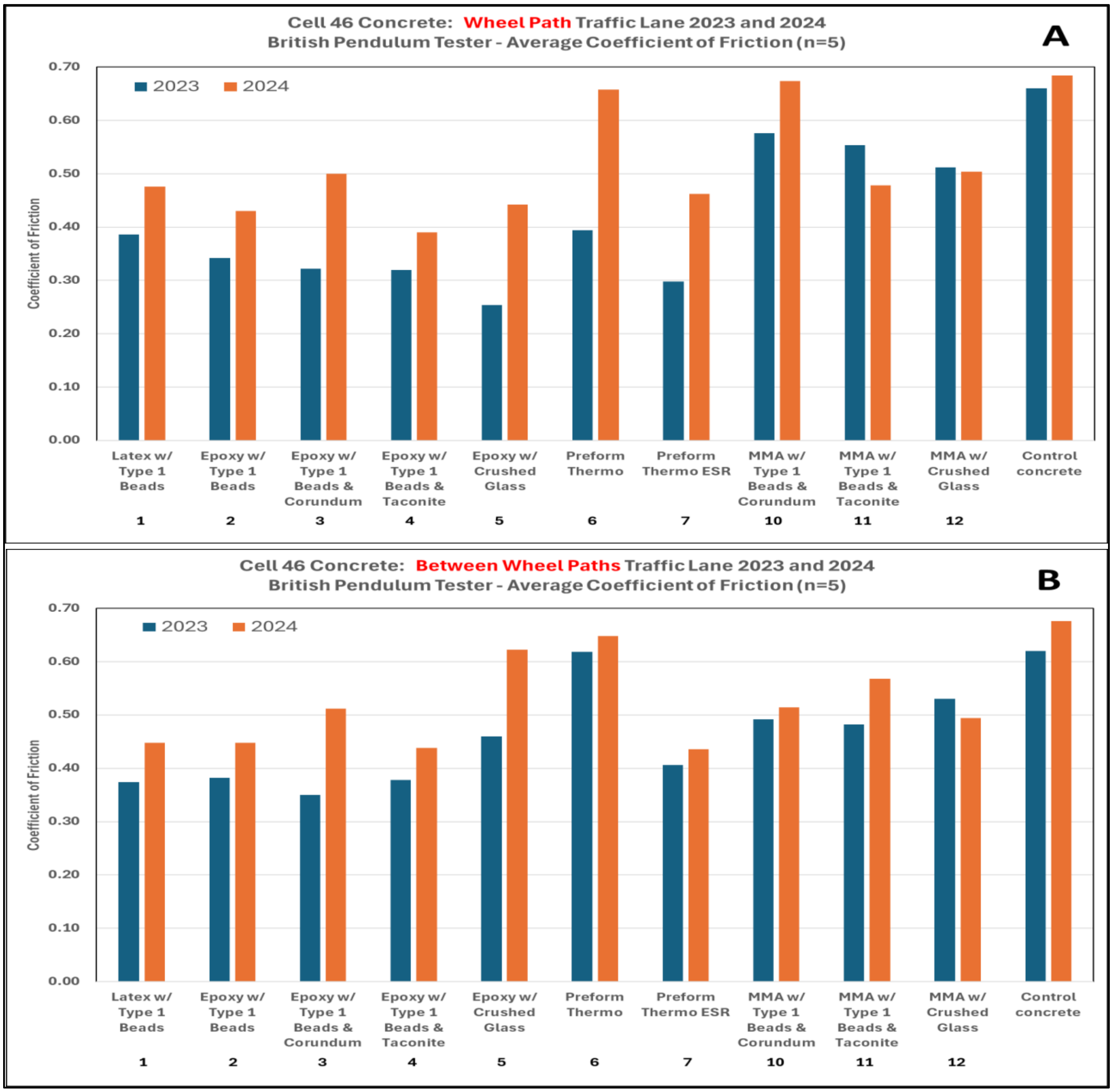


Figure 6.7 Average coefficient of friction measured by the BPT for Cell 46 markings: WP (A) and BWP (B)

Cell 139/339 markings exhibited similar coefficient of friction increases from 2023 to 2024, although the differences were generally greater than that exhibited in Cell 46 for between wheel paths measurements (see Figures 6.8 A and B).

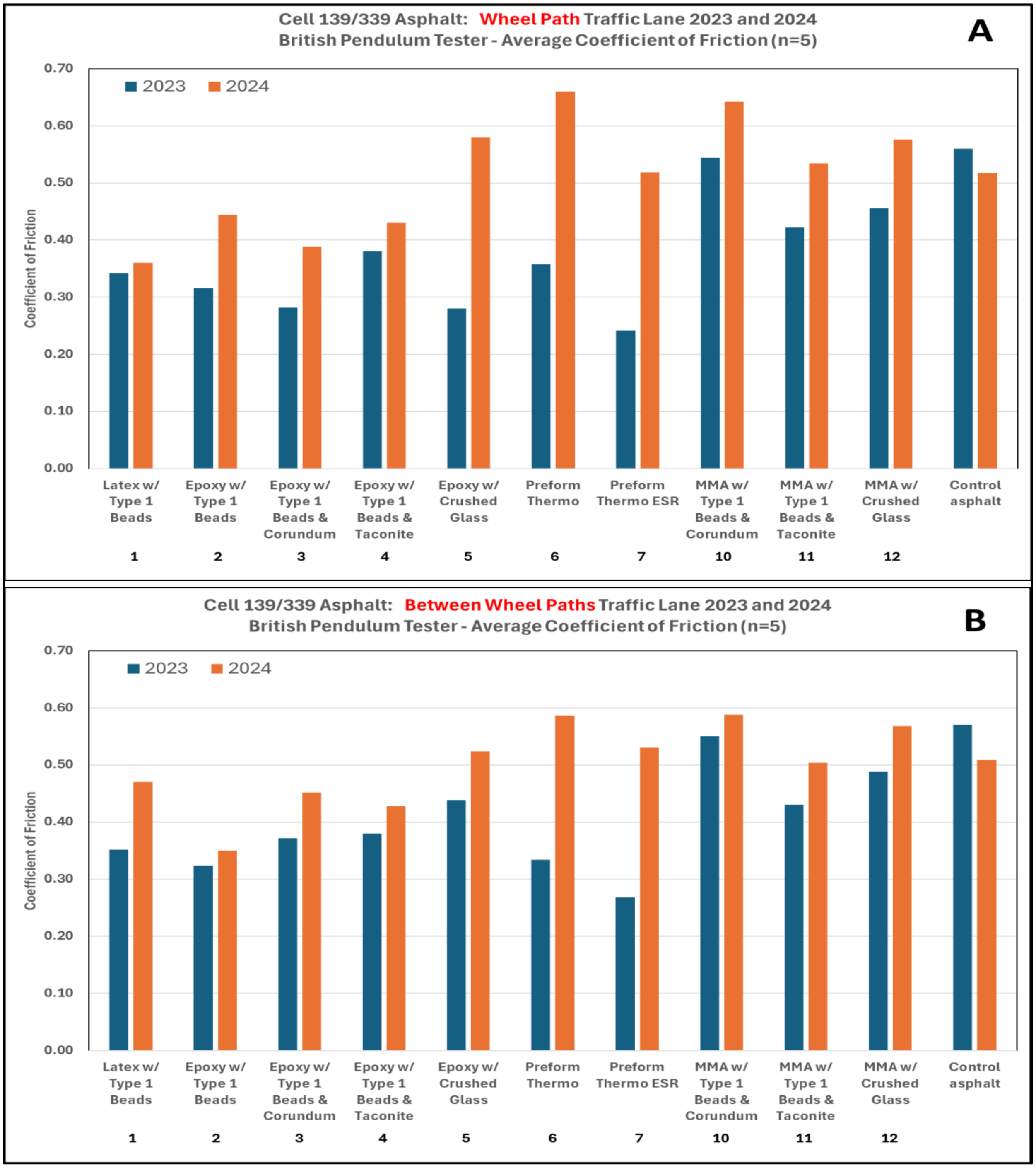
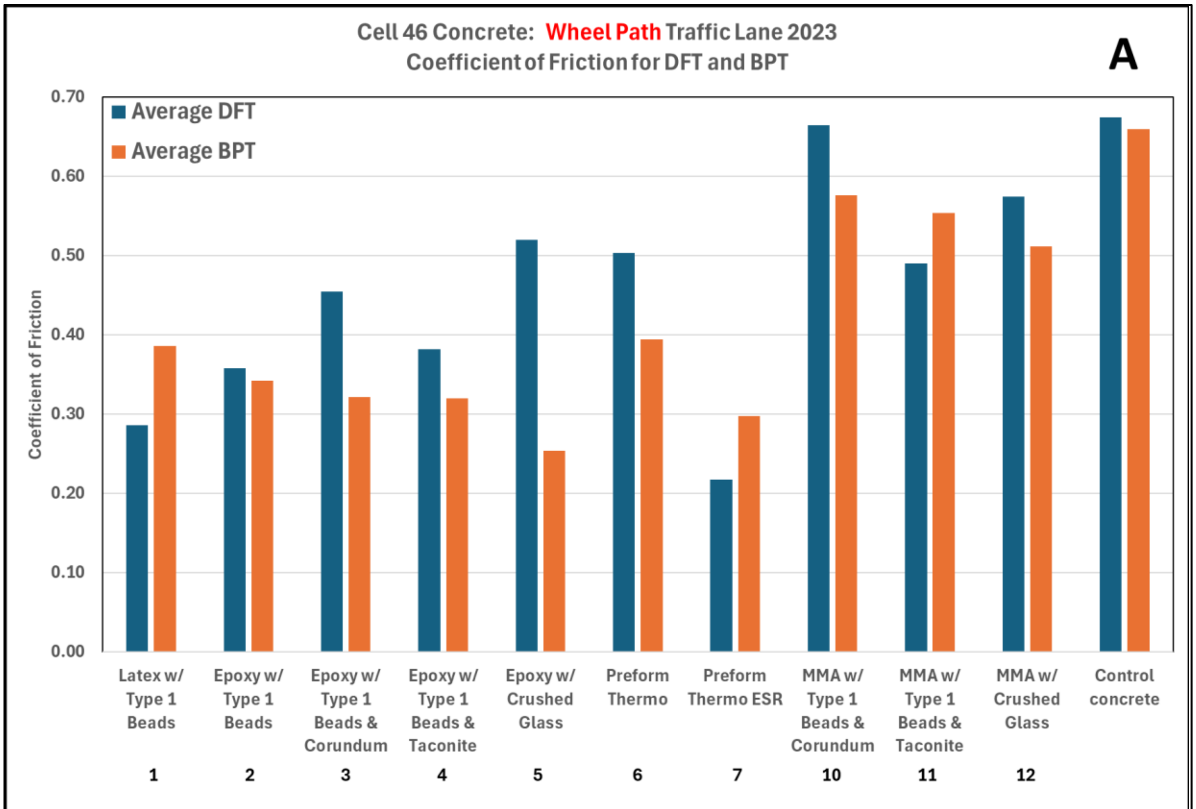


Figure 6.8 Average coefficient of friction measured by the BPT for Cell 139 markings: WP (A) and BWP (B)

Interestingly, 2024 coefficient of friction values measured by the British Pendulum Tester for most of the markings *increased* relative to the 2023 baseline values, in the wheel path and between wheel paths of both pavements, but to a significantly lesser extent between wheels paths of Cell 46. Perhaps the increase reflects (so to speak) attrition of lower-friction retroreflective beads due to the wearing effects of the circulating truck plus eight months of weather. This bead and marking attrition may have led to “exposing” more of the underlying transversely tined concrete pavement surface of Cell 46, or the underlying skid aggregate

The DFT and BPT results are plotted and compared in Figures 6.9A-A’ and B-B’ (Cell 46) and 6.10A-A’ and B-B’ (Cell 139/339). Visual observation indicates that the markings have similar friction characteristics, as measured by the two devices. Again, measurements made in the wheel path are denoted by A, and between wheel paths are denoted by B of the traffic lane; A’ and B’ refer to measurement made in 2024.



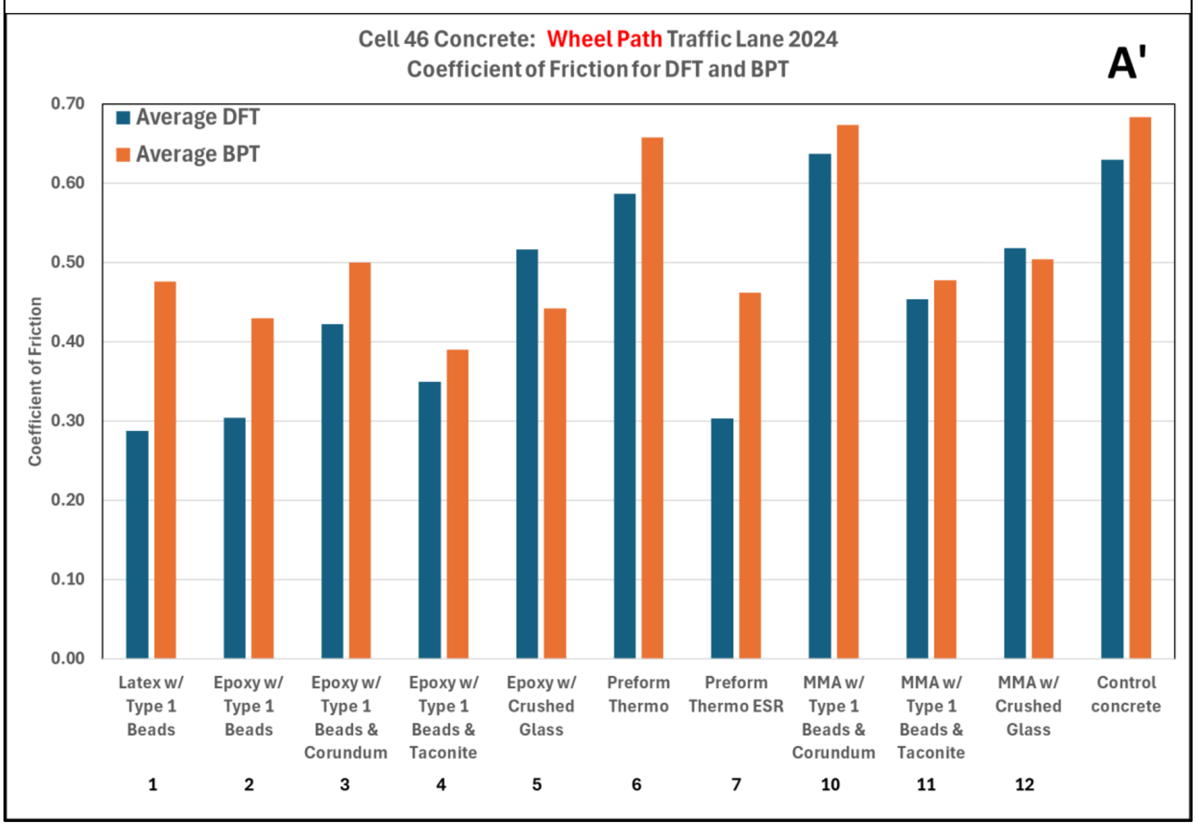


Figure 6.9 DFT and BPT measurements of WP of Cell 46 markings and control (A and A')

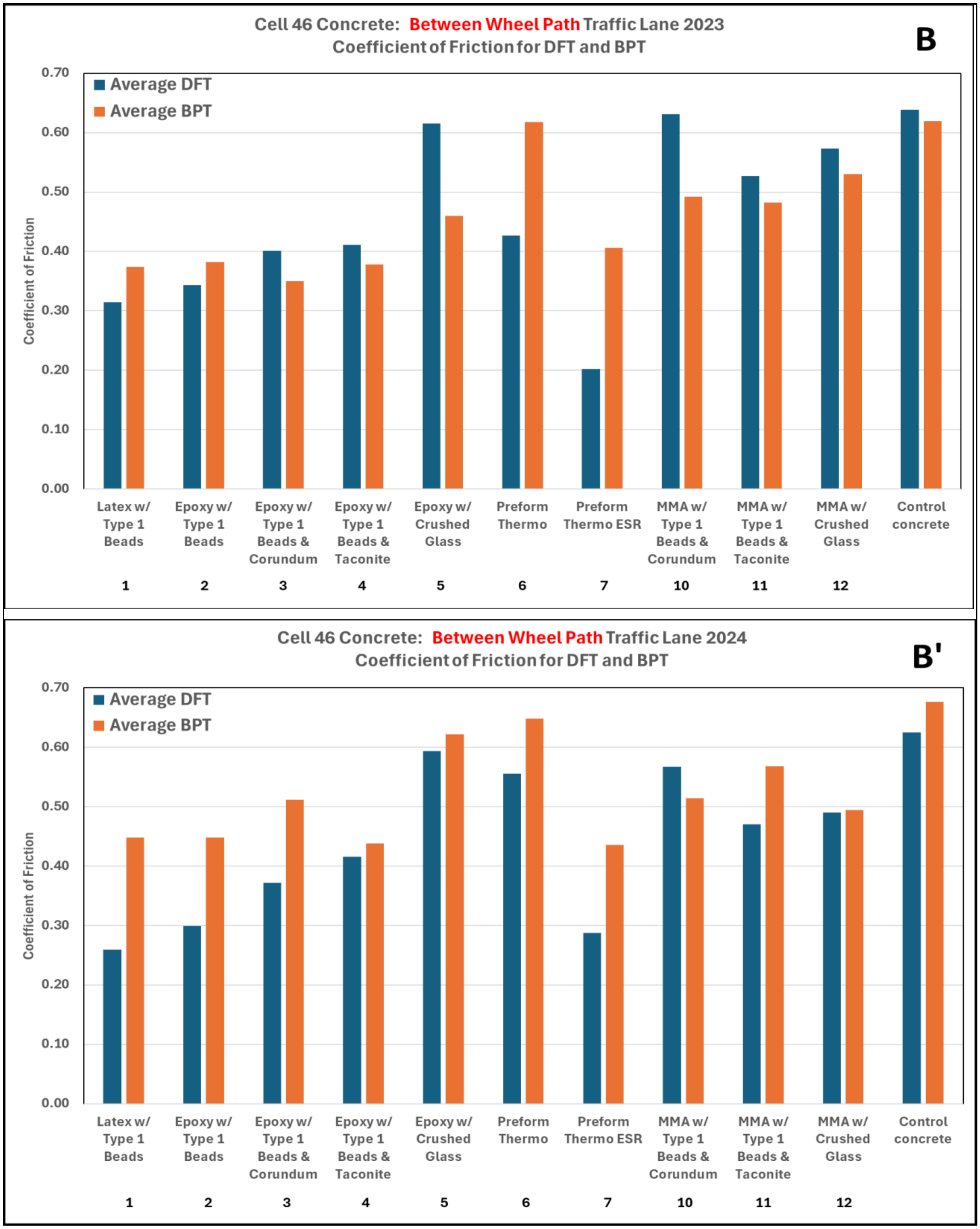


Figure 6.10 DFT and BPT measurements BWP of Cell 46 markings and control (B and B')

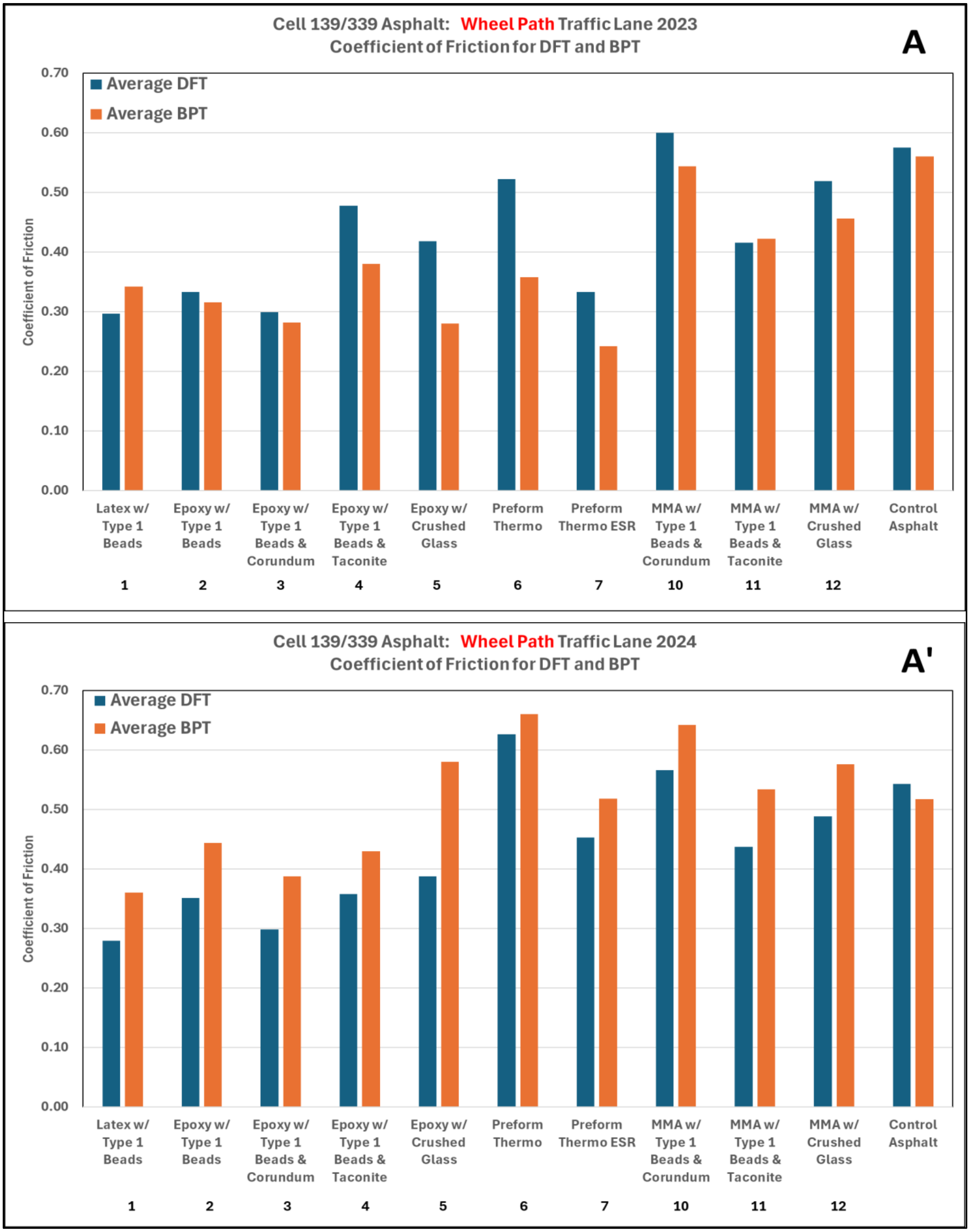


Figure 6.11 DFT and BPT measurements in WP of Cell 139/339 markings and control (A and A')

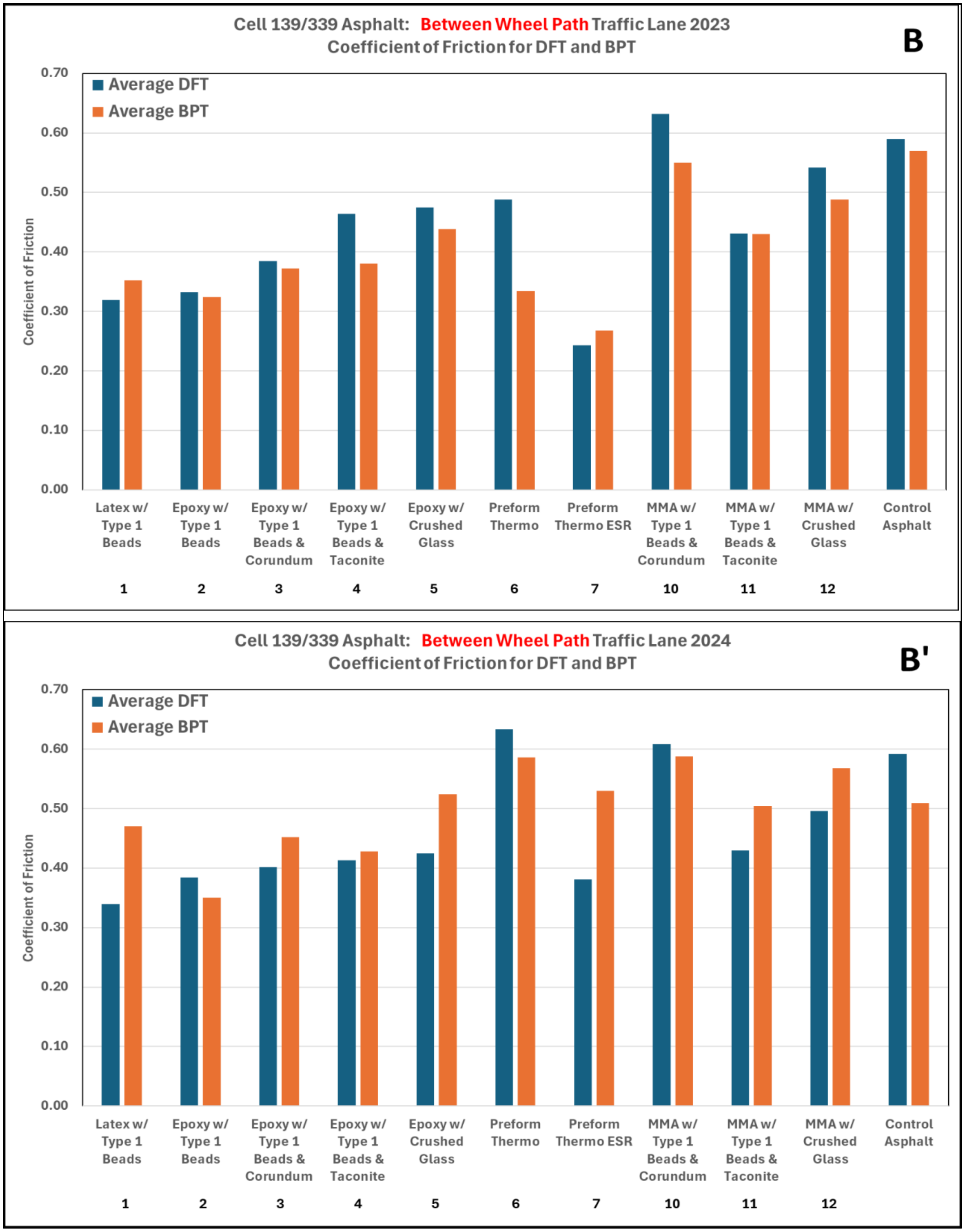


Figure 6.12 DFT and BPT measurements BWP of Cell 139/339 markings and control (B and B')

Both measurement techniques returned friction values that correlated reasonably well, as shown in Figure 6.11, for readings taken within the wheel path of both pavements. DFT and BPT measurements were more strongly correlated for asphalt Cell 139 than concrete Cell 46, as their respective R^2 values indicate (Cell 139 R^2 values are shown on the lower left; Cell 46 R^2 values are shown on the upper right).

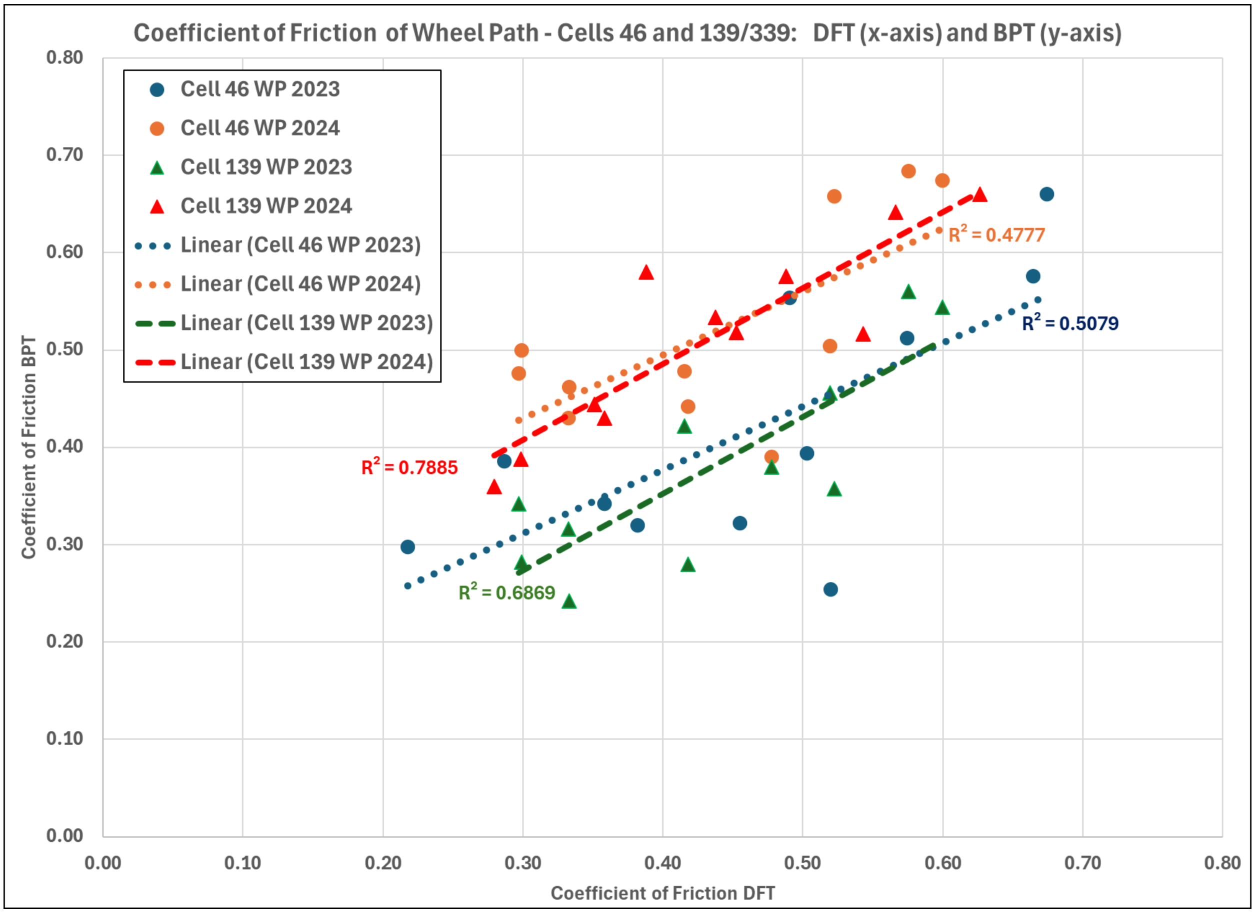


Figure 6.13 Scatter plot of 2023 and 2024 DFT vs BPT measurements made in the wheel path of Cell 46 and Cell 139, showing trend lines and linear regression (R2) values

6.2 Data analysis

Quantifying the friction differential (i.e., the friction delta) between pavement markings and the pavements to which they are applied has been the project's primary objective. The magnitude of the friction differential (delta) between the Control values and those of the markings is a key metric for assessing potential safety issues. For example, a coefficient of friction <0.4 (or a skid number <40, as determined by a locked wheel friction tester operated at 40 mph/64 km/h) has generally been considered problematic for low and moderate traffic levels (Papageorgiou and Mouratidis (2013). Likewise, a recent Highways England (2021) study lists various levels of friction for specific situations such as approaches to pedestrian crossings and roundabouts. With that in mind, pavement markings having friction properties which correspond most closely to the pavements they are applied to would seem to be a desirable installation objective.

6.2.1 DFT and BPT testing

The two sets of DFT and BPT data, collected in November 2023 and June 2024 and the July 2024 SCRIM testing data form the basis of our analysis. What follows is a summary of:

- the friction differential as determined by all three project test methods
- the degree of change in the friction characteristics of the markings from 2023 to 2024, as an indicator of wear; and
- the consistency and/or variability of the November 2023 and June 2024 DFT and BPT data.

The consistency (or variability) of the DFT and BPT data from November 2023 and June 2024, was evaluated by comparing friction measurements made of the unmarked (control) pavements and friction measurements made of the pavement markings *between the wheel paths* of the traffic lane. The *between the wheel paths* measurements would theoretically represent markings that remained unimpacted (unworn) by the Low Volume Road's circulating truck.

Table 6.1 illustrates how the 2023 and 2024 coefficients of friction determined by the DFT and BPT for Cells 46 and 139 compare: lower values reds and oranges, higher values greens.

Based on the coefficients of friction shown in Section 5.1.1, the friction differentials (deltas) of the markings relative to the pavements to which they were applied were determined for both DFT and BPT measurements made in 2023 and 2024. This was done by simply calculating the percentage difference each marking's coefficient of friction differed from that of their respective control pavements. The resulting percentage differences are color-coded as follows in Table 6.1 to illustrate the magnitude of the differentials:

Table 6.1 The friction differentials of markings relative to pavements

< +/- 12.5%
+/- 12.5 to 25.0%
+/- 25.0 to 50.0%
> +/- 50.0%

Table 6.2 Average coefficient of friction values as measured by DFT (A) and BPT (B)

A

DFT 2023/2024	Test Cell 46: Concrete	Coefficient of Friction November 2023			Coefficient of Friction June 2024	
Code	Marking Type	Wheel Path	Between Wheel Paths		Wheel Path	Between Wheel Paths
1	Latex w/ Type 1 Beads	0.29	0.31		0.29	0.26
2	Epoxy w/ Type 1 Beads	0.36	0.34		0.30	0.30
3	Epoxy w/ Type 1 Beads &	0.45	0.40		0.42	0.37
4	Epoxy w/ Type 1 Beads &	0.38	0.41		0.35	0.42
5	Epoxy w/ Crushed Glass	0.52	0.62		0.52	0.59
6	Preform Thermo	0.50	0.43		0.59	0.56
7	Preform Thermo ESR	0.22	0.20		0.30	0.29
10	MMA w/ Type 1 Beads &	0.66	0.63		0.64	0.57
11	MMA w/ Type 1 Beads &	0.49	0.53		0.45	0.47
12	MMA w/ Crushed Glass	0.57	0.57		0.52	0.49
0	Control Concrete	0.67	0.64		0.63	0.63

DFT 2023/2024	Test Cell 139/339: Asphalt	Coefficient of Friction November 2023			Coefficient of Friction June 2024	
Code	Marking Type	Wheel Path	Between Wheel Paths		Wheel Path	Between Wheel Paths
1	Latex w/ Type 1 Beads	0.30	0.32		0.28	0.34
2	Epoxy w/ Type 1 Beads	0.33	0.33		0.35	0.38
3	Epoxy w/ Type 1 Beads &	0.30	0.38		0.30	0.40
4	Epoxy w/ Type 1 Beads &	0.48	0.46		0.36	0.41
5	Epoxy w/ Crushed Glass	0.42	0.47		0.39	0.42
6	Preform Thermo	0.52	0.49		0.63	0.63
7	Preform Thermo ESR	0.33	0.24		0.45	0.38
10	MMA w/ Type 1 Beads &	0.60	0.63		0.57	0.61
11	MMA w/ Type 1 Beads &	0.42	0.43		0.44	0.43
12	MMA w/ Crushed Glass	0.52	0.54		0.49	0.50
0	Control Asphalt	0.58	0.59		0.54	0.59

B

BPT 2023/2024	Test Cell 46: Concrete	Coefficient of Friction November 2023			Coefficient of Friction June 2024	
Code	Marking Type	Wheel Path	Between Wheel Paths		Wheel Path	Between Wheel Paths
1	Latex w/ Type 1 Beads	0.39	0.37		0.48	0.45
2	Epoxy w/ Type 1 Beads	0.34	0.38		0.43	0.45
3	Epoxy w/ Type 1 Beads &	0.32	0.35		0.5	0.51
4	Epoxy w/ Type 1 Beads &	0.32	0.38		0.39	0.44
5	Epoxy w/ Crushed Glass	0.25	0.46		0.44	0.62
6	Preform Thermo	0.39	0.62		0.66	0.65
7	Preform Thermo ESR	0.3	0.41		0.46	0.44
10	MMA w/ Type 1 Beads &	0.58	0.49		0.67	0.51
11	MMA w/ Type 1 Beads & Taconite	0.55	0.48		0.48	0.57
12	MMA w/ Crushed Glass	0.51	0.53		0.5	0.49
0	Control Concrete	0.66	0.62		0.68	0.68

BPT 2023	Test Cell 139/339:	Coefficient of Friction November 2023			Coefficient of Friction June 2024	
Marking Code	Marking Type	Wheel Path	Between Wheel Paths		Wheel Path	Between Wheel Paths
1	Latex w/ Type 1 Beads	0.34	0.35		0.36	0.47
2	Epoxy w/ Type 1 Beads	0.32	0.32		0.44	0.35
3	Epoxy w/ Type 1 Beads &	0.28	0.37		0.39	0.45
4	Epoxy w/ Type 1 Beads &	0.38	0.38		0.43	0.43
5	Epoxy w/ Crushed Glass	0.28	0.44		0.58	0.52
6	Preform Thermo	0.36	0.33		0.66	0.59
7	Preform Thermo ESR	0.24	0.27		0.52	0.53
10	MMA w/ Type 1 Beads &	0.54	0.55		0.64	0.59
11	MMA w/ Type 1 Beads & Taconite	0.42	0.43		0.53	0.5
12	MMA w/ Crushed Glass	0.46	0.49		0.58	0.57
0	Control Asphalt	0.56	0.57		0.52	0.51

Table 6.3 Friction differentials (percentage differences) of pavement markings applied to Cell 46 and Cell 139 for DFT (A) and BPT (B) measurements in 2023 and 2024, relative to each cell's pavement (Control)

	DFT 2023	**MnROAD Test Cell 46: Concrete**	**% Difference from Control: Nov 2023**		**% Difference from Control: June 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**	**Wheel Path**	**Between Wheel Paths**
	1	Latex w/ Type 1 Beads	-57.5%	-50.8%	-54.3%	-58.5%
	2	Epoxy w/ Type 1 Beads	-46.9%	-46.2%	-51.7%	-52.2%
	3	Epoxy w/ Type 1 Beads &	-32.6%	-37.1%	-33.0%	-40.5%
	4	Epoxy w/ Type 1 Beads &	-43.4%	-35.7%	-44.5%	-33.5%
	5	Epoxy w/ Crushed Glass	-22.9%	-3.6%	-17.9%	-5.0%
	6	Preform Thermo	-25.4%	-33.1%	-6.8%	-11.2%
	7	Preform Thermo ESR	-67.7%	-68.4%	-51.8%	-54.0%
	10	MMA w/ Type 1 Beads &	-1.5%	-1.2%	1.1%	-9.3%
	11	MMA w/ Type 1 Beads & Taconite	-27.3%	-17.5%	-27.9%	-24.7%
	12	MMA w/ Crushed Glass	-14.9%	-10.2%	-17.7%	-21.5%
	0	Control Concrete	0.0%	0.0%	0.0%	0.0%
A	**DFT 2023**	**MnROAD Test Cell 139/339: Asphalt**	**% Difference from Control: Nov 2023**		**% Difference from Control: June 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**	**Wheel Path**	**Between Wheel Paths**
	1	Latex w/ Type 1 Beads	-48.4%	-45.9%	-48.6%	-42.7%
	2	Epoxy w/ Type 1 Beads	-42.2%	-43.6%	-35.4%	-35.2%
	3	Epoxy w/ Type 1 Beads &	-48.1%	-34.9%	-45.1%	-32.1%
	4	Epoxy w/ Type 1 Beads &	-17.0%	-21.3%	-34.1%	-30.2%
	5	Epoxy w/ Crushed Glass	-27.4%	-19.5%	-28.6%	-28.3%
	6	Preform Thermo	-9.2%	-17.2%	15.3%	6.9%
	7	Preform Thermo ESR	-42.1%	-58.8%	-16.7%	-35.7%
	10	MMA w/ Type 1 Beads &	4.2%	7.2%	4.3%	2.7%
	11	MMA w/ Type 1 Beads & Taconite	-27.8%	-27.0%	-19.4%	-27.4%
	12	MMA w/ Crushed Glass	-9.7%	-8.3%	-10.1%	-16.3%
	0	Control Asphalt	0.0%	0.0%	0.0%	0.0%
	BPT 2023	**MnROAD Test Cell 46: Concrete**	**% Difference from Control: Nov 2023**		**% Difference from Control: June 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**	**Wheel Path**	**Between Wheel Paths**
	1	Latex w/ Type 1 Beads	-41.5%	-39.7%	-30.4%	-33.7%
	2	Epoxy w/ Type 1 Beads	-48.2%	-38.4%	-37.1%	-33.7%
	3	Epoxy w/ Type 1 Beads &	-51.2%	-43.5%	-26.9%	-24.3%
	4	Epoxy w/ Type 1 Beads &	-51.5%	-39.0%	-43.0%	-35.2%
	5	Epoxy w/ Crushed Glass	-61.5%	-25.8%	-35.4%	-8.0%
	6	Preform Thermo	-40.3%	-0.3%	-3.8%	-4.1%
	7	Preform Thermo ESR	-54.8%	-34.5%	-32.5%	-35.5%
	10	MMA w/ Type 1 Beads &	-12.7%	-20.6%	-1.5%	-24.0%
	11	MMA w/ Type 1 Beads & Taconite	-16.1%	-22.3%	-30.1%	-16.0%
	12	MMA w/ Crushed Glass	-22.4%	-14.5%	-26.3%	-26.9%
	0	Control Concrete	0.0%	0.0%	0.0%	0.0%
B	**BPT 2023**	**MnROAD Test Cell 139/339: Asphalt**	**% Difference from Control: Nov 2023**		**% Difference from Control: June 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**	**Wheel Path**	**Between Wheel Paths**
	1	Latex w/ Type 1 Beads	-38.9%	-38.2%	-30.4%	-7.7%
	2	Epoxy w/ Type 1 Beads	-43.6%	-43.2%	-14.1%	-31.2%
	3	Epoxy w/ Type 1 Beads &	-49.6%	-34.7%	-25.0%	-11.2%
	4	Epoxy w/ Type 1 Beads &	-32.1%	-33.3%	-16.8%	-15.9%
	5	Epoxy w/ Crushed Glass	-50.0%	-23.2%	12.2%	2.9%
	6	Preform Thermo	-36.1%	-41.4%	27.7%	15.1%
	7	Preform Thermo ESR	-56.8%	-53.0%	0.2%	4.1%
	10	MMA w/ Type 1 Beads &	-2.9%	-3.5%	24.2%	15.5%
	11	MMA w/ Type 1 Beads & Taconite	-24.6%	-24.6%	3.3%	-1.0%
	12	MMA w/ Crushed Glass	-18.6%	-14.4%	11.4%	11.6%
	0	Control Asphalt	0.0%	0.0%	0.0%	0.0%

The DFT and BPT methods produced comparable results. The epoxy-based pavement markings generally had a significantly higher friction differential from the control pavements than that of MMA-based markings, in which the same friction-enhancing materials (corundum, taconite, and crushed glass) are used in combination with retroreflective beads. While the epoxy-based markings used Type 1 Beads, MMA-based markings 10 and 11 used a bead mixture referred to as the "Colorado blend" in combination with corundum and taconite, respectively, and a bead mixture referred to as the "Utah blend" for potters crushed glass (12). The Colorado and Utah blends are similar (and are larger) than Type 1. (E. Peterson, personal communication, October 14, 2024).

The degree of difference between these three Epoxy-based (3-5) and MMA-based (10-12) markings – as well as Marking 2 (Epoxy w/ Type 1 Beads) – is summarized in Table 6.4 and further illustrated in the series of histogram plots shown in Figures 6.11 and 6.12.

Table 6.4 Percentage difference between MMA (10-12) and Epoxy-based (3-5) markings by DFT (A) and BPT (B)

	DFT 2023	**MnROAD Test Cell 46: Concrete**	**% Diff. MMA vs Epoxy: Nov 2023**			**% Diff. MMA vs Epoxy: Nov 2024**	
A	**Marking Code**	**Marking Type**	**Wheel Path**	**Between Wheel Paths**		**Wheel Path**	**Between Wheel Paths**
	10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	46.1%	57.1%		50.9%	52.5%
	11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	28.4%	28.3%		29.9%	13.2%
	12 vs 5	MMA vs Epoxy: w/ Crushed Glass	10.4%	-6.9%		0.3%	-17.4%
	DFT 2023	**MnROAD Test Cell 139/339: Asphalt**	**% Diff. MMA vs Epoxy: Nov 2023**			**% Diff. MMA vs Epoxy: Nov 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**		**Wheel Path**	**Between Wheel Paths**
	10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	100.7%	64.5%		89.8%	51.3%
	11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	-13.0%	-7.2%		22.2%	3.9%
	12 vs 5	MMA vs Epoxy: w/ Crushed Glass	24.3%	14.0%		25.8%	16.9%
	BPT 2023	**MnROAD Test Cell 46: Concrete**	**% Diff. MMA vs Epoxy: Nov 2023**			**% Diff. MMA vs Epoxy: Nov 2024**	
B	**Marking Code**	**Marking Type**	**Wheel Path**	**Between Wheel Paths**		**Wheel Path**	**Between Wheel Paths**
	10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	78.9%	40.6%		34.8%	0.4%
	11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	73.1%	27.5%		22.6%	29.7%
	12 vs 5	MMA vs Epoxy: w/ Crushed Glass	101.6%	15.2%		14.0%	-20.6%
	BPT 2023	**MnROAD Test Cell 139/339: Asphalt**	**% Diff. MMA vs Epoxy: Nov 2023**			**% Diff. MMA vs Epoxy: Nov 2024**	
	Marking Code	**Marking Type**	**Wheel Path**	**Between Wheel Paths**		**Wheel Path**	**Between Wheel Paths**
	10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	92.9%	47.8%		65.5%	30.1%
	11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	11.1%	13.2%		24.2%	17.8%
	12 vs 5	MMA vs Epoxy: w/ Crushed Glass	62.9%	11.4%		-0.7%	8.4%

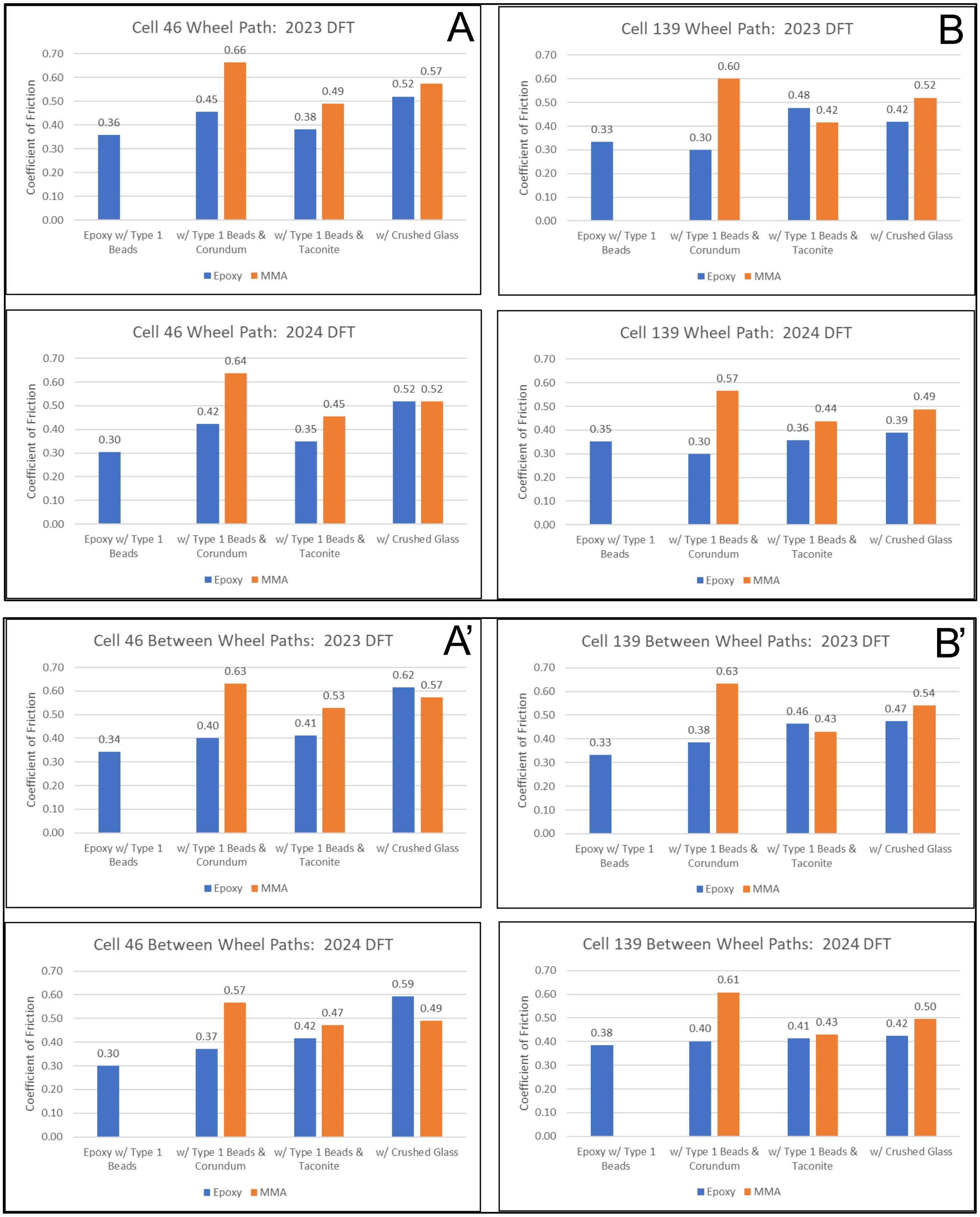


Figure 6.14 DFT-measured coefficients of friction for epoxy-based and MMA-based markings: wheel path (A and B) and between wheel paths (A' and B') in 2023 and 2024 of Cells 46 and 139, respectively.

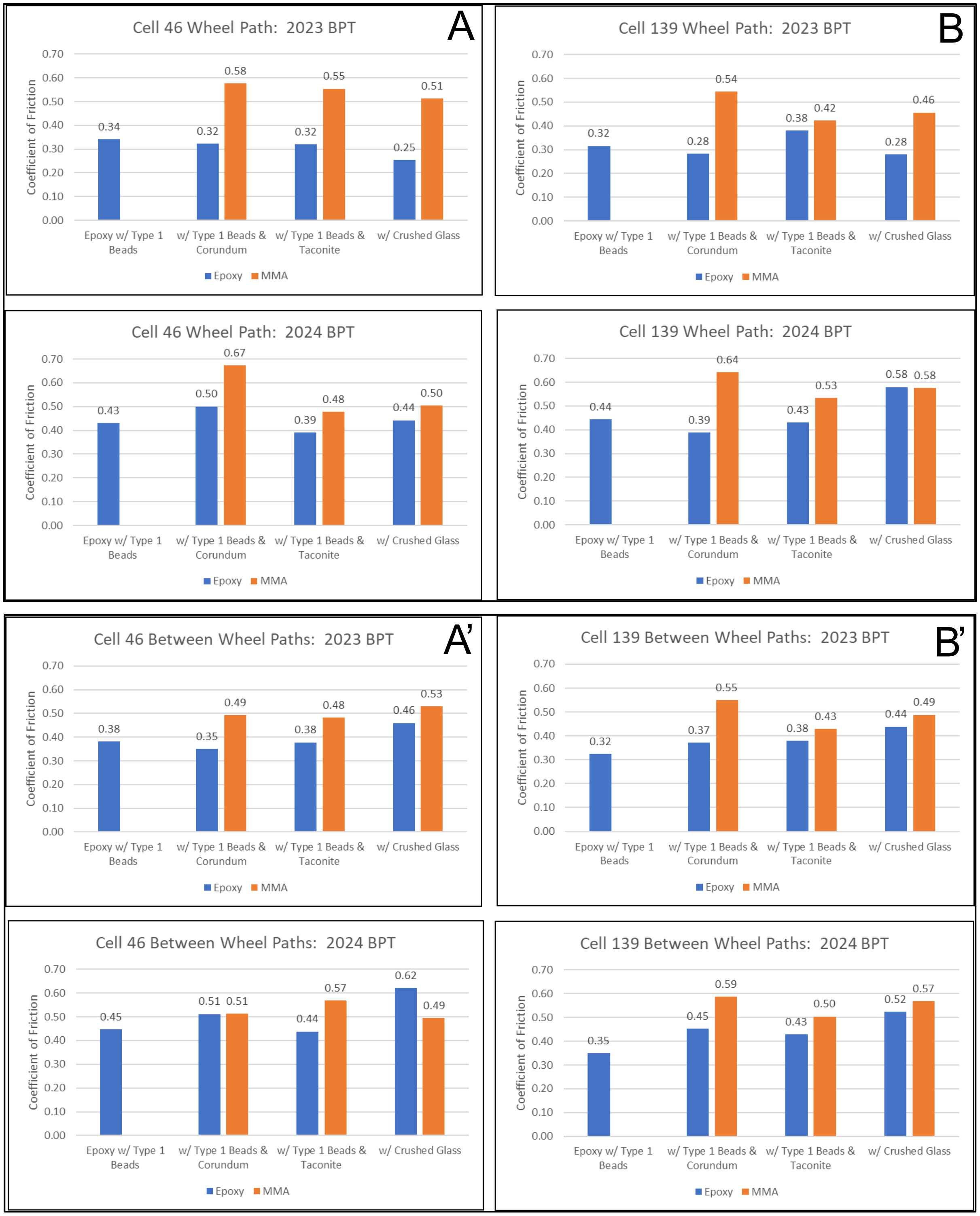


Figure 6.15 BPT-measured coefficients of friction for epoxy-based and MMA-based markings: wheel path (A and B) and between wheel paths (A’ and B’) in 2023 and 2024 of Cells 46 and 139, respectively.

6.2.2 SCRIM testing relative to DFT testing

The SCRIM tested the wheel path of the trafficked and non-trafficked lanes of both test cells at three speeds: 15 mph (24.1 km/h), 30 mph (48.3 km/h), and 40 mph (64.4 km/h). Triplicate runs were made at each speed, and the results are shown in Tables 6.5 and 6.6.

Table 6.5 shows the results obtained for the pavement markings only. Table 6.6 shows the SCRIM friction testing results for each marking and for the unmarked (control) intervals of Cells 46 and 139. In Table 6.6, the unmarked pavement intervals between markings are designated as “Control X-Y”, with X and Y representing the marking numbers which bracket a particular control interval. For example, Control 3-4 represents the unmarked portion of pavement between Markings 3 and 4, while the portions of the pavement immediately preceding the first marking (1) and following the last marking (12) are designated as “Control Before 1” and “Control After 12”, respectively.

Table 6.5 SCRIM friction testing results: speed-corrected rolling average at test speeds of 15, 30, and 40 mph

Test Cells and Markings			SCRIM Results 2024			SCRIM Results 2024		
Cell	Marking	Marking Type	Traffic Lane 15 mph avg	Traffic 30 mph avg	Traffic 40 mph avg	No Traffic 15 mph avg	No Traffic 30 mph avg	No Traffic 40 mph avg
46	1	Latex w/ Type 1 Beads	22.92	16.58	9.03	49.00	35.24	32.06
46	2	Epoxy w/ Type 1 Beads	33.76	30.01	26.64	39.77	36.45	33.89
46	3	Epoxy w/ Type 1 Beads & Corundum	31.87	28.13	22.24	37.83	20.14	26.25
46	4	Epoxy w/ Type 1 Beads & Taconite	34.32	27.57	25.48	44.07	36.00	29.37
46	5	Epoxy w/ Crushed Glass	46.23	43.48	45.89	47.81	45.86	34.57
46	6	Preform Thermo	57.70	47.38	40.62	58.35	46.80	38.50
46	7	Preform Thermo ESR	46.16	30.54	26.97	46.98	22.35	17.74
46	10	MMA w/ Type 1 Beads & Corundum	58.67	53.68	57.33	56.06	51.83	48.11
46	11	MMA w/ Type 1 Beads & Taconite	65.25	61.11	50.73	63.39	57.75	52.38
46	12	MMA w/ Crushed Glass	56.04	52.22	45.92	62.64	59.42	59.93
46	Control	Control concrete	*66.62*	*69.59*	*69.61*	*74.60*	*76.28*	*75.12*
139	1	Latex w/ Type 1 Beads	39.50	25.11	6.04	43.48	29.56	18.74
139	2	Epoxy w/ Type 1 Beads	34.15	31.14	22.30	37.88	29.54	29.43
139	3	Epoxy w/ Type 1 Beads & Corundum	38.96	31.45	26.27	38.34	32.33	19.33
139	4	Epoxy w/ Type 1 Beads & Taconite	37.85	33.51	31.26	41.33	34.42	26.25
139	5	Epoxy w/ Crushed Glass	39.25	36.38	36.60	41.59	33.91	24.43
139	6	Preform Thermo	54.77	39.39	37.58	57.95	41.68	32.12
139	7	Preform Thermo ESR	44.65	30.31	21.88	51.42	40.43	28.61
139	10	MMA w/ Type 1 Beads & Corundum	58.56	48.56	45.20	62.14	49.27	47.44
139	11	MMA w/ Type 1 Beads & Taconite	47.66	39.88	36.24	50.81	40.87	34.37
139	12	MMA w/ Crushed Glass	55.95	52.90	45.96	58.44	56.14	50.46
139	Control	Control asphalt	*63.63*	*65.61*	*66.55*	*71.14*	*67.84*	*66.23*

Table 6.6 SCRIM friction testing results: alternating marked and unmarked (control) intervals – Cells 46 and 139

Cell	Marking	Traffic 15mph avg	Traffic 30mph avg	Traffic 40mph avg	No Traffic 15mph avg	No Traffic 30mph avg	No Traffic 40mph avg
46	Control Before 1	64.03	67.16	67.66	75.78	79.73	81.47
46	1	22.92	16.58	9.03	49.00	35.24	32.06
46	Control 1-2	64.66	68.51	66.81	75.77	76.49	75.99
46	2	33.76	30.01	26.64	39.77	36.45	33.89
46	Control 2-3	63.80	66.31	67.43	75.68	78.50	76.37
46	3	31.87	28.13	22.24	37.83	20.14	26.25
46	Control 3-4	66.16	69.27	70.08	77.03	77.59	78.23
46	4	34.32	27.57	25.48	44.07	36.00	29.37
46	Control 4-5	67.50	71.04	69.74	76.80	78.30	75.83
46	5	46.23	43.48	45.89	47.81	45.86	34.57
46	Control 5-6	67.80	71.11	74.13	76.33	76.51	75.55
46	6	57.70	47.38	40.62	58.35	46.80	38.50
46	Control 6-7	68.92	73.12	73.60	74.18	74.79	73.26
46	7	46.16	30.54	26.97	46.98	22.35	17.74
46	Control 7-10	68.99	72.03	72.99	72.44	74.90	72.34
46	10	58.67	53.68	57.33	56.06	51.83	48.11
46	Control 10-11	67.59	69.19	68.61	73.27	73.37	72.51
46	11	65.25	61.11	50.73	63.39	57.75	52.38
46	Control 11-12	67.03	69.57	68.16	72.17	74.99	71.99
46	12	56.04	52.22	45.92	62.64	59.42	59.93
46	Control After 12	66.39	68.23	66.49	71.11	73.93	72.78
46	*Control Average*	*66.62*	*69.59*	*69.61*	*74.60*	*76.28*	*75.12*
139	Control Before 1	64.73	68.21	70.34	70.91	66.17	65.74
139	1	39.50	25.11	6.04	43.48	29.56	18.74
139	Control 1-2	62.88	65.69	66.65	70.23	68.90	65.50
139	2	34.15	31.14	22.30	37.88	29.54	29.43
139	Control 2-3	63.65	66.07	64.32	71.76	66.18	65.52
139	3	38.96	31.45	26.27	38.34	32.33	19.33
139	Control 3-4	63.40	63.84	64.19	71.79	67.04	61.71
139	4	37.85	33.51	31.26	41.33	34.42	26.25
139	Control 4-5	61.38	63.33	63.79	70.82	66.87	63.74
139	5	39.25	36.38	36.60	41.59	33.91	24.43
139	Control 5-6	63.62	64.75	66.08	70.80	65.83	65.39
139	6	54.77	39.39	37.58	57.95	41.68	32.12
139	Control 6-7	66.41	67.71	69.23	73.17	67.90	67.52
139	7	44.65	30.31	21.88	51.42	40.43	28.61
139	Control 7-10	63.12	64.10	65.58	70.84	68.34	66.87
139	10	58.56	48.56	45.20	62.14	49.27	47.44
139	Control 10-11	63.86	67.37	67.91	71.50	70.43	70.77
139	11	47.66	39.88	36.24	50.81	40.87	34.37
139	Control 11-12	63.79	66.48	68.65	70.77	69.30	66.95
139	12	55.95	52.90	45.96	58.44	56.14	50.46
139	Control After 12	63.10	64.16	65.37	69.98	69.25	68.79
139	*Control Average*	*63.63*	*65.61*	*66.55*	*71.14*	*67.84*	*66.23*

DFT results corresponding to the three SCRIM testing speeds were extracted from the DFT datasets (the sources for Figures 6.1 to 6.4) to allow for a direct speed-to-speed (and average DFT) comparison of the two testing methods.

Figures 6.13 and 6.14 illustrate the SCRIM friction numbers relative to the unmarked intervals immediately before, between, and after the pavement markings for Cells 46 and 139, respectively. The SCRIM friction numbers are reported in the format used in AASHTO T242 (1996) or ASTM E274 (2015) standard for the locked-wheel tester method.

NOTE: *the DFT (and BPT) tested only the markings of the trafficked lane of both cells – in the wheel path (WP) and between the wheel paths (BWP) of MnROAD's circulating truck. Therefore, the "between the wheel paths" DFT and BPT friction measurements are considered analogues to SCRIM friction measurements made in the wheel path of MnROAD's non-trafficked lane and are used as proxies for that purpose in the following comparison and presentation of results and findings.*

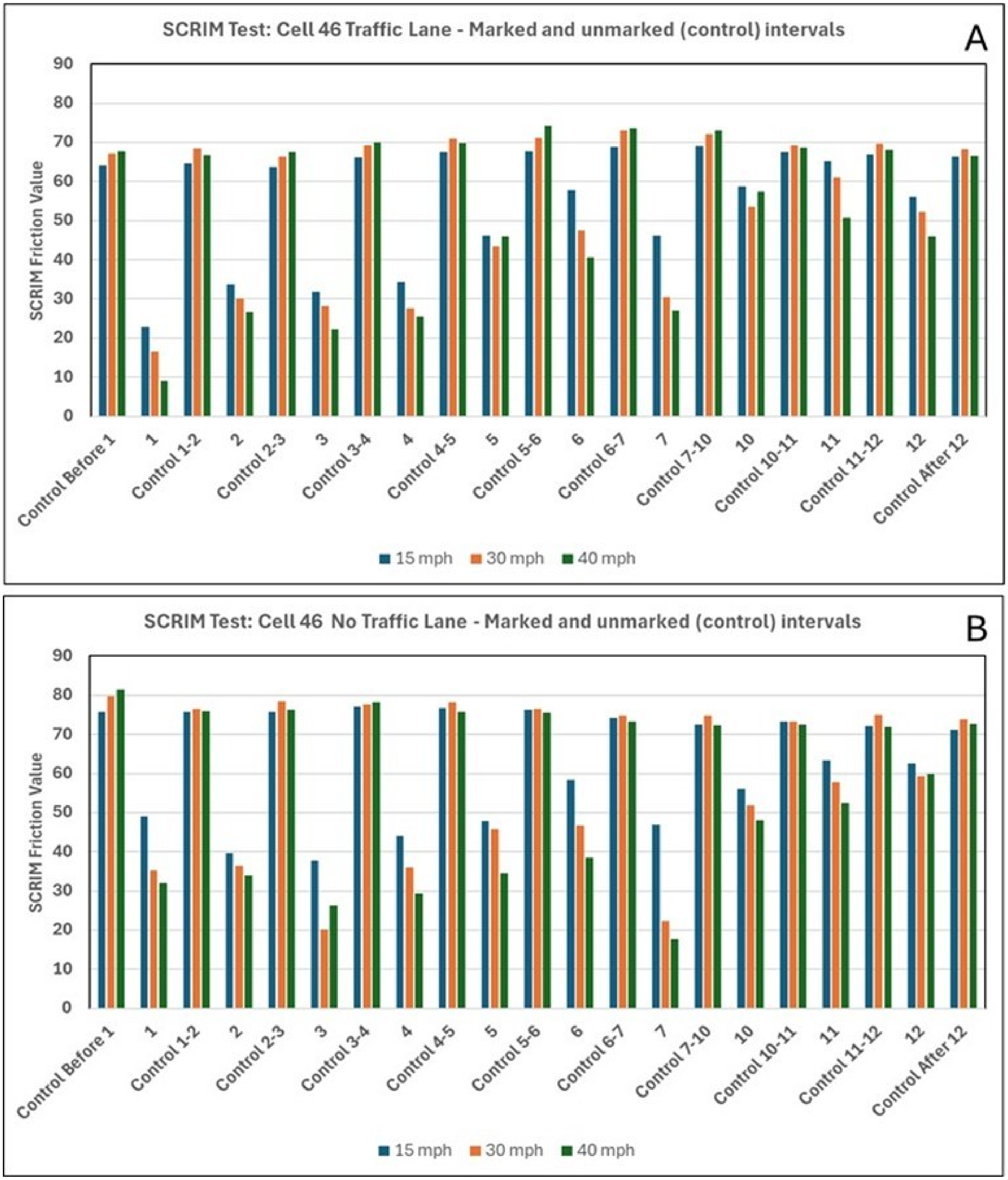


Figure 6.16 SCRIM friction numbers for Cell 46 relative to the unmarked intervals immediately before, between, and after the pavement markings: Traffic Lane (A) and No Traffic Lane (B)

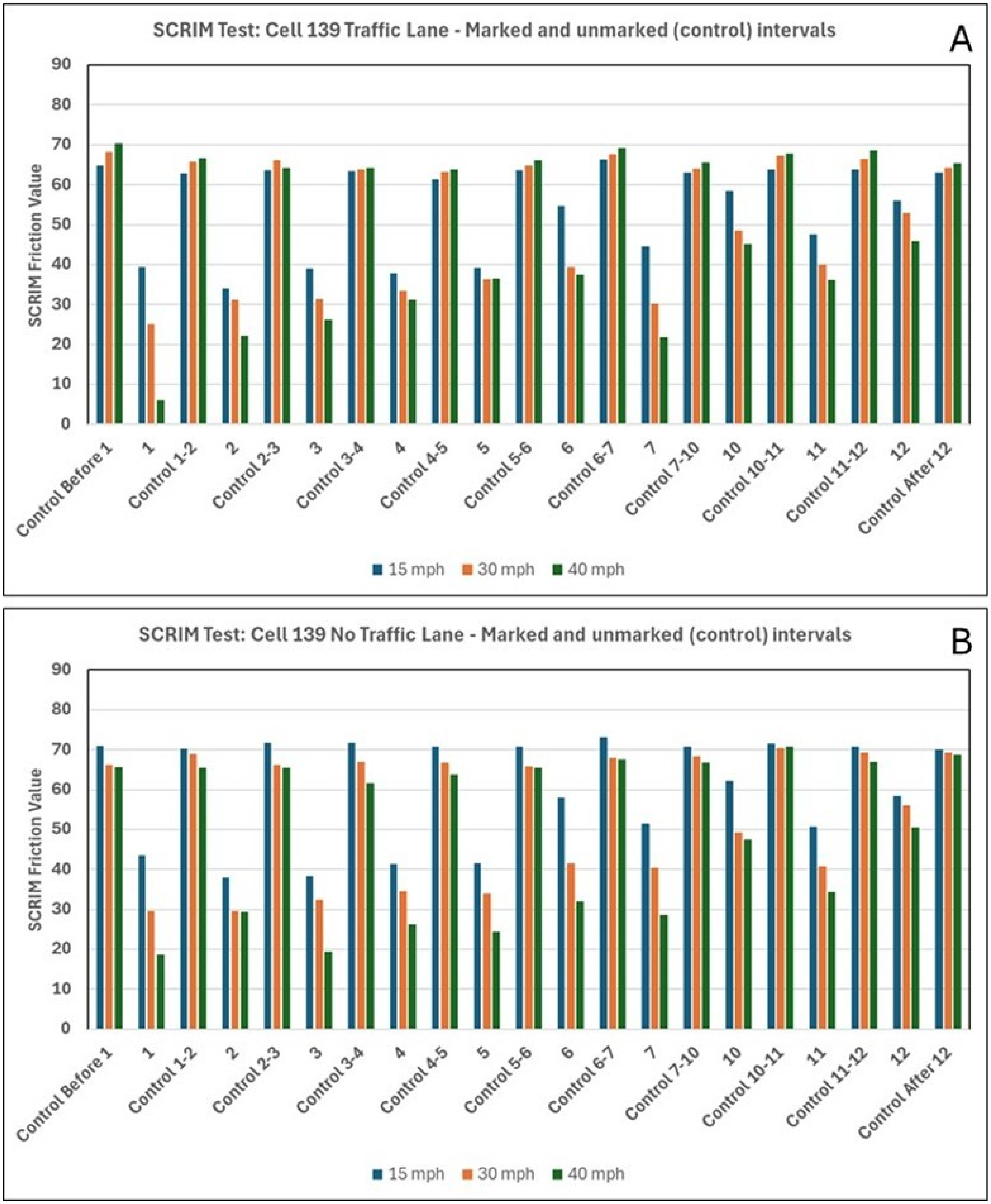


Figure 6.17 SCRIM friction numbers for Cell 139 relative to the unmarked intervals immediately before, between, and after the pavement markings: Traffic Lane (A) and No Traffic Lane (B)

The SCRIM data shows consistently similar friction values for the Control (unmarked) portions of the pavement cells and identifies degrees of pavement marking friction variability like that identified by the

DFT. A comparison of both methods' friction values shows that they are reasonably well-correlated, as indicated by the scatter plots and liner regressions shown in Figure 6.15A-A' (Cell 46) and Figure 6.16B-B' (Cell 139), especially for measurements made in the traffic lane where the pavement markings have experienced 10 months of wear.

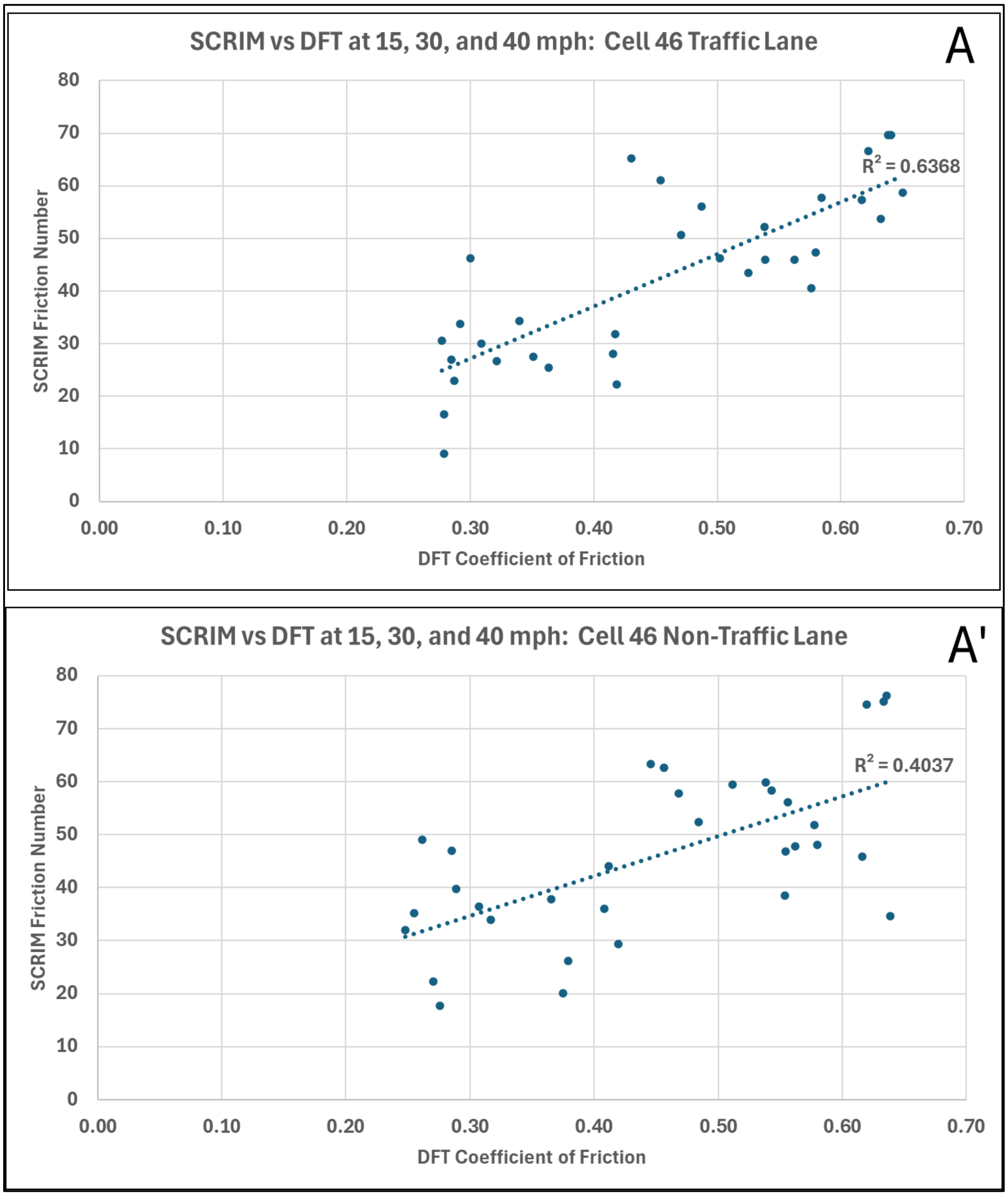


Figure 6.18 Scatter plots of SCRIM vs DFT friction values and linear regressions for Cell 46 Traffic Lane (A) and Non-Traffic Lane (A')

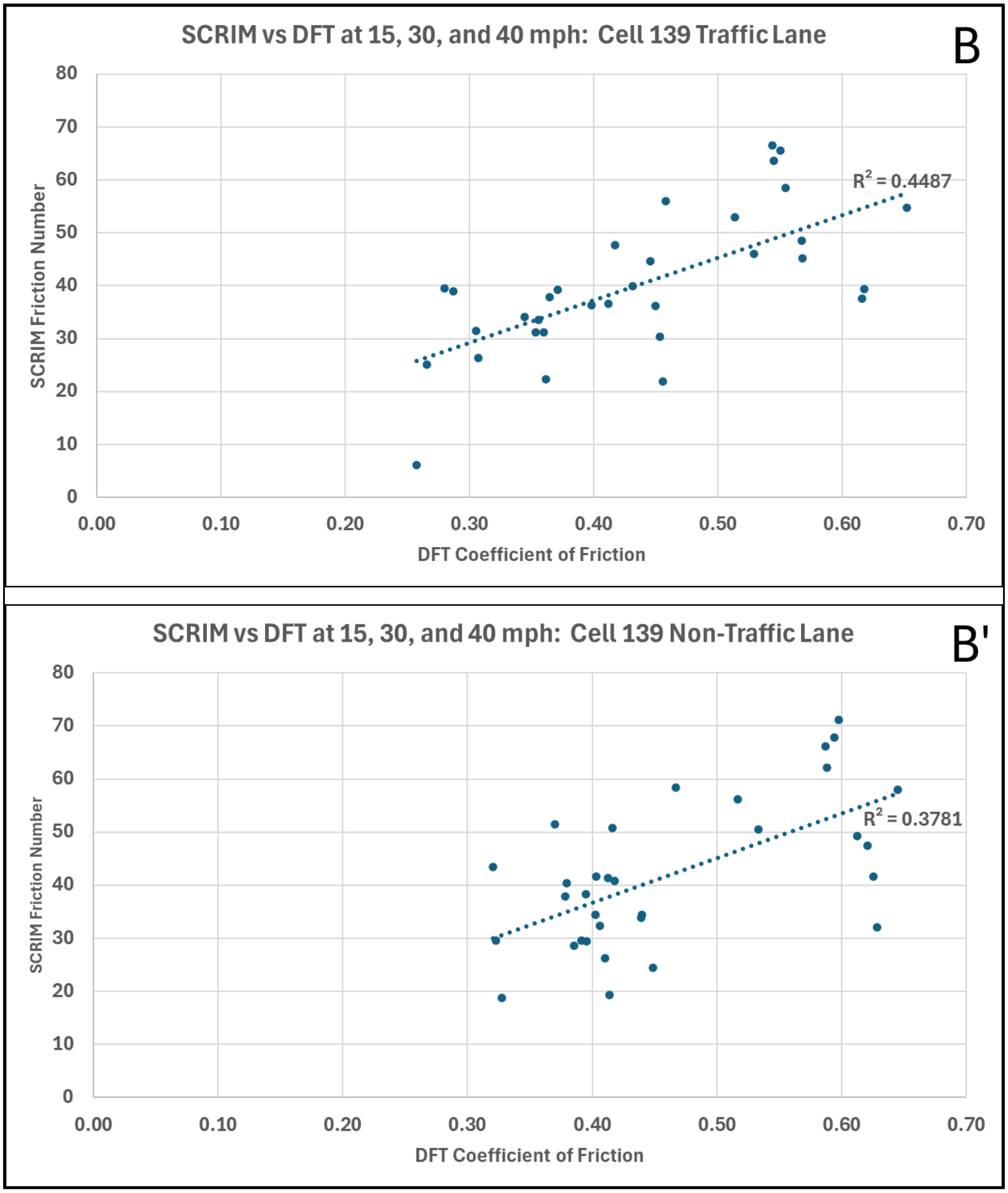


Figure 6.19 Scatter plots of SCRIM vs DFT friction values and linear regressions for Cell 139 Traffic Lane (B) and Non-Traffic Lane (B').

As measured by the SCRIM, the friction values and differentials of the pavement markings relative to the control pavements identifies similar magnitudes of variability and difference (Tables 6.7 and 6.8) to that of the DFT (compare and refer to Tables 6.1 and 6.2), including the difference between MMA and Epoxy-based markings (Table 6.9 vs 6.3A).

Also noteworthy is how the pavement markings friction values decrease, and the magnitude of their friction differentials increase as the testing speed of the SCRIM increases from 15 to 40 mph (24 to 64.4 km/h). The friction values of the *unmarked* intervals (control), however, remain largely unchanged.

Table 6.7 Average coefficient of friction values as measured by SCRIM: Cell 46 and Cell 139

SCRIM 2024	MnROAD Test Cell 46: Concrete	Friction Values Traffic Lane			Friction Values No Traffic Lane		
Marking Code	Marking Type	Traffic Lane 15 mph	Traffic Lane 30 mph	Traffic Lane 40 mph	No Traffic Lane 15 mph	No Traffic Lane 30 mph	No Traffic Lane 40 mph
1	Latex w/ Type 1 Beads	22.9	16.6	9.0	49.0	35.2	32.1
2	Epoxy w/ Type 1 Beads	33.8	30.0	26.6	39.8	36.4	33.9
3	Epoxy w/ Type 1 Beads & Corundum	31.9	28.1	22.2	37.8	20.1	26.3
4	Epoxy w/ Type 1 Beads & Taconite	34.3	27.6	25.5	44.1	36.0	29.4
5	Epoxy w/ Crushed Glass	46.2	43.5	45.9	47.8	45.9	34.6
6	Preform Thermo	57.7	47.4	40.6	58.4	46.8	38.5
7	Preform Thermo ESR	46.2	30.5	27.0	47.0	22.4	17.7
10	MMA w/ Type 1 Beads & Corundum	58.7	53.7	57.3	56.1	51.8	48.1
11	MMA w/ Type 1 Beads & Taconite	65.3	61.1	50.7	63.4	57.7	52.4
12	MMA w/ Crushed Glass	56.0	52.2	45.9	62.6	59.4	59.9
0	Control Concrete	66.6	69.6	69.6	74.6	76.3	75.1

SCRIM 2024	MnROAD Test Cell 139/339: Asphalt	Friction Values Traffic Lane			Friction Values No Traffic Lane		
Marking Code	Marking Type	Traffic Lane 15 mph	Traffic Lane 30 mph	Traffic Lane 40 mph	No Traffic Lane 15 mph	No Traffic Lane 30 mph	No Traffic Lane 40 mph
1	Latex w/ Type 1 Beads	39.5	25.1	6.0	43.5	29.6	18.7
2	Epoxy w/ Type 1 Beads	34.1	31.1	22.3	37.9	29.5	29.4
3	Epoxy w/ Type 1 Beads & Corundum	39.0	31.5	26.3	38.3	32.3	19.3
4	Epoxy w/ Type 1 Beads & Taconite	37.9	33.5	31.3	41.3	34.4	26.2
5	Epoxy w/ Crushed Glass	39.3	36.4	36.6	41.6	33.9	24.4
6	Preform Thermo	54.8	39.4	37.6	57.9	41.7	32.1
7	Preform Thermo ESR	44.7	30.3	21.9	51.4	40.4	28.6
10	MMA w/ Type 1 Beads & Corundum	58.6	48.6	45.2	62.1	49.3	47.4
11	MMA w/ Type 1 Beads & Taconite	47.7	39.9	36.2	50.8	40.9	34.4
12	MMA w/ Crushed Glass	55.9	52.9	46.0	58.4	56.1	50.5
0	Control Asphalt	63.6	65.6	66.6	71.1	67.8	66.2

Table 6.8 Friction differentials (percentage differences) of pavement markings relative to Control, by SCRIM: Cell 46 and 139

SCRIM 2024	MnROAD Test Cell 46: Concrete	% Difference from Control: Traffic Lane				% Difference from Control: No Traffic Lane		
Marking Code	Marking Type	15 mph	30 mph	40 mph		15 mph	30 mph	40 mph
1	Latex w/ Type 1 Beads	-65.6%	-76.2%	-87.0%		-34.3%	-53.8%	-57.3%
2	Epoxy w/ Type 1 Beads	-49.3%	-56.9%	-61.7%		-46.7%	-52.2%	-54.9%
3	Epoxy w/ Type 1 Beads & Corundum	-52.2%	-59.6%	-68.1%		-49.3%	-73.6%	-65.1%
4	Epoxy w/ Type 1 Beads & Taconite	-48.5%	-60.4%	-63.4%		-40.9%	-52.8%	-60.9%
5	Epoxy w/ Crushed Glass	-30.6%	-37.5%	-34.1%		-35.9%	-39.9%	-54.0%
6	Preform Thermo	-13.4%	-31.9%	-41.6%		-21.8%	-38.7%	-48.8%
7	Preform Thermo ESR	-30.7%	-56.1%	-61.3%		-37.0%	-70.7%	-76.4%
10	MMA w/ Type 1 Beads & Corundum	-11.9%	-22.9%	-17.6%		-24.8%	-32.1%	-36.0%
11	MMA w/ Type 1 Beads & Taconite	-2.1%	-12.2%	-27.1%		-15.0%	-24.3%	-30.3%
12	MMA w/ Crushed Glass	-15.9%	-25.0%	-34.0%		-16.0%	-22.1%	-20.2%
0	Control Concrete	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
SCRIM 2024	MnROAD Test Cell 139/339: Asphalt	% Difference from Control: Traffic Lane				% Difference from Control: No Traffic Lane		
Marking Code	Marking Type	15 mph	30 mph	40 mph		15 mph	30 mph	40 mph
1	Latex w/ Type 1 Beads	-37.9%	-61.7%	-90.9%		-38.9%	-56.4%	-71.7%
2	Epoxy w/ Type 1 Beads	-46.3%	-52.5%	-66.5%		-46.8%	-56.5%	-55.6%
3	Epoxy w/ Type 1 Beads & Corundum	-38.8%	-52.1%	-60.5%		-46.1%	-52.3%	-70.8%
4	Epoxy w/ Type 1 Beads & Taconite	-40.5%	-48.9%	-53.0%		-41.9%	-49.3%	-60.4%
5	Epoxy w/ Crushed Glass	-38.3%	-44.6%	-45.0%		-41.5%	-50.0%	-63.1%
6	Preform Thermo	-13.9%	-40.0%	-43.5%		-18.5%	-38.6%	-51.5%
7	Preform Thermo ESR	-29.8%	-53.8%	-67.1%		-27.7%	-40.4%	-56.8%
10	MMA w/ Type 1 Beads & Corundum	-8.0%	-26.0%	-32.1%		-12.6%	-27.4%	-28.4%
11	MMA w/ Type 1 Beads & Taconite	-25.1%	-39.2%	-45.5%		-28.6%	-39.7%	-48.1%
12	MMA w/ Crushed Glass	-12.1%	-19.4%	-30.9%		-17.8%	-17.2%	-23.8%
0	Control Asphalt	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%

Table 6.9 Percentage difference between MMA (10-12) and Epoxy-based (3-5) markings by SCRIM

SCRIM 2024	MnROAD Test Cell 46: Concrete	% Difference MMA vs Epoxy: Traffic Lane				% Difference MMA vs Epoxy: No Traffic Lane		
Marking Code	Marking Type	15 mph	30 mph	40 mph		15 mph	30 mph	40 mph
10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	84.1%	90.8%	157.9%		48.2%	157.3%	83.3%
11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	90.1%	121.6%	99.1%		43.8%	60.4%	78.3%
12 vs 5	MMA vs Epoxy: w/ Crushed Glass	21.2%	20.1%	0.1%		31.0%	29.6%	73.3%
SCRIM 2023	**MnROAD Test Cell 139/339: Asphalt**	**% Difference MMA vs Epoxy: Traffic Lane**				**% Difference MMA vs Epoxy: No Traffic Lane**		
Marking Code	**Marking Type**	**15 mph**	**30 mph**	**40 mph**		**15 mph**	**30 mph**	**40 mph**
10 vs 3	MMA vs Epoxy: w/ Type 1 Beads & Corundum	50.3%	54.4%	72.0%		62.1%	52.4%	145.4%
11 vs 4	MMA vs Epoxy: w/ Type 1 Beads & Taconite	25.9%	19.0%	16.0%		22.9%	18.7%	31.0%
12 vs 5	MMA vs Epoxy: w/ Crushed Glass	42.5%	45.4%	25.6%		40.5%	65.5%	106.6%

6.2.3 SCRIM testing, roundabout sites

A limited number of tests were performed with the SCRIM device in a number of roundabouts in in Little Canada/Vadnais Heights and in Duluth, respectively, as shown in Figure 6.17. Performing friction testing in roundabouts was one of the initial goals of the research team, but due to lack of resources for traffic control, the idea was abandoned.

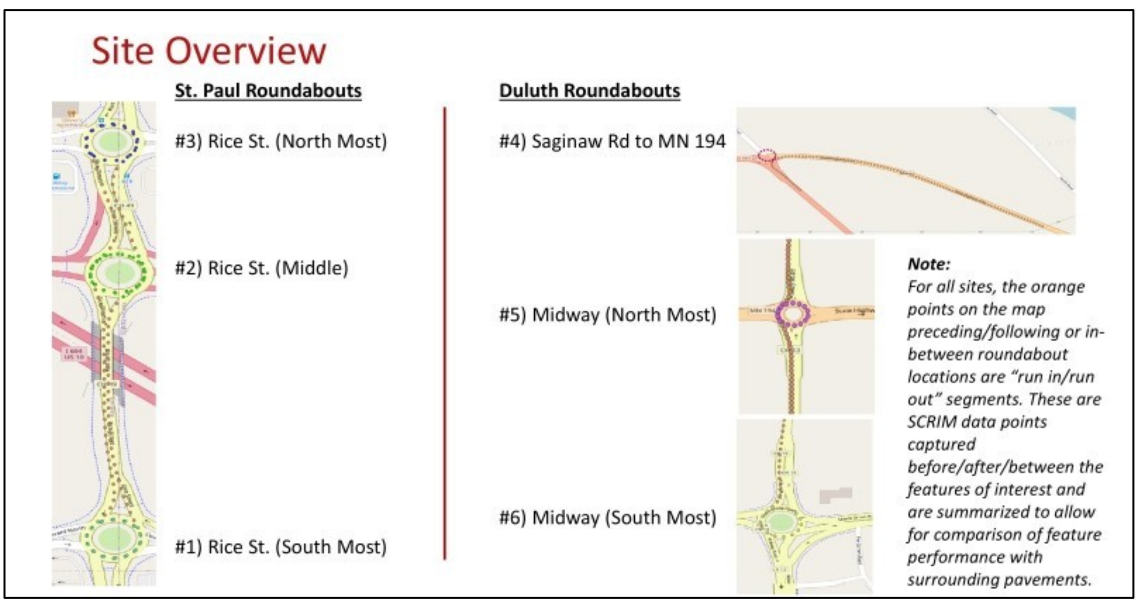


Figure 6.20 Roundabout locations for SCRIM testing

However, since SCRIM testing does not require any traffic control, the research team was finally able to obtain roundabout friction data. The results are shown in Table 6.10, and also include mean profile depth (MPD) results for surface texture.

Table 6.10 Roundabout friction and macrotexture results using SCRIM

	Site	NB Mean SR	NB Mean MPD	SB Mean SR	SB Mean MPD
St. Paul Roundabouts	1	60	0.603	53	0.553
	Run In/Out (between 1 & 2)	*57*	*0.539*	*53*	*0.503*
	2	53	0.546	56	0.522
	3	55	0.508	59	0.58
Duluth Roundabouts	4	48	0.556	-	-
	4a. Run In/Out (primarily on MN-194)	*62*	*0.706*	-	-
	5	-	-	36	0.599
	5a. Run In/Out (before & after #5	-	-	*40*	*1.48*
	6	-	-	38	0.754

It can be seen that the results obtained in St. Paul locations are similar to the values measured at MnROAD in the control sections. Locations 5 and 6 in Duluth area, appeared to have significantly lower values. This issue needs to be further investigated.

It should be mentioned that, while SCRIM is much more expensive than the other testing equipment, it provides significant more data, in a significantly shorter period of time, and measurements are done in very safe conditions without any traffic control requirements.

6.2.4 Retroreflectivity Impact

Lastly, to assess whether the retroreflectivity of a pavement marking has an impact on its friction characteristics, the 2024 retroreflectivity measurements made at MnROAD are compared to the 2024 SCRIM data at each SCRIM testing speed for Cells 46 and 139 (Figures 6.17 and 6.18, respectively).

At the lowest SCRIM test speed of 15 mph (24 km/h), there is a slight negative correlation between SCRIM friction values and retroreflectivity for the traffic lane markings. The correlation is strongest in the traffic lane of concrete Cell 46 at 15 mph (R^2 of 0.43; Figure 6.17A), but any correlation largely weakens or disappears entirely for markings with increasing SCRIM testing speeds for both test cells.

The negative correlation suggests that as retroreflectivity increases, friction decreases. However, given the fact that pavement marking friction is also nominally greater in the no traffic lane (where attrition/loss of retroreflective beads would be expected to be somewhat less than that of beads in the traffic lane), any definitive assessment of retroreflectivity impact on friction requires further investigation.

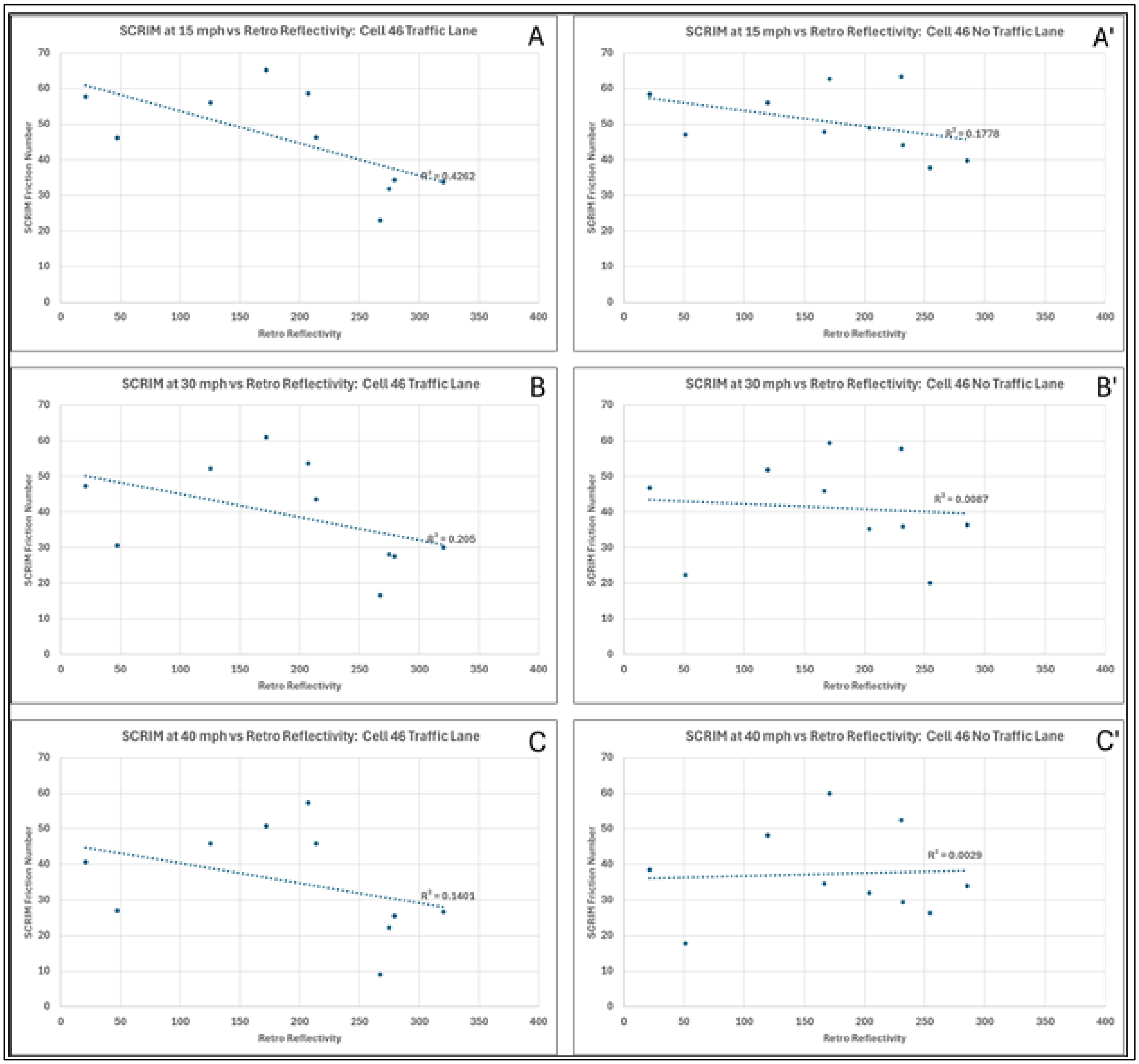


Figure 6.21 SCRIM friction measurements vs retroreflectivity for traffic and no traffic lanes at 15, 30, and 40 mph (A-A', B-B', and C-C', respectively) – Cell 46

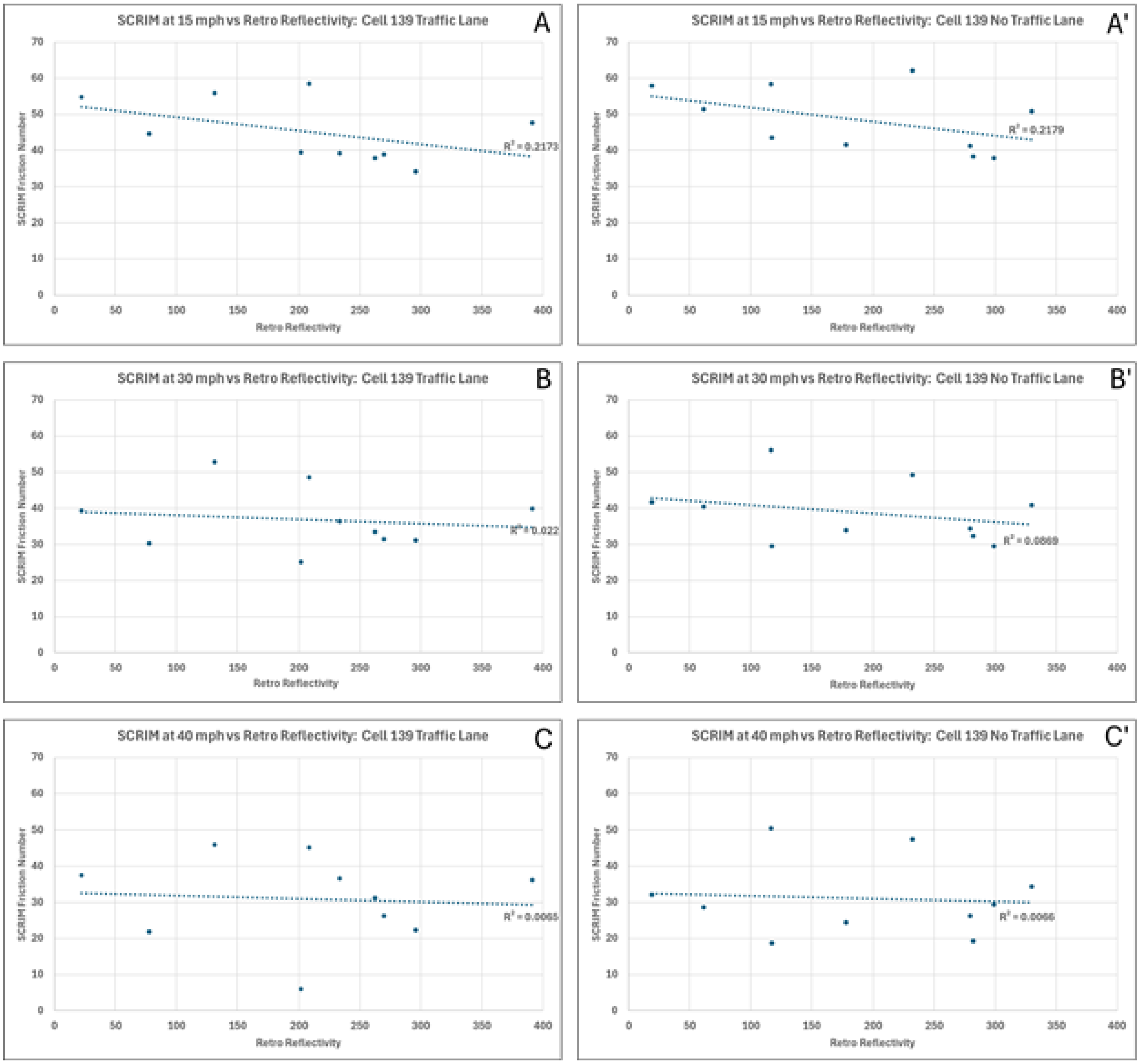


Figure 6.22 SCRIM friction measurements vs retroreflectivity for traffic and no traffic lanes at 15, 30, and 40 mph (A-A', B-B', and C-C', respectively) – Cell 139

Chapter 7: Conclusions and Recommendations

The frictional characteristics of pavement surfaces is a major component of safety. Pavement markings play a very important role in traffic flow and safety, but they also have different friction characteristics than pavement. The sudden change in frictional characteristics can create a safety hazard for pedestrians, motorcyclists, and bicyclists, especially under wet conditions.

In this research effort, this issue was addressed first by performing a literature review, including a comprehensive review of the NordicCert certification process used in Scandinavian countries for selecting pavement marking products and a survey conducted by the research team to evaluate how users are affected by the friction differential between pavement markings and normal pavement surface.

Based on TAP member recommendations, the research team developed and performed in situ experiments at MnROAD to determine the friction properties of various pavement markings, using a dynamic friction tester (DFT) and British pendulum test (BPT). A Sideway-force Coefficient Routine Investigation Machine (SCRIM) was also used to provide continuous friction measurement data.

Based on the analysis of the data collected in this research effort, we concluded that all three test methods (DFT, BPT, and SCRIM) produced comparable results and identified similar relationships. It should be noted that the measurement capabilities were significantly different among the three pieces of equipment. At one end, the BPT generated limited point results, obtained at only one very low speed, while at the other end, SCRIM provided continuous measurements at different speeds, without the need for traffic control, which makes SCRIM an ideal piece of equipment for network-level monitoring.

The following key findings were identified:

1) Marking types having the lowest coefficients of friction (and therefore the greatest friction differentials) are Latex w/ Type 1 Beads (1), Epoxy w/ Type 1 Beads (2), and Preform Thermo ESR (7).
2) In most instances, corundum, crushed glass, and taconite enhance the friction characteristics of both epoxy and MMA-based markings.
3) Epoxy-based pavement markings generally have a significantly higher friction differential from the control pavements than do MMA-based markings in which the same friction-enhancing materials (corundum, taconite, and crushed glass) are used in combination with Type 1 Beads (markings 3, 4, and 5) and Colorado and Utah blend beads (markings 10, 11, and 12).
4) Preform Thermo (6, green) returned consistently higher coefficients of friction compared to Preform Thermo ESR (7, white). Preformed Thermo (6) has a corundum topping whereas Preformed Thermo ESR (7) contains a corundum and proprietary bead blend (similar to something like a Utah blend) in the material. Preform Thermo ESR (7) showed significant improvement in friction from 2023 to 2024, which might mean that as its surface abraded over time, the embedded aggregate became more exposed, thus increasing its friction characteristics.
5) The 2024 SCRIM testing clearly showed that its measurement resolution could distinguish the friction characteristics of narrow pavement markings from the pavements to which they are applied, making the SCRIM a potentially important tool for assessing multiple lane miles of pavements and pavement markings quickly with no traffic control.

The markings installed at MnROAD can provide opportunities for follow-up testing and could act as a basis for comparing and evaluating additional marking types and friction-enhancements. For example, testing a finer gradation of taconite friction material that is more comparable in size to that of corundum could result in a material with better frictional characteristics. Conducting testing during sub-freezing temperatures is a desirable option given Minnesota's climate, to better assess, for example, epoxy-based markings, as epoxy can be more slippery under winter conditions.

The information provided in Chapter 4.6, regarding the NordicCert certification system for road marking materials in Denmark, Iceland, Norway and Sweden can be used to develop a similar system to select pavement marking materials in Minnesota. One possible alternative is to use MnROAD facility for testing and certifying these materials. At this time, such a specification does not exist in US.

At the end of this limited investigation, the research team was not able to provide numerical recommendations regarding the friction coefficient of pavement markings. However, the research team has identified a procedure used in the United Kingdom (Highways England, 2021) that can be adapted to Minnesota conditions and implemented, after additional research, in the future.

Section 4 of this document contains a detailed procedure for setting what is called an "investigatory level," followed by various levels of actions to correct any skid resistance problems. Figure 7.1 shows a diagram of the process.

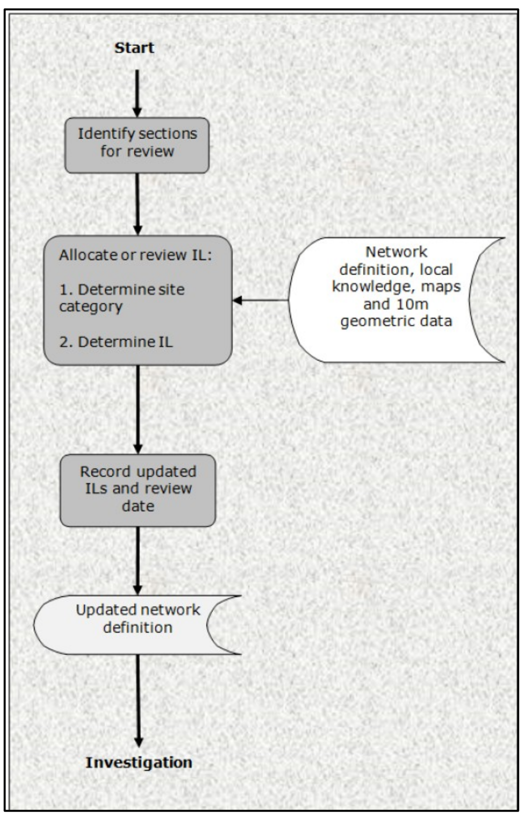


Figure 7.1 Process that shall be followed for the initial investigation (Highways England, 2021)

An investigatory level (IL) is assigned for every part of the network by determining the most appropriate site category for each location and then selecting an appropriate IL from the range indicated in Table 7.1 for that site category. The process is then split into the following steps:

1) identify sites at or below the IL;
2) identify other sites requiring investigation;
3) data validation;
4) and identify sites for detailed investigation.

All sites where the measured characteristic skid coefficient (CSC) is at or below the IL need to be investigated.

Site category and definition		IL for CSC data (skid data speed corrected to 50km /h and seasonally corrected)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway	LR	ST						
B	Non-event carriageway with one-way traffic	LR	ST	ST					
C	Non-event carriageway with two-way traffic		LR	ST	ST				
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals (see 4.5)				ST	ST	ST		
K	Approaches to pedestrian crossings and other high risk situations (see 4.5)					ST	ST		
R	Roundabout				ST	ST			
G1	Gradient 5-10%, longer than 50m (see 4.6)				ST	ST			
G2	Gradient >10%, longer than 50m (see 4.6)				LR	ST	ST		
S1	Bend radius <500m – carriageway with one-way traffic (see 4.7 and 4.9)				ST	ST			
S2	Bend radius <500m – carriageway with two-way traffic (see 4.8 and 4.10)				LR	ST	ST		

Figure 7.2 Investigatory levels for different types of roads and sites (Highways England, 2021)

ST indicates the range of ILs that should generally be used for roads carrying significant levels of traffic. LR indicates a lower IL that may be appropriate in lower-risk situations, such as low traffic levels or where the risks present are mitigated by other means, providing this has been confirmed by the crash history.

The research team is also not able to provide recommendations regarding the frictional differential between the unmarked pavement and the pavement markings. However, smaller differential values are preferred. In this limited study, the differential values varied between less than -2% to more than -50%.

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APPENDIX A: SURVEY QUESTIONS

Pavement Markings and Colored Pavements Survey

The research group in the Civil, Environmental, and Geo-Engineering Department at University of Minnesota is investigating the impact of pavement markings and colored pavements over the safety of cyclists, motorcyclists, and joggers/pedestrians. As part of the study, we are conducting a brief survey to identify and better understand the contributing factors. The survey consists of three individual sets of questions, one for each category of users. You have the option to answer one set of questions, or two, or all three sets of questions. Please respond to the survey by Thursday, March 31.

* Required

1. Which organization(s) are you a member of? *

Check all that apply.

- [ ] Association of Pedestrian & Bicycle Professionals
- [ ] Minnesota Motorcycle Safety Advisory Task Force
- [ ] American Motorcycle Association
- [ ] Motorcycle Safety Foundation
- [ ] Local bicycling organizations
- [ ] Interdisciplinary Transportation Student Organization (ITSO)
- [ ] North Central Section of the Institute of Transportation Engineers (NCITE)
- [ ] City Engineer's Association of Minnesota (CEAM)
- [ ] American Public Works Association - MN Chapter (MnAPWA)
- [ ] CEGE Student
- [ ] CEGE Faculty and Staff
- [ ] Other or N/A

Skip to question 2

Bicycles Survey Intro

2. Do you participate in bicycling? *

Mark only one oval.

( ) Yes *Skip to question 3*

( ) No *Skip to question 10*

Bicycles

3. How often do you bike?

Mark only one oval.

- ( ) Daily
- ( ) Weekly
- ( ) Occasionally

4. 2. At what temperature do you bike?

Mark only one oval.

- ( ) Above 50 F
- ( ) Above 32 F
- ( ) Above 0 F

5. 3. On what surfaces do you bike?

Mark only one oval.

- ( ) Dry surface only
- ( ) dry and wet
- ( ) dry, wet, snow plowed, ice covered

6. 4. Which road types do you bike on?

Check all that apply.

- [ ] City street
- [ ] Bicycle lanes
- [ ] Paved trail
- [ ] Colored lanes

7. 5. When biking on surfaces with pavement markings, did you notice any changes in friction when transitioning from bare surface to pavement markings?

Mark only one oval per row.

	Yes, even in dry pavement conditions	Just in wet conditions	Just in wet/icy conditions	No
Normal ride (cruising)	◯	◯	◯	◯
Accelerate	◯	◯	◯	◯
Brake	◯	◯	◯	◯
Colored lanes (no markings)	◯	◯	◯	◯

8. 6. Have you slipped on surfaces with pavement markings or did you see someone else slip on surfaces with pavement markings? Please describe.

9. 7. Do you have any suggestions for improving biking safety related to pavement markings and colored lanes?

Motorcycles Survey Intro

10. Do you participate in motorcycling? *

Mark only one oval.

- ( ) Yes *Skip to question 11*
- ( ) No *Skip to question 20*

Motorcycles

11. 1. How often do you motorcycle?

Mark only one oval.

- ( ) Daily
- ( ) Weekly
- ( ) Occasionally

12. 2. At what temperature do you motorcycle?

Mark only one oval.

- ( ) Above 65 F
- ( ) Above 50 F
- ( ) Above 32 F

13. 3. On what surfaces do you motorcycle?

Mark only one oval.

- ( ) Dry surface only
- ( ) Dry and wet
- ( ) Dry, wet, snow plowed, ice covered

14. 4. What road types do you motorcycle on?

Check all that apply.

- [ ] City streets (less than 45 mph)
- [ ] Highways (50 mph and up)
- [ ] Rural roads

15. 5. What types of motorcycle do you use most often?

Check all that apply.

- [ ] Cruisers
- [ ] Three wheels
- [ ] ADV, Touring
- [ ] Scooter/Moped
- [ ] Sport bike

16. 6. When motorcycling on surfaces with pavement markings, did you notice any changes in friction when transitioning from bare surface to pavement markings?

Mark only one oval per row.

	Yes, even in dry pavement conditions	Just in wet conditions	Just in wet/icy conditions	No
Normal ride (cruise)	○	○	○	○
Accelerate	○	○	○	○
Brake	○	○	○	○
Turn	○	○	○	○
Roundabout	○	○	○	○

17. 7. Have you slipped on any of the following pavement markings or did you see someone else slip on the following pavement markings?

Check all that apply.

- [ ] Lane markings
- [ ] Turning Arrows or other symbol on intersections
- [ ] Crosswalk markings
- [ ] Green-zones for bicycles

Other: [ ] ______________________

18. 8. Have you slipped on any of the following marking surface types or did you see someone else slip on the following marking surface types?

Check all that apply.

- [ ] Smooth
- [ ] Rough
- [ ] Painted
- [ ] Raised
- [ ] Flush

19. 9. Do you have any suggestions for improving motorcycling safety related to pavement markings?

____

____

____

____

____

Joggers/Pedestrians Survey Intro

20. Would you like to fill out the joggers/pedestrian survey? *

Mark only one oval.

- Yes *Skip to question 21*
- No

Joggers/Pedestrians

21. 1. How often do you walk/run?

Mark only one oval.

- Daily
- Weekly
- Occasionally

22. 2. At what temperature do you walk/run?

Mark only one oval.

- Above 50 F
- Above 32 F
- Above 0 F

23. 3. On what surfaces do you walk/run on?

Mark only one oval.

- Dry surface only
- Dry and wet
- Dry, wet, snow plowed, ice covered

24. 4. Have you slipped on surfaces with pavement markings or did you see someone else slip on surfaces with pavement markings? Please describe.

25. 5. Do you have any suggestions for improving jogging/walking safety related to pavement markings?

APPENDIX B: SURVEY INDIVIDUAL RESPONSES

Bicycle question set: Answer analysis on key words.

6. Have you slipped on surfaces with pavement markings, or did you see someone else slip on surfaces with pavement markings? Please describe.

NO = 4

Pavement marking

- I have slipped while wet braking on pavement markings.
- On my bike I have noticed some slipping on pavement markings during biking on ice, especially during acceleration and braking. If I don't bike slower on these surfaces the bike can fall over.
- Yes! I've taken many spills riding on the pavement markings. Sometimes it's as simple as crossing over them, which if approached at the wrong angle, is enough to take you out. Other times, it's riding over the pavement markings on a particularly wet day. On these days, I just prefer to ride on the street as it's safer to have cars honking at me than to risk crashing on the slippery markings.
- No. If I need to turn across pavement markings I will slow down and turn with caution so that I don't slip. I have not personally ever slipped on a pavement marking.
- Yes - nothing terrible, but there's a definite slippage on them.
- i have concerns about front tire slipping out on markings, so i make sure to ride across it as straight as possible
- I've crashed as a result of them.
- Not me but I know the traction on painted streets is not the same
- No, but I have been nearly hit by cars many times while riding over pavement markings, because paint is not protection.
- Not biking, but I have while walking/running
- I have not, but I try to avoid riding on any painted surface when the roads are wet because I know they can be slippery
- No, but I'm aware that lane markings are often much more slippery when wet or icy.
- Only when breaking in the wet
- No, I have not. But I avoid riding on bike paths painted on roads
- Yes. I don't recall the specifics, but I try to avoid painted markings.
- yes. dozens of times, because i ride year-round (including below 0, which wasn't an option on that question). wet or icy, etc.
- Not "slipped" in the sense of falling to the ground, but I have had tires slip into a horizontal skid while crossing white lines on pavement. Specifically on white lines marking the roadway shoulder, or a lined bike lane, etc.
- Yes, the paint can be slicker than pavement without paint and can cause you to slip.
- I have seen riders go down due to painted lane markings being wet or moist in humid/damp conditions.

- Yes, I've slipped on painted markings e.g. lines on the road, under wet conditions
- All pavement markings I have slipped on. Especially when wet. There is no grip on the markings. Like Ice, even in the summer.
- Have not slipped, personally, but am extra cautious when riding over pavement markings, as these can be quite slick, especially when wet.
- I have lost traction and slipped--but have not fallen--while walking and bicycling over markings and painted lanes. Wet conditions seem to make it slightly more slippery, but the more textured painted surfaces are not as treacherous. It seems like the paint can smooth out the natural texture of lanes, so a rougher texture of road surface under the paint might counteract that.
- No, but I usually try to not make sharp turning motions on pavement markings
- Yes. Even walking when it's Icey it is easy to slip. Al's I see professional racers slip on markings all the time when watching grand tour racing. Usually only when wet in that situation.

Pavement marking PAINT vs VINYL

(Please note that vinyl is something the respondents mentioned themselves in a free-response question. Most likely, it refers to polymer preformed tape, or preformed thermoplastic).

- Yes, I've slipped when turning and accelerating in wet and/or icy conditions. Only on painted markings however, never on thermoplastic
- Where there is heavy paint, yeah. When it's wet or I guess if there's a layer of fine sand
- Yes, but not to the point of falling. Even walking, they can sometimes be slippery if they are the "tape" style vs. paint.
- Absolutely. Paint (other than not protecting cyclists at all) can be risky, especially in the wet. I've seen lots of cyclists (and I have) slip on paint
- yes, vinyl lines are more slippery than paint.
- Yes, I have slipped when riding on a white line after rainfall.
- Yes, a little. Paint loses its slippery properties faster than heat applied tape

Crosswalk marking

- Yes, I have slipped on the white "zebra" crosswalk markings, in below-freezing weather.
- Yes, reflective cross walk
- Yes, when cornering across pedestrian paths. Particularly dangerous when paint is applied, and glass beads used as a nonstick on top
- Yes. On a corner when wet on crosswalk markings.
- Wheel spin on a dry day on pedestrian crossing markings.
- Person making a turn across a lane marking.
- Yes, braking at a stoplight w crossing markings
- Plastic curb cut inserts
- I've slipped on the yellow plastic curb cut inserts (the bumpy ones for people with visual impairments)

General

- yes, especially with braking in wet conditions
- I've felt tire slip when accelerating, especially from a stop. I have not witnessed a full loss of control/wipeout caused by such conditions
- slipped while making a right turn
- Yes, I have slipped when braking..
- yes, especially with braking in wet conditions
- Yes, it happens often in the winter. If I am waiting at a red light with a continental crosswalk in front of me, I have to position myself in between the white markings because otherwise I would be trying to accelerate on a slippery surface. It's the only type of surface that my studded tires don't help on.
- Yes, but have been able to right myself.
- The difference is too subtle to be a safety concern.
- I did not fall, but the tires have slipped.
- Yes, front and rear wheel washouts/loss of traction.
- Yes, where the bike trail crosses the Blue Line on 15th Ave South

7. Do you have any suggestions for improving biking safety related to pavement markings and colored lanes?

NO = 8

Positive

- I think pavement markings and colored lanes are great and there should be more of them.
- The markings are a positive trade-off as they reduce the risk of being struck by a vehicle, which is much more dangerous than slipping on the markings
- Pavement colors work very well in bicycle-mad Netherlands where is rains a lot.
- Love to see more markings and bike lanes -- they are necessary!
- Maintain them. Post clearly visible and pictorial signs for motorists to provide guidance on using Bike Boxes, etc
- I still think they're a great idea. Maybe signage to warn of being slippery when wet or icy?
- I've had good experiences crossing pavement markings when they are slightly recessed, painted over milled pavement. And I'll take this moment to advocate for physical barriers separating cycling infrastructure from motor vehicle infrastructure- safer for so many reasons!
- Honestly, the colored lanes make me feel safest, because they're super obvious. The lanes that look like narrow streets and have dotted lines in the middle I see drivers in all the time
- Corners, especially off-camber or otherwise tight corners, are especially high-risk for friction issues. Avoiding the use of untextured or lightly textured plastics, preferring colored pavements and other textured options.

- I'm honestly still not sure if or when turn boxes are a good idea and when they are not. Sometimes they work OK, and sometimes they just don't.
- more pavement markings and colored lanes and
- To me it is more education. Because the markings that are non-painted or non-slick paint are harder to see as a motorist in darker/poor weather conditions. I would rather train as a cyclist (this is well known and communicated in cycling circles) than have poor visibility for motorists that can create even more dangerous situations for everyone involved.
- Bike paths/markings just need to be consistent. Some sort of standard that everyone can begin to understand. If I get confused upon seeing a new method of marking a path, beginning cyclists and motorists will be confused and that never ends well.

Texture

- texture the paint
- Add grit to the paint somehow
- somehow creating more texture in the markings.
- more texture?
- Improving roughness of the painted surface to improve friction during wet conditions.
- Texturize all pavement markings and colored lanes.
- Would more sand in the paint or thermoplastic create more friction when wet?
- The markings should be rough, like sandpaper, not smooth.
- Mix grit in the paint.
- Texture pavement markings to provide traction while crossing in any direction.
- Is it possible to incorporate some grit into the pavement marking material? Don't cite pavement markings where people will be turning. I don't believe they pose a slip risk when just biking straight.
- Finding/inventing pavement markings that aren't slippery!
- Sand in the paint would work until it gets polished smooth, which happens pretty quickly unfortunately.
- A simple application of a grip material into the paint when the paint is being applied could make a difference. Small silica sand comes to mind.
- Make surface rougher but then they may get dirty to the point where they don't reflect for cars
- Maybe add sand to the paint?
- Explore different paints/surfaces to improve friction. Alternate paint with pavement to improve friction, instead of large swaths of paint (i.e. narrow stripes). Ensure proper drainage of stormwater.

General

- I think better friction so less slipping in wet/icy conditions
- Make sure they are durable and are most resistant to being worn or scraped away. If they don't wear, that should help with traction as well, assuming they have some traction to begin with.

- Whatever it is that is making us slip and fall should be eliminated...maybe use more signage?
- Use and recommend more non-white-colored lines or markings. White paint gets obscured in snow and it's not distinctive from other pavement markings.
- While MnDOT is going to 6-inch fog lines, that adds more area for slipping unless there can be an additive to the paint to add friction/traction.
- Keep coloring the lanes please! It alerts drivers to look for bicycles
- Completely separate bike ped infrastructure from cars
- Add the British cats eyes to street marking.
- Gonna have to get those material scientists to come up with a material that is retro reflective and also not slippery as all get out.
- maintenance. Too often they become faded/worn out.
- Much of the signage and marking is distracting noise. We should be watching for each other instead.
- I think better markings on colored lanes are needed because i have had countless people ask what the green lanes are for
- Explain the meaning of the different types of lines to the public, I do not know what it means when there is a green dashed line going through an intersection
- yes, make sure they're maintained regularly and clear roads/bike lanes adequately so people can actually see them
- More frequent signage (multiple times each block) both as paint on the road/path and the metal signs at head/eyesight level would be helpful for all path users, as they indicate who is expected to use each/which lane. Painted pavement is difficult to see when roads are covered with snow, or in the late winter/early spring after snowplows have scraped off last season's street paint-- it can be very confusing and more dangerous for shared road/path users. The highly-textured, reflective green paint strips in bike lanes are extremely helpful for motor vehicle users to become more aware. In conjunction with eye-level signs it helps indicate who to expect will also be using that particular road section.
- If we had more bike lanes in central Minnesota, that would be great (and far safer!).
- The markings are worn off and hard to see on many streets in Minneapolis
- Markings and colored lanes are definitely not enough to ensure safety for people on bikes, but fully colored lanes are better than only markings, as drivers don't seem to notice or care about markings. Bike lanes aren't truly safe unless they're curb, concrete, or (not plastic) bollard protected, so they will understandably not be used by the vast majority of the population even with colored lanes.
- Be mindful of the markings, and of potential hazards they may present.
- I haven't ridden on enough colored lanes to know about friction, but I love the visual reminder of the designated bicycle lane, where physical barriers are not practical. Have there been any studies surrounding whether persons who have difficulty distinguishing color (commonly called 'color-blind') are able to distinguish the differences between unpainted pavement (asphalt, concrete, etc.) and the green typically used as in indicator of a bikeway?

- Fiercer enforcement for motorists that drive down bike lanes or pass on shoulders designated for bike lanes
- Develop marking tape similar to boat decking tread tape that incorporates a skid resistant surface
- Yes! Please stop cars from using some roads. Bikes and cars cannot safely share the road.

Construction (physical separation)

- Protected bike lanes that don’t require paint (paint really isn’t any protection at all. Better surface treatments for paint, and thoughts on where paint is (not in corners, braking zones, etc)
- Concrete enforces better than paint or paper. Bicycle riders need to be protected from people driving cars by concrete - typically curbs. Drivers do not obey painted lines. They somewhat obey full color bikeways but not extremely well. Full color bikeways are useful for making drivers aware of crossings of side roads and driveways. The CROW standards have so far proven to produce the safest road designs.
- 2-way lines on the same side of the street are dangerous. People coming to intersections are only expecting riders from on direction and will enter intersection when on one is coming from that direction putting opposite direction at risk.
- Leave room on the shoulder for bicycles. The road to the local trailhead was repaved with a wide center lane with a few turning lanes areas, mostly a bare lane, and they left us 10" of shoulder to ride bicycle on.
- Don't use paint to mark bike lanes. Use concrete jersey strips.
- Add physical separation
- Paint does not protect cyclists. Let's start using infrastructure that will damage cars if they drive into bike traffic.
- Big curbs between cars and bikes.
- Put in cement curbs and bollars. Paint doesnt protect.
- I would get rid of them and build physically protected bike paths.
- Curb protected lanes
- Line them with permanent physical barriers disallowing auto traffic intrusion.
- Some physical barrier between bike lanes and car lanes---plastic bollards maybe
- Make the painted marking brighter or add physical barriers so cars see them. I fee like so many still don't.
- Bright markings are always better but nothing compares to a pure grade separated bike lane. And anything would be better than the arrows in the middle of lanes that express a shared lane. Usually gives a false sense of security to the cyclist.
- physical barriers that prevent motor vehicles from entering/parking on colored lanes
- I’d prefer physical dividers between street and bike lane over any markings. Drivers do not pay attention to markings and they do nothing, in my experience, to improve safety of bikers.
- Don't bother. Please prioritize installation of tall cement lane separators and pylons. If it doesn't mess up their bumper, drivers don't care.

- Don’t
- dont color the lanes
- Leave a channel of bare pavement to ride in.
- Don't use markings
- Don't use paint to mark bike lanes. Use concrete jersey strips.
- I’d prefer physical dividers between street and bike lane over any markings. Drivers do not pay attention to markings and they do nothing, in my experience, to improve safety of bikers.
- Don't bother. Please prioritize installation of tall cement lane separators and pylons. If it doesn't mess up their bumper, drivers don't care.
- Do not put bike lanes on very crowded traffic streets, unless the pavement is wide enough for both.

Paint vs plastic

- Use thin paints rather than thicker substances like those common for road markers.
- Prioritize thermoplastic over latex paint for longevity, maintenance, traction, and reflectivity. Or tinted aggregate/concrete.
- Not sure how it would be done but friction needs to be improved on these markings. Perhaps reducing the amount of colored lanes and adding signs could help? There should certainly be markings for cars to be informed of the bike's right of way, but perhaps reducing the markings on the ground and adding some friction promoting agent/additive in the places where markings are necessary (i.e. grading the surface/roughening the surface/paint additives).

Visibility

- Maybe all a certain color
- Make then brighter
- The brighter the color the better. Possibly some embedded sparkly things for night riding.
- Colored markings and lanes definitely better than white (winter snow etc), Reflective 3M markings and signage. Bike sharrows.
- Consistent choice of colors and symbols. I think green is a questionable choice as it is associated with go; not caution. Keep them painted. Many sharrows are just shadows now.
- Don't mark lanes with slick paints!
- Too much color is unnecessary, maybe slippery
- Need standard color to indicate bike facilities. Too much variation in style and markings in Rochester, MN
- Provide a contrasting color with markings to better highlight them.
- Only mark the outside of the lanes
- The color for lanes needs to be a strong contrast with the roadway.
- Different pavement color for bicycle lanes/paths to differentiate from motor vehicle traffic

Motorcyclist question set: Answer analysis on key words.

9. Do you have any suggestions for improving motorcycling safety related to pavement markings?

Texture

- Sand or rough like texture.
- Larger texture of crosswalk and large markings near intersections or on turns.
- The textured markings seem to be less slippery than the painted ones.
- Texture paint with grit to improve traction
- Put some sort of friction material 8n paint or possibly a less slippery paint
- As with bicycling, add a texture to markings that provides traction in all directions and all conditions
- Rough Surface
- Add a small aggregate to the paint.
- Grit added to paint.
- If possible, make all road markings with a friction surface to reduce slippage.
- Thick paint has little grip as does almost all reflective paint
- Don’t
- Tar used to seal cracks... really bad on exit. Entrance freeway ramps
- Don't use markings
- Again, the glass beads are extremely dangerous and there appears to be no protocol for safe application. And of course chip seal and in line rain grooves. The paints are slippery when wet and unfortunately cross walks must be placed at corners so this is where we encounter them while leaning over
- Whatever type of “plastic” marking product that is being used is slippery and dangerous. Any type of white marking is suspicious at all times

General

- No, just get the word out to the public, raise awareness
- Anywhere you paint should be cut like the corners on a highway. Busy intersections would be much safer in the winter as well

Visibility

- Reflective, no bumps or raised sections

Construction

- Dedicated roads to motorcycles.
- Minimize size of crosswalk blocks - add more grit to pavement markings (arrows - large text, etc)

- The painted markings become very slippery when even slightly damp. I rode in downtown Minneapolis for years and the crosswalk markings are a challenge to avoid.
- No, but the pot holes and gaps are an issue
- Fill or notify spots with potholes. One tire in and we can flip!
- Same as bicycling. Leave a channel of bare pavement to ride in.
- Cats eyes
- Early season pothole repair.

Pedestrian Question Set: Answer analysis of key words.

4. Have you slipped on surfaces with pavement markings, or did you see someone else slip on surfaces with pavement markings? Please describe.

No = 12

Yes = 4

No markings

- No. There are no pavement markings on the sidewalks where I walk (and bike).
- I have not encountered pavement markings while using sidewalks

Crosswalk

- yes - those white zebra crossings at the crosswalk
- Never actually slipped, but certain crosswalks that have been installed with thermoplastic or similar coatings can sometimes have less traction than regular paint
- Yes both. When walking on crosswalks I try to avoid the white boxes and only walk on the pavement because its rougher. I have seen students try to walk across crosswalks and slip because they stepped on the white sections in the winter.
- yes, on wet pavement markings (crosswalk marking) without grit or an abrasive additive
- Crosswalk markings and tactile paving in the wet
- Yes, especially painted crosswalks when icy
- Yes. I slipped on crosswalks when it's been icy. I think the marking made the crosswalk harder to walk on in these bad conditions.
- Yes I have slipped many times in Mpls crosswalks with zebra markings, under below-freezing conditions. At this point, I try to walk outside the markings whenever possible.
- Yes. Wet crosswalk marking when wet and changing directions.
- Yes. When it is cold, the crosswalk markings are like ice. One wrong step and I’m on the ground.
- slipped on crosswalk markings
- I have noticed white rectangular crosswalk street markings can sometimes be slippery, especially when wet.

- more friction/traction material in it, especially in zebra or crosswalks where you have larger painted surfaces than just lane lines.

Paint

- YES! The paint is slippery
- It seems the ice melts slower on paint stripes, which can make them more slippery. Aside from the painted areas having slightly less traction, they don't cause much difference in terms of safety.
- Yes, paint.
- Yes, I've slipped on latex painted pavement markings in wet and/or icy conditions while running.
- Pretty rarely, but occasionally in wet/icy conditions I have slid on painted white lines (road shoulder, bike lane, etc)

Icy/Wet

- Yes, I have slipped on surfaces with pavement markings in wet/icy conditions.
- Just ice & snow
- No, I slip mostly because of ice
- Sidewalks that are not salted or plowed just turn into ice rinks and I have seen people slip
- I have not. I have only tripped on a lip in the sidewalk or on ice while running.
- yes, seems to happen when wet, especially when wet with salt water from melting snow/ice, but it's not as prevalent or impacted as when biking.
- Yes. Ice was the real problem.
- Yeah, fine sand or wet.
- Yes, this happens often in icy weather
- Yes, I have slipped on cross walk pavement markings before when the pavement has been wet. Luckily it was a minor slip and I did not fall to the ground.
- I slipped and fell on wet pavement markings while wearing flat-soled shoes.
- Only on icy
- No - Walking and running primarily is only slippery in icy/refreezing conditions.
- Yes, I often slip on pavement markings when it is wet, snowy, or icy.

General

- Only on unshoveled surfaces
- I have slipped, but it's not clear if the pavement marking was the cause.
- Slippage on trail lane markings
- yes - but not because of the markings
- Yes, at slushy intersections multiple times on white pavement markings
- Yes- regularly have to be mindful of marked surfaces as they get super slippery.
- Yes, the "tape" style markings can be slippery. I try to avoid them.

- I have not slip on surfaces with pavement markings nor have I seen anyone else. But that could also be dependent on the type of marking in-place as well as the type of shoes one is wearing.
- We had an issue where someone slipped on the glass beads that were spread onto the new pavement markings and the contractor failed to property clean up that day.
- I've slipped, but not because of markings.

5. Do you have any suggestions for improving jogging/walking safety related to pavement markings?

No = 8

Texture

- Texturize all pavement markings.
- Again, give them a sandpaper-like texture that provides grip in all conditions
- texture the markings
- Use texture to reduce slipperiness.
- only mark the outside w/ thin lines or increase their texture
- textured treatments are necessary, and they need to be effective when wet or icy.
- Texture variation?
- add grit to the pavement marking material.
- Add grit to paint somehow.

Separation

- need better separation from traffic.
- We need clearly distinguished marked walking right of ways from bike right of ways, preferring walkers who cannot move quickly. I am 71, and not getting faster.
- Keep cars out of bike lanes so bikers don't use sidewalks :)
- Completely separate bike ped infrastructure from cars
- Concrete enforces better than paint or paper. EVERY Road designed for motor vehicle speeds of greater than 20-25 MPH should have a concrete protected bikeway AND protected walkway. Within more populated areas there should be each on both sides of most roads.

Paint

- I have always thought someone should find a better way to have pavement markings without painting it and causing it to be too smooth.
- Explore different paints/surfaces to improve friction. Alternate paint with pavement to improve friction, instead of large swaths of paint (i.e. narrow stripes). Ensure proper drainage of stormwater.
- Same as when biking. Apply silica sand into the paint mix. When the pain goes down there will then be a grip for your shoes or runners.

- Prioritize thermoplastic over latex paint to improve traction.
- Make the markings smaller so there is not one big patch of white paint, but mor like stripes or checkerboard so there can be some traction
- Increase the friction in the paint or thermoplastic.

Maintenance

- No raised sections. Maintain ice and snow free in winter. Avoid white, winter, use green or color. Reflective markings and signage at night - 3M road safety markings
- Maintenance. Often become faded/worn
- No. This is a non-issue compared to poor winter sidewalk and intersection maintenance and enforcement.
- Clear the sidewalk from snow as quickly after the storm as possible
- Get sidewalks plowed quickly on high pedestrian corridors

Visibility

- The more obvious it is where pedestrians are/are coming from, the safer I feel
- Improved reflectivity of markings!

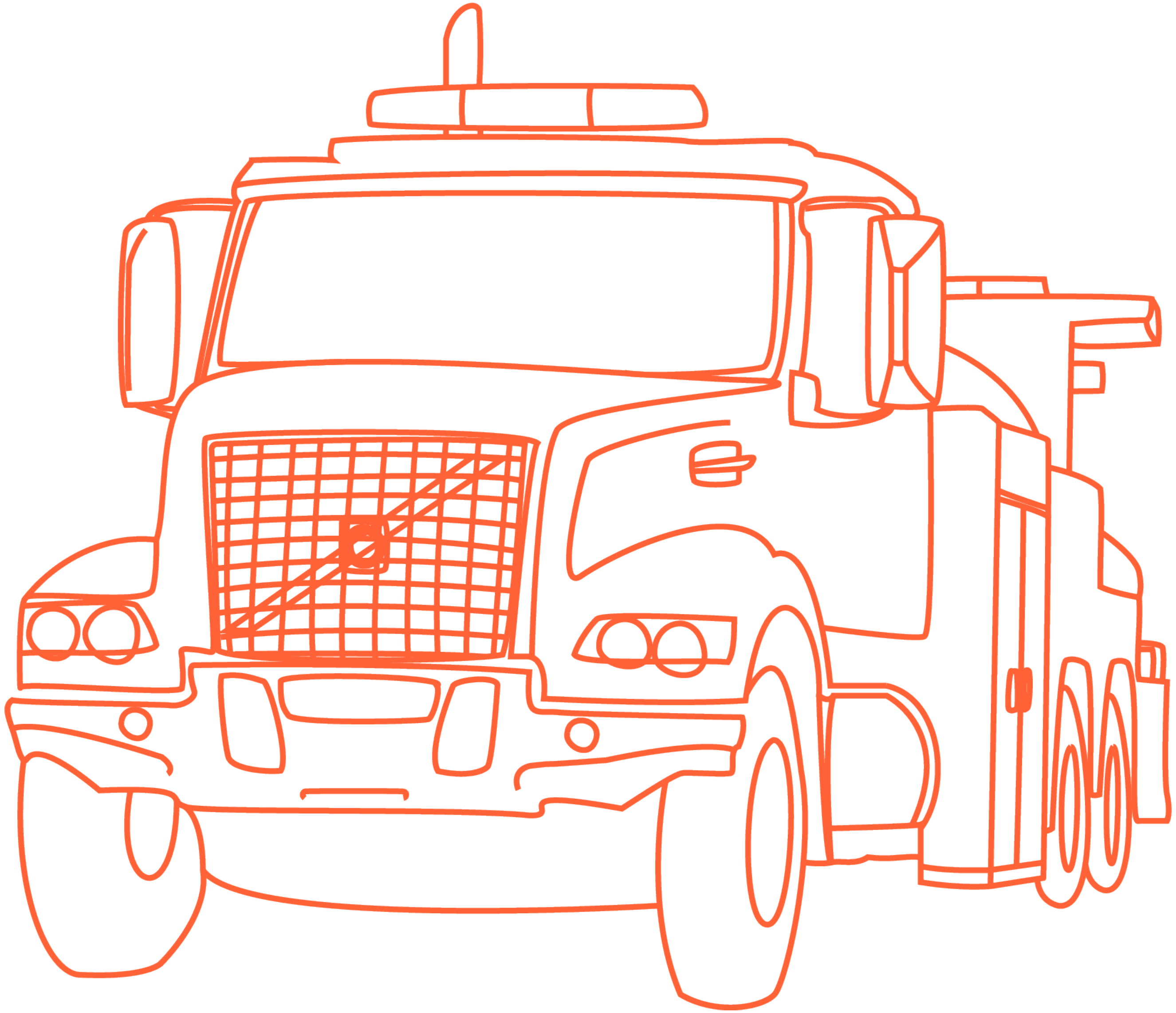
General

- Develop a nonskid tape
- Drivers really need to be educated as to what the pavement markings mean.
- Fewer pavement marking for a more consistent jogging/walking surface
- Overall, they are fine.
- It seems the pavement marking material does not provide good friction when wet. I have also noticed lack of friction in a vehicle when accelerating from an intersection. I am not sure the best way to improve this but may need to have an admixture to provide a non-slip surface.
- Lower speed limit. Bigger curbs
- high traction soles on shoes/boots.
- Better friction?
- make markings more skid resistant
- Use something else. The materials used in Mpls are dangerous.
- Avoid smooth surfaces (like bricks)
- Large unbroken areas provide no recovery. Perhaps open patterns would be better. Use some friction material.
- Avoid large/solid color patches
- Having enough shoulder /room so that you don't need to walk/run on the pavement markings.

APPENDIX C: WDM SUMMARY OF SCRIM TESTING AT MNROAD

MnROADS Pavement Marking Results

August 23th, 2024



Outline

1. Data Overview
    1. Data Alignment
    2. Marking Identification
2. Initial Results
    1. Data Summary
    2. Cell Comparison
    3. Pavement Marking Comparison
    4. Traffic Comparison
    5. Speed Comparison
3. Contact Information

Data Overview

- Two Cells (46 and 139) each with 10 pavement markings (1-7, 10-12)
- Three data collection runs under each pair of conditions
  - Three collection speeds (15, 30, 40mph)
  - Two traffic conditions (trafficked, non-trafficked)
- Resulting in six datasets of three observations across both cells
- For each combination of speed and traffic condition, observations joined geospatially
  - GPS-located data is typically produced at 1 m intervals
- Raw friction values are produced at 0.1 m (10 cm) intervals which is used to identify the pavement markings in this analysis
  - Note: Values at the 0.1m level are a reflection of the relationship between horizonal and vertical load. They can fall outside of the typical range of friction values.

Data Alignment – Aerial Views

- Aerial images of the pavement markings in each cell were overlayed with the 1 m datapoints to provide a rough visual estimation of the position of the observations in relation to the pavement markings
  - This allows us to roughly locate the rows in the raw 0.1 m data associated with each marking
- Retro markers were used to identify the start and end bounds of the area of interest for each run
- In addition to spatial position, the distance along each run, images, and friction values were used to identify rows in 0.1 m data that correspond with pavement markings
  - Distance is calculated from the start of the survey and should not be compared between speed/traffic pairs

Data Alignment – Survey Data Format

Excel file of 0.1 m data provided

- 6 tabs (1 for each speed/traffic pair)
- 18 columns

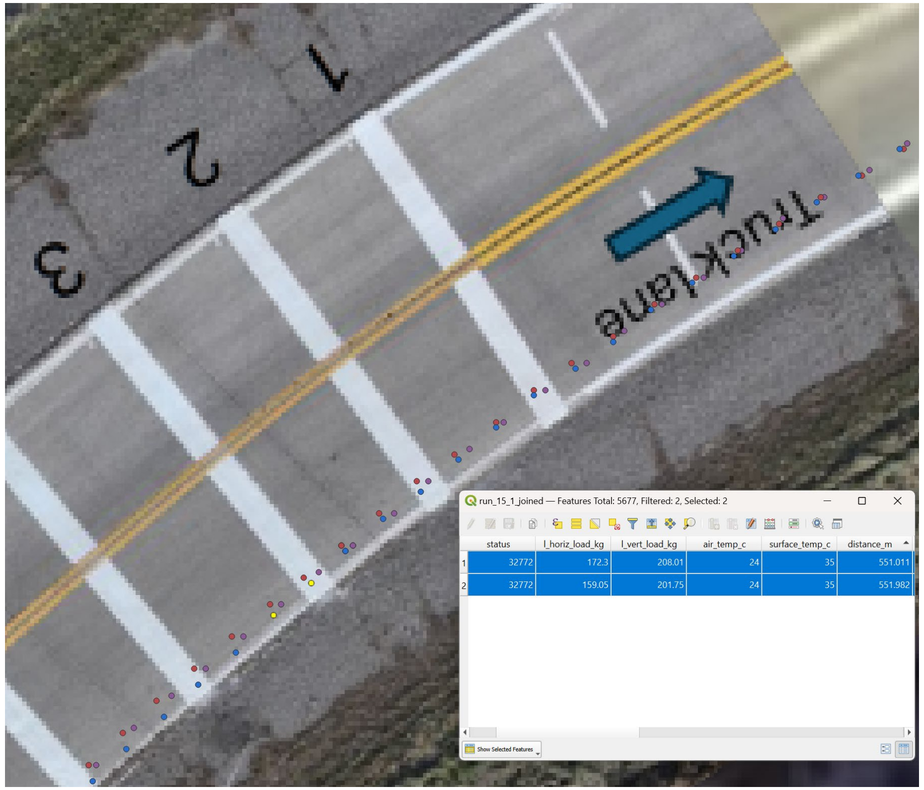
	A	B	C	D	E	F	G	H	I	J
1	Distance (ft)	Distance (m)	Latitude	Longitude	Cell	Marking	SR_0.3_1	SR_0.3_2	SR_0.3_3	SR_0.3_speed_corrected
185	255.215866	77.786			139		83.31512337	63.55847569	64.13785387	79.253922
186	255.534123	77.883			139		84.75322365	60.73078761	58.8328156	80.621922
187	255.855661	77.981	45.260393	-93.706206	139		78.45179391	57.67533851	64.07352867	74.627656
188	256.173918	78.078			139		66.43076398	67.8526971	79.86051959	63.192592
189	256.492175	78.175			139		54.84693878	85.33114085	94.59568114	52.173421
190	256.810432	78.272			139		42.49405002	94.67683004	85.86100468	40.42267
191	257.128689	78.369			139		47.18713483	80.30499475	73.47579199	44.886994
192	257.446946	78.466			139		75.41337168	60.18240402	65.78373929	71.737341
193	257.765203	78.563			139		96.6624784	47.44191062	57.54294789	91.950659
194	258.08346	78.66			139		81.73967746	54.90499573	61.71997902	77.755271
195	258.401717	78.757			139		71.80475981	71.02120536	67.0002846	68.304632
196	258.723255	78.855			139	1	51.26265499	78.84079709	68.82539382	48.763853
197	259.041512	78.952	45.260388	-93.706197	139	1	23.5223966	61.38453765	50.9502135	22.375795
198	259.359769	79.049	45.260388	-93.706197	139	1	13.50215517	34.95847215	25.36511741	12.843991
199	259.678026	79.146			139	1	21.34495109	13.69026068	13.06199292	20.304490
200	259.996283	79.243			139	1	29.62350477	13.57683742	6.703740713	28.179505
201	260.31454	79.34			139	1	43.50224566	15.44542414	10.68769366	41.381725
202	260.632797	79.437			139	1	53.54290726	34.46477465	26.84253208	50.932954
203	260.951054	79.534			139	1	73.32382989	49.29057764	59.95020653	69.749655
204	261.272592	79.632			139		92.86121132	68.51310622	156.5898792	88.334685
205	261.590849	79.729			139		83.59310109	103.7186976	123.2280928	79.518349
206	261.909106	79.826			139		85.86071604	106.7594433	85.29958852	81.675429
207	262.227363	79.923			139		68.50984936	85.03968254	58.66225362	65.170332
208	262.54562	80.02	45.260382	-93.706187	139		79.68163524	54.45944661	41.0084538	75.797548
209	262.863877	80.117			139		88.40488875	66.85933577	61.61321182	84.095586
210	263.182134	80.214			139		82.78503046	81.44762846	82.31575702	78.749668
211	263.500391	80.311			139		73.79014804	86.32830597	90.53187086	70.193242
212	263.818648	80.408			139		52.67869253	78.9675637	78.04055729	50.110866
213	264.140186	80.506			139		42.00864925	56.11805802	57.59192782	39.960934
214	264.458443	80.603			139		47.83950617	47.89882092	50.48440738	45.507566
215	264.7767	80.7			139		87.08037286	50.18398807	58.13275668	82.835634
216	265.094957	80.797			139		115.2119556	69.91349076	80.26114028	109.59594
217	265.413214	80.894			139		100.63249	95.61032864	94.29362629	95.727152
218	265.731471	80.991	45.260376	-93.706177	139		81.63284133	101.6279605	88.57205431	77.653643
219	266.049728	81.088			139		60.23383372	86.22938938	71.49641654	57.297731
220	266.367985	81.185			139		49.18065153	66.61805003	54.97224694	46.783337
221	266.686242	81.282			139		56.82133333	52.66158066	49.45852975	54.051573
222	267.00778	81.38			139		73.69463932	53.10362627	50.871817	70.102389
223	267.326037	81.477			139		83.19674192	59.4374631	57.1301208	79.141311
224	267.644294	81.574			139		86.06095076	67.89225073	67.82520513	81.865904
225	267.962551	81.671			139		85.96000367	70.52127022	84.93925429	81.769877
226	268.280808	81.768			139		81.07173725	71.88763847	96.74020034	77.119890
227	268.599065	81.865			139	2	65.33411278	72.70197487	84.92282531	62.149397
228	268.917322	81.962	45.260371	-93.706167	139	2	36.98138007	59.71759259	53.9331525	35.17872
229	269.235579	82.059			139	2	18.09554841	33.20050148	20.43355734	17.213479
230	269.553836	82.156			139	2	21.23210552	17.63921164	6.609268169	20.197145
231	269.875374	82.254			139	2	22.36714789	16.26375531	15.23939922	21.276859
232	270.193631	82.351			139	2	32.42069856	17.86091289	17.12683893	30.84034
233	270.511888	82.448			139	2	48.2430604	28.95861148	30.84477664	45.891449
234	270.830145	82.545			139	2	77.21921731	47.37951384	42.18072234	73.455161
235	271.148402	82.642			139		128.1392351	83.49528235	113.132558	121.89307
236	271.466659	82.739			139		90.78448076	131.9549519	142.2942643	86.359185
237	271.784916	82.836			139		77.11889565	96.18542469	102.1823155	73.359730
238	272.103173	82.933			139		59.50343071	77.43179939	65.08452536	56.602932
239	272.42143	83.03	45.260365	-93.706158	139		61.41343686	42.49295113	41.76785544	58.41983

15mph_traffic | 15mph_no_traffic | 30mph_traffic | 30mph_no_traffic | 40mph_traffic | 40mph_no_traffic

Column Name	Description
Distance (ft)	Distance from start of survey in feet
Distance (m)	Distance from start of survey in meters
Latitude	Latitude coordinate of first run
Longitude	Longitude coordinate of first run
Cell	Cell number 146 or 139
Marking	Marking identification number (spans relevant rows)
SR_0.3_1	Friction value for run 1
SR_0.3_2	Friction value for run 2
SR_0.3_3	Friction value for run 3
SR_0.3_speed_corrected_1	Speed corrected friction value for run 1
SR_0.3_speed_corrected_2	Speed corrected friction value for run 2
SR_0.3_speed_corrected_3	Speed corrected friction value for run 3
rolling_avg_6_right_1	6-row right edge rolling average for run 1
rolling_avg_6_right_2	6-row right edge rolling average for run 2
rolling_avg_6_right_3	6-row right edge rolling average for run 3
rolling_avg_7_center_1	7-row centered rolling average for run 1
rolling_avg_7_center_2	7-row centered rolling average for run 2
rolling_avg_7_center_3	7-row centered rolling average for run 3

Data Alignment

- The below image highlights the distance along the survey that corresponds with the highlighted points at marking 3 and the associated rows in the data on the right
- Each cluster of three datapoints represent a 0.1 m row that was joined between runs
- Small offsets of the position of the joined 1 m datapoints will show similar offsets in the 0.1 m data to the right where the third run is slightly offset from runs 1 and 2 (2 rows ≈ 20 cm)
  - This offset may not remain consistent across a full route due to travel path differences



Distance (ft)	Distance (m)	Latitude	Longitude	Cell	Marking	SR_0.3_1	SR_0.3_2	SR_0.3_3
1810.098171	551.691			46		74.29045894	73.1095835	75.65295876
1810.416428	551.788			46		70.52620855	67.11925658	74.61014383
1810.734685	551.885			46		75.1928151	72.711812	77.45642597
1811.052942	551.982	45.258605	-93.70128	46		78.83519207	78.42063727	77.88908936
1811.371199	552.079			46		74.75617839	74.17517209	78.20500797
1811.689456	552.176			46		73.81570869	73.82576496	77.38554881
1812.01099[illegible]	552.274			46		78.49983052	75.13694912	72.78692976
1812.329[illegible]51	552.371			46		74.36557187	73.54577117	75.52262019
1812.64[illegible]508	552.468			46	3	71.07112883	74.87466667	46.13986882
1812.9[illegible]5765	552.565			46	3	72.33297985	70.43414736	12.60718227
1813[illegible]284022	552.662			46	3	40.44531324	31.56351792	37.40418345
181[illegible]3.602279	552.759			46	3	14.50877435	19.86126323	49.32758183
1[illegible]13.920536	552.856			46	3	43.11095714	50.29364656	14.92418196
[illegible]814.238793	552.953	45.258611	-93.701271	46	3	46.04883676	37.30072378	21.56153809
1814.55705	553.05	45.258611	-93.701271	46	3	13.44061232	14.82821805	68.36548104
1814.878588	553.148			46	3	28.41500803	38.09336222	92.05000308
1815.196845	553.245			46	3	72.69005545	72.78720864	60.13994238
1815.515102	553.342			46		92.43222048	82.76694939	63.85400083
1815.833359	553.439			46		63.62368258	69.40554822	84.11924119
1816.151616	553.536			46		70.06398771	72.22593068	72.43898295
1816.469873	553.633			46		82.07775527	74.85924864	70.38723182
1816.78813	553.73			46		70.2017764	71.86361649	79.5166565
1817.106387	553.827			46		74.51330763	76.59554155	78.82779687
1817.424644	553.924			46		81.68353608	76.85728015	67.99639503
1817.746182	554.022	45.258617	-93.701261	46		71.60385221	70.03622313	66.88359642
1818.064439	554.119			46		59.05515565	64.99974564	81.5175008
1818.382696	554.216			46		71.81574458	69.28710437	80.4452961
1818.700953	554.313			46		84.24031967	82.25494804	72.97248615
1819.01921	554.41			46		69.67291967	68.12435233	73.51484044
1819.337467	554.507			46		66.9715747	66.16641743	77.81885397
1819.655724	554.604			46		81.7174802	80.347639	72.59660258
1819.973981	554.701			46		75.64777645	72.25831104	74.94411415
1820.295519	554.799			46		69.70141435	69.6121271	80.26687073
1820.613776	554.896			46		80.87609643	80.08816256	72.96973186
1820.932033	554.993	45.258622	-93.701251	46		76.05684568	77.65601218	68.2250095
1821.25029	555.09			46		69.78066613	67.62589928	76.50682569
1821.568547	555.187			46		74.83059051	74.85722377	75.21140856
1821.886804	555.284			46		79.60215618	84.59422925	69.18581012
1822.205061	555.381			46		73.58045652	73.53742439	70.06468305
1822.523318	555.478			46		77.95415285	70.47428493	72.33698981
1822.841575	555.575			46	2	77.51934393	74.84750462	51.68049351
1823.163113	555.673			46	2	66.03431441	70.76197216	27.7624101
1823.48137	555.77			46	2	52.46422162	49.66540061	39.35890699
1823.799627	555.867			46	2	36.11197789	32.75520535	41.80170418
1824.117884	555.964	45.258628	-93.701241	46	2	34.04273953	38.3675251	27.82049422
1824.436141	556.061			46	2	29.24197713	30.8326086	26.06849703
1824.754398	556.158			46	2	34.54198473	32.45277591	53.74128898
1825.072655	556.255			46	2	37.53865481	38.00565841	100.6902297
1825.390912	556.352			46	2	47.37029321	55.10012169	72.9553229
1825.709169	556.449			46		100.5142204	91.62854815	62.74937965
1826.030707	556.547			46		76.64745287	70.73667971	84.54069442
1826.348964	556.644			46		59.60286283	64.8335403	78.28157555
1826.667221	556.741			46		80.67910363	80.15653775	68.15409787
1826.985478	556.838			46		83.45983727	80.12384919	75.4616512

Marking Identification

Identifying Pavement Marking Rows

- Pavement markings span 6-8 rows of the data
  - A 7-row block of data spans a distance of approx. 1.9 ft
- A row may include portions of both the pavement marking and the adjacent pavement at the edge of the marking
- Friction values often spike briefly for 1-3 rows after a marking
- The average friction value for each run is captured
- The average value of all three runs is used in the summary and analysis

Distance (ft)	Distance (m)	Latitude	Longitude	Cell	Marking	SR_0.3_1	SR_0.3_2	SR_0.3_3
1810.098171	551.691			46		74.29045894	73.1095835	75.65295876
1810.416428	551.788			46		70.52620855	67.11925658	74.61014383
1810.734685	551.885			46		75.1928151	72.711812	77.45642597
1811.052942	551.982	45.258605	-93.70128	46		78.83519207	78.42063727	77.88908936
1811.371199	552.079			46		74.75617839	74.17517209	78.20500797
1811.689456	552.176			46		73.81570869	73.82576496	77.38554881
1812.010994	552.274			46		78.49983052	75.13694912	72.78692976
1812.329251	552.371			46		74.36557187	73.54577117	75.52262019
1812.647508	552.468			46	3	71.07112883	74.87466667	46.13986882
1812.965765	552.565			46	3	72.33297985	70.43414736	12.60718227
1813.284022	552.662			46	3	40.44531324	31.56351792	37.40418345
1813.602279	552.759			46	3	14.50877435	19.86126323	49.32758183
1813.920536	552.856			46	3	43.11095714	50.29364656	14.92418196
1814.238793	552.953	45.258611	-93.701271	46	3	46.04883676	37.30072378	21.56153809
1814.55705	553.05	45.258611	-93.701271	46	3	13.44061232	14.82821805	68.36548104
1814.878588	553.148			46	3	28.41500803	38.09336222	92.05000308
1815.196845	553.245			46	3	72.69005545	72.78720864	60.13994238
1815.515102	553.342			46		92.43222048	82.76694939	63.85400083
1815.833359	553.439			46		63.62368258	69.40554822	84.11924119
1816.151616	553.536			46		70.06398771	72.22593068	72.43898295
1816.469873	553.633			46		82.07775527	74.85924864	70.38723182
1816.78813	553.73			46		70.2017764	71.86361649	79.51665645
1817.106387	553.827			46		74.51330763	76.59554155	78.82779687
1817.424644	553.924			46		81.68353608	76.85728015	67.99639503
1817.746182	554.022	45.258617	-93.701261	46		71.60385221	70.03622313	66.88359642
1818.064439	554.119			46		59.05515565	64.99974564	81.5175008
1818.382696	554.216			46		71.81574458	69.28710437	80.4452961
1818.700953	554.313			46		84.24031967	82.25494804	72.97248615
1819.01921	554.41			46		69.67291967	68.12435233	73.51484044
1819.337467	554.507			46		66.9715747	66.16641743	77.81885397
1819.655724	554.604			46		81.7174802	80.347639	72.59660258
1819.973981	554.701			46		75.64777645	72.25831104	74.94411415
1820.295519	554.799			46		69.70141435	69.6121271	80.26687073
1820.613776	554.896			46		80.87609643	80.08816256	72.96973186
1820.932033	554.993	45.258622	-93.701251	46		76.05684568	77.65601218	68.2250095
1821.25029	555.09			46		69.78066613	67.62589928	76.50682569
1821.568547	555.187			46		74.83059051	74.85722377	75.21140856
1821.886804	555.284			46		79.60215618	84.59422925	69.18581012
1822.205061	555.381			46		73.58045652	73.53742439	70.06468305
1822.523318	555.478			46		77.95415285	70.47428493	72.33698981
1822.841575	555.575			46	2	77.51934393	74.84750462	51.68049351
1823.163113	555.673			46	2	66.03431441	70.76197216	27.7624101
1823.48137	555.77			46	2	52.46422162	49.66540061	39.35890699
1823.799627	555.867			46	2	36.11197789	32.75520535	41.80170418
1824.117884	555.964	45.258628	-93.701241	46	2	34.04273953	38.3675251	27.82049422
1824.436141	556.061			46	2	29.24197713	30.8326086	26.06849703
1824.754398	556.158			46	2	34.54198473	32.45277591	53.74128898
1825.072655	556.255			46	2	37.53865481	38.00565841	100.6902297
1825.390912	556.352			46	2	47.37029321	55.10012169	72.9553229
1825.709169	556.449			46		100.5142204	91.62854815	62.74937965
1826.030707	556.547			46		76.64745287	70.73667971	84.54069442
1826.348964	556.644			46		59.60286283	64.8335403	78.28157555
1826.667221	556.741			46		80.67910363	80.15653775	68.15409787
1826.985478	556.838			46		83.45983727	80.12384919	75.4616512

Do data inclusion strategies need refinement and/or standardization at the 0.1m level?

Developed a set of guidelines to improve standardization when identifying which rows to include for each pavement marking.

1. The default number of rows to include is 7. Including 6 or 8 rows is acceptable in some cases
2. A 7-row, centered, rolling window can help identify the center of the pavement marking with the lowest value corresponding with the middle row of the marking
   - In most cases, including the 3 rows prior to and following this row is suitable
   - If the lowest value is within 0.5 SR_0.3 of an adjacent row, consider a two-row middle with 6 or 8 total rows
3. A 6-row, right edge, rolling window can identify the end of the pavement marking with the lowest value corresponding with the last row of the marking
   - This is true in many cases, but can be overridden by the previous two rules
   - If the lowest value is within 1 SR_0.3 of an adjacent row, consider expanding the row selection to include the adjacent row

Marking Identification - Example

Distance (ft)	Distance (m)	Latitude	Longitude	Cell	Marking	SR_0.3_1	SR_0.3_2	SR_0.3_3
1772.819449	540.329			46		101.4944405	96.28915014	90.6612314
1773.137706	540.426			46		84.89063744	86.91178427	88.4235085
1773.455963	540.523			46		74.02033272	79.67648096	75.61626629
1773.77422	540.62			46		83.69065145	78.18508299	70.91942713
1774.092477	540.717			46		89.85664541	76.92840327	76.38948729
1774.410734	540.814			46		97.37236896	76.69049966	83.76957494
1774.732272	540.912			46		97.09174231	80.03259202	94.72677015
1775.050529	541.009	45.258608	-93.701351	46		95.3125	92.25680734	88.98108838
1775.368786	541.106			46		82.54672698	92.51707885	86.74613645
1775.687043	541.203			46		72.61371468	88.67478933	82.43828071
1776.0053	541.3			46		67.76082328	81.08108108	82.505688
1776.323557	541.397			46		67.06545655	78.93138717	81.31689912
1776.641814	541.494			46		74.8457299	77.55309474	89.82190643
1776.960071	541.591			46		96.47213791	75.52392458	89.89128449
1777.278328	541.688			46		121.5697306	77.66508534	82.02068778
1777.599866	541.786			46		96.84046961	80.01426377	76.69780245
1777.918123	541.883			46		79.8671199	81.07234422	69.42470162
1778.23638	541.98	45.258613	-93.701342	46	4	59.84112528	76.44280929	66.28573989
1778.554637	542.077			46	4	30.06205802	50.98413001	56.28390799
1778.872894	542.174			46	4	11.34774462	32.94454127	34.17107584
1779.191151	542.271			46	4	21.27939243	30.15006821	14.30969737
1779.509408	542.368			46	4	[illegible]	35.15532317	19.42870413
1779.827665	542.465			46	4	41.81281152	35.52817062	25.69599241
1780.145922	542.562			46	4	53.27007996	43.3645644	36.3114231
1780.46746	542.66			46	4	78.9341583	56.28725245	73.54618987
1780.785717	542.757			46		133.2124889	115.8779762	99.77501004
1781.103974	542.854			46		117.9816514	149.9178339	130.0148938
1781.422231	542.951	45.258619	-93.701332	46		97.56346328	110.6380299	94.23810109
1781.740488	543.048	45.258619	-93.701332	46		77.64987293	75.24630542	77.64729038
1782.058745	543.145			46		58.70910261	46.77401382	59.99884406
1782.377002	543.242			46		62.95314718	49.12269786	59.94214637
1782.695259	543.339			46		85.18814652	66.50104603	74.14731696
1783.013516	543.436			46		102.0065857	94.28320692	98.34425462
1783.335054	543.534			46		101.936398	105.1007337	101.2268337

Distance (ft)	SR_0.3_speed_corrected_1	SR_0.3_speed_corrected_2	SR_0.3_speed_corrected_3
1772.819449	96.86704117	91.89907375	86.52774668
1773.137706	81.02024932	82.94924674	84.39204747
1773.455963	70.64555047	76.04381999	72.16872122
1773.77422	79.87497386	74.62041879	67.68602335
1774.092477	85.75984389	73.42103441	72.90668903
1774.410734	92.93290577	73.19397736	79.95029902
1774.732272	92.66507363	76.38369501	90.40792679
1775.050529	90.96695167	88.05057611	84.92420581
1775.368786	78.78320392	88.29898115	82.79115124
1775.687043	69.30306386	84.63187174	78.67970201
1776.0053	64.67142858	77.38438069	78.74403602
1776.323557	64.00776545	75.33269699	77.60944716
1776.641814	71.43331561	74.01724455	85.72668875
1776.960071	92.07371863	72.31647372	85.79290368
1777.278328	116.0270459	74.3667008	78.28114824
1777.599866	92.42525712	76.61611119	73.20094729
1777.918123	76.2257672	77.62925567	66.25944632
1778.23638	57.1128105	73.19633401	63.26359814
1778.554637	28.69144948	48.81886791	53.71777614
1778.872894	10.830371	31.54540851	32.71985297
1779.191151	20.30920879	28.86961486	13.70197404
1779.509408	34.54857622	33.66229997	18.60357999
1779.827665	39.90645513	34.01931283	24.6047007
1780.145922	50.84135648	41.52290018	34.76930111
1780.46746	75.33534178	53.89677027	70.42273209
1780.785717	127.1389801	110.9567156	95.53763171
1781.103974	112.6025566	143.5509232	124.4932477
1781.422231	93.1152876	105.9393063	90.2358716
1781.740488	74.10961036	72.05064486	74.34966159
1782.058745	56.03239973	44.78755255	57.26333847
1782.377002	60.08294712	47.03648954	57.20922578
1782.695259	81.30419418	63.67679082	70.76674517
1783.013516	97.35583636	90.27906181	93.8604806
1783.335054	97.28884867	100.6371154	96.61163532

Distance (ft)	rolling_avg_6_right_1	rolling_avg_6_right_2	rolling_avg_6_right_3	rolling_avg_7_center_1	rolling_avg_7_center_2	rolling_avg_7_center_3
1772.819449	81.54585888	85.66220892	76.00450856	90.35306003	89.82412784	82.10057248
1773.137706	88.8506598	89.50061877	80.64334419	92.2904528	88.38616046	83.14755016
1773.455963	91.46346146	91.76396865	83.9640967	90.85803814	84.89429694	83.37523836
1773.77422	92.69608737	90.29578665	84.27389397	89.77383125	82.10199903	82.92946653
1774.092477	89.77231633	86.26159651	83.30951559	88.8906969	81.52595006	82.6894461
1774.410734	88.55417941	82.4469002	80.96324926	88.55585255	82.32670643	82.44982152
1774.732272	87.82039638	79.73747385	81.64083905	88.35490711	83.61217905	83.42439501
1775.050529	89.55737348	80.62831102	81.73376903	86.07921737	84.02589307	85.07957513
1775.368786	90.97843919	82.76841067	83.58874739	82.82333325	84.31203362	85.78349111
1775.687043	89.13228306	84.51669506	85.50855632	79.60524196	84.43526151	86.64810989
1776.0053	85.44964603	85.20880803	86.52792311	79.51672704	83.79116616	85.95732623
1776.323557	80.39849397	85.5822893	86.1191438	83.26775999	81.70663444	84.96298328
1776.641814	76.69082523	85.16903975	85.30166652	85.30972322	79.920518	83.527507
1776.960071	76.88409821	82.38022596	85.45336587	86.34592397	78.83445441	81.66842427
1777.278328	83.38793216	79.90489371	84.66579109	85.21453854	78.17184416	79.35128883
1777.599866	87.42572465	78.46147278	83.70904471	79.92833875	74.17937885	75.77514724
1777.918123	89.44344075	78.46001664	81.52888031	70.857198	67.80672835	67.82502858
1778.23638	88.23938554	78.04525366	79.02368711	60.11537722	61.32474887	57.02765899
1778.554637	80.77544023	73.61709287	73.4340207	47.91955818	55.25192571	48.08594704
1778.872894	66.58804135	66.52052898	64.14731926	40.05846216	48.89676954	40.79997418
1779.191151	49.87298498	58.60135946	52.86215419	[illegible]	43.50994385	[illegible]
1779.509408	39.7660706	51.12486936	43.31730448	[illegible]	[illegible]	37.10671296
1779.827665	33.42368587	43.53417376	36.02918627	53.72223702	[illegible]	43.31972754
1780.145922	32.32851165	38.02113295	31.63346681	68.95565227	66.61159843	57.01170153
1780.46746	40.4738617	38.90498869	33.91051379	79.85337667	78.10987866	68.43004492
1780.785717	60.78465241	62.72722584	44.84450282	85.77493232	83.83716184	76.74698581
1781.103974	76.90169557	72.68852013	64.12870222	88.18868819	85.44371087	81.64739319
1781.422231	87.12910889	85.26897124	76.59693505	89.57198351	86.26630136	85.0232108
1781.740488	93.10195246	91.88866038	85.25548471	90.4654104	87.72541473	85.1090861
1782.058745	94.00845623	92.45690195	89.20338821	86.00742423	84.64044769	84.90469247
1782.377002	91.34495438	91.26280951	86.93604762	83.71524517	78.23800479	80.79211246
1782.695259	83.34089732	83.03332115	82.66476544	83.20110448	76.64185034	81.41987714
1783.013516	80.67838637	73.76088332	77.38632558	82.60532657	78.26675614	84.32224794
1783.335054	81.40720882	72.83800062	78.55111435	83.91931891	81.64394208	87.98003383

The minimum 7-row, centered rolling average indicates the middle of a pavement marking (orange)

The minimum 6-row, right-edge rolling average indicates the end of a pavement marking (blue)

In run 2, we’ve overridden guideline 3 to include the last row given the strong evidence of guidelines 1 and 2. Consideration was also given to how close the adjacent value is to the lowest value.

Data Summary

	SR-0.3											
	15 mph				30 mph				40 mph			
	Cell 139		Cell 46		Cell 139		Cell 46		Cell 139		Cell 46	
	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic
1_before	75.2	81.6	75.0	87.8	71.7	70.0	72.7	84.2	71.3	63.6	71.0	84.8
1_mark	45.4	50.1	26.4	56.1	26.5	31.1	17.4	36.8	6.1	18.8	9.2	32.7
1_2_gap	73.3	81.9	75.4	87.9	71.9	75.2	74.9	83.4	72.2	71.2	73.0	82.8
2_mark	39.3	43.5	38.9	45.6	32.7	31.1	31.3	38.2	22.3	29.4	27.2	34.5
2_3_gap	73.9	83.1	74.1	87.8	70.5	73.6	76.0	88.7	70.2	67.4	75.5	86.3
3_mark	44.8	44.0	36.7	43.4	33.1	34.0	29.4	21.1	26.3	19.4	22.7	26.7
3_4_gap	73.6	83.2	77.4	88.9	69.4	73.1	78.1	84.9	67.6	67.3	79.0	84.8
4_mark	43.6	47.3	39.6	50.5	35.2	36.2	28.8	37.7	31.3	26.3	26.0	30.0
4_5_gap	71.4	82.4	78.7	88.6	66.6	71.5	77.4	84.9	65.7	70.5	74.4	83.5
5_mark	45.1	47.6	53.3	54.8	38.2	35.6	45.5	48.0	36.7	24.5	46.6	35.2
5_6_gap	73.6	82.1	78.6	87.9	68.1	73.3	77.8	84.6	66.2	68.7	78.1	82.0
6_mark	63.0	66.4	66.7	66.9	41.4	43.7	49.5	49.0	37.7	32.2	41.4	39.2
6_7_gap	76.6	84.0	80.4	86.1	73.4	75.5	79.1	81.8	69.3	72.8	79.1	81.9
7_mark	51.4	58.8	53.4	53.9	31.9	42.5	32.0	23.2	21.9	28.7	27.5	18.1
7_10_gap	73.9	82.2	78.0	83.3	69.7	74.1	74.0	77.3	68.2	71.2	71.9	74.8
10_mark	67.4	70.6	68.0	64.3	50.9	51.8	56.2	54.3	45.3	47.5	58.2	49.1
10_11_gap	73.8	81.6	78.8	84.2	70.8	77.2	73.9	78.6	69.1	74.4	72.2	78.1
11_mark	54.8	58.1	75.6	72.6	41.9	43.0	63.9	60.4	36.3	34.0	51.6	53.3
11_12_gap	73.4	80.9	77.3	82.9	69.9	74.6	72.9	77.7	70.3	72.3	70.9	74.6
12_mark	64.4	66.8	64.9	71.6	55.5	59.0	54.7	62.3	45.9	50.3	46.8	61.4
12_after	73.0	80.2	76.4	81.5	67.9	73.7	71.2	77.3	67.7	70.7	67.6	74.2

	SR-0.3 Speed Corrected											
	15 mph				30 mph				40 mph			
	Cell 139		Cell 46		Cell 139		Cell 46		Cell 139		Cell 46	
	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic	Traffic	No Traffic
1_before	65.4	70.9	65.1	76.7	68.2	66.7	69.6	80.4	71.2	63.4	69.5	83.3
1_mark	39.5	43.5	22.9	49.0	25.2	29.6	16.6	35.2	6.0	18.7	9.0	32.1
1_2_gap	63.7	71.3	65.5	76.7	68.4	71.5	71.7	79.7	72.1	71.0	71.5	81.3
2_mark	34.1	37.9	33.8	39.8	31.1	29.5	30.0	36.4	22.3	29.3	26.6	33.9
2_3_gap	64.2	72.4	64.3	76.6	67.1	70.0	72.7	84.7	70.1	67.2	73.9	84.6
3_mark	39.0	38.3	31.9	37.8	31.5	32.3	28.1	20.1	26.3	19.3	22.2	26.3
3_4_gap	63.9	72.6	67.2	77.5	66.0	69.5	74.7	81.1	67.5	67.2	77.5	83.2
4_mark	37.9	41.3	34.3	44.1	33.5	34.4	27.6	36.0	31.3	26.2	25.5	29.4
4_5_gap	62.1	71.9	68.2	77.3	63.3	68.0	74.1	81.0	65.6	70.3	73.0	81.9
5_mark	39.3	41.6	46.2	47.8	36.4	33.9	43.5	45.9	36.6	24.4	45.7	34.6
5_6_gap	64.0	71.7	68.1	76.6	64.8	69.7	74.3	80.9	66.1	68.5	76.5	80.4
6_mark	54.8	57.9	57.7	58.4	39.4	41.6	47.4	46.8	37.6	32.1	40.6	38.5
6_7_gap	66.6	73.4	69.5	75.1	69.8	71.8	75.6	78.1	69.2	72.7	77.6	80.4
7_mark	44.7	51.4	46.2	47.0	30.3	40.4	30.5	22.2	21.9	28.6	27.0	17.7
7_10_gap	64.3	71.9	67.4	72.6	66.3	70.6	70.6	73.8	68.0	71.0	70.6	73.4
10_mark	58.6	62.1	58.7	56.1	48.5	49.3	53.7	51.8	45.2	47.4	57.1	48.1
10_11_gap	64.1	71.5	68.0	73.5	67.4	73.4	70.5	75.0	69.0	74.3	70.9	76.6
11_mark	47.7	50.8	65.3	63.4	39.9	40.9	61.1	57.7	36.2	34.0	50.7	52.4
11_12_gap	63.8	70.8	66.7	72.5	66.5	70.9	69.6	74.2	70.1	72.2	69.6	73.2
12_mark	55.9	58.4	56.1	62.6	52.9	56.1	52.2	59.4	45.8	50.3	45.9	59.7
12_after	63.4	70.1	66.0	71.3	64.6	70.2	68.0	73.9	67.5	70.6	66.3	72.9

The prevailing patterns here are the alternating friction levels:
The pavement markings tend to have lower average friction (red) than the unmarked gaps between them.

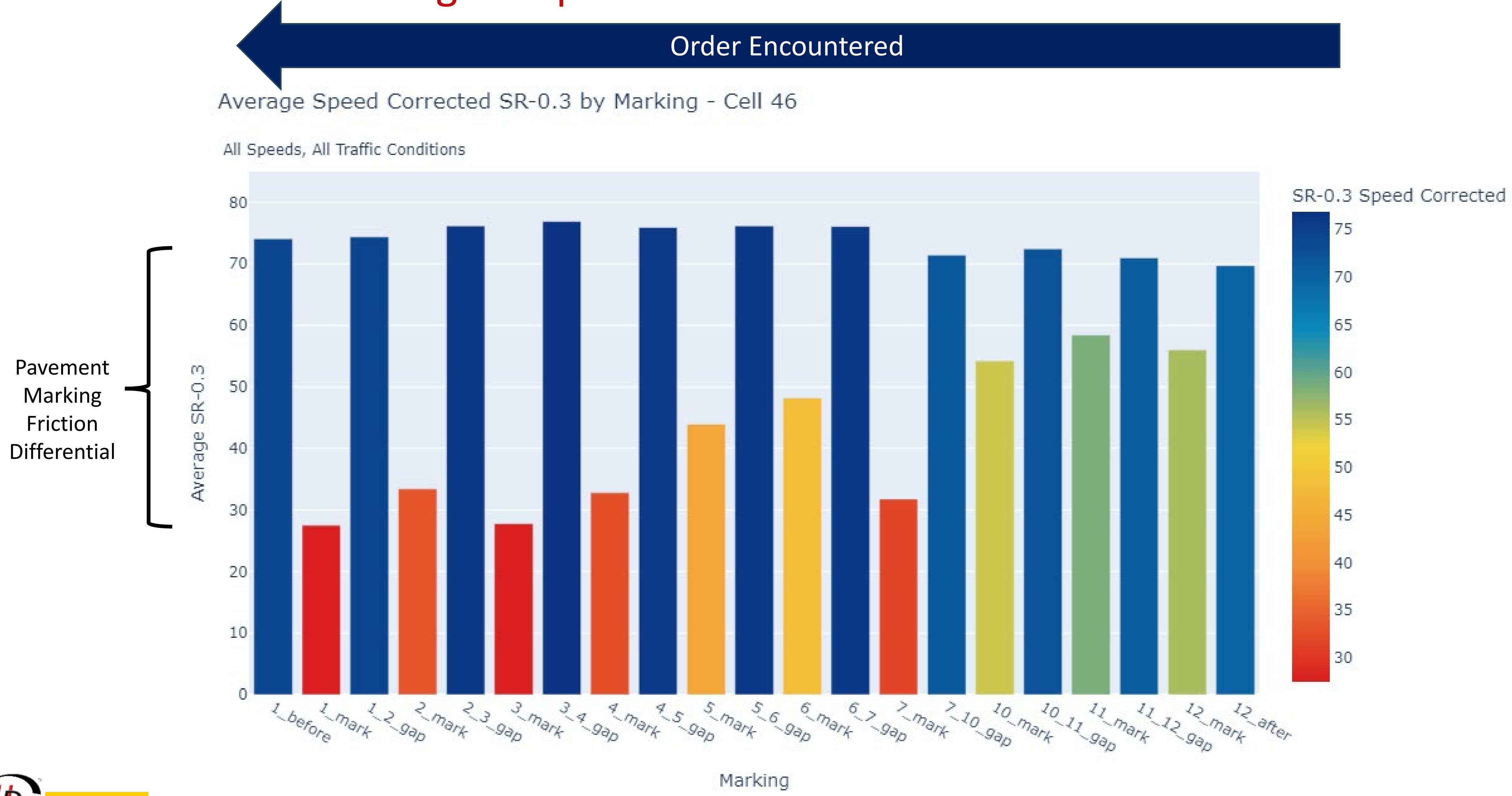
Cell Comparison

- Cell 46 had higher average friction than Cell 139
  - For markings and non-markings
  - At all speeds
  - Under all traffic conditions
  - Speed-corrected or not

Marking	Speed (MPH)	Trafficked	Cell	SR-0.3	SR-0.3 Speed Corrected
Non Marking	15	No traffic	46	86.1	75.1
			139	82.1	71.7
		Trafficked	46	77.3	66.9
			139	73.8	64.1
	30	No traffic	46	82.1	78.4
			139	73.8	70.2
		Trafficked	46	75.3	71.9
			139	70.0	66.6
	40	No traffic	46	80.7	79.2
			139	70.0	69.9
		Trafficked	46	73.9	72.5
			139	68.9	68.8
Marking	15	No traffic	46	58.0	50.6
			139	55.3	48.3
		Trafficked	46	52.4	45.3
			139	51.9	45.1
	30	No traffic	46	43.1	41.2
			139	40.8	38.8
		Trafficked	46	40.9	39.1
			139	38.7	36.9
	40	No traffic	46	38.0	37.3
			139	31.1	31.0
		Trafficked	46	35.7	35.0
			139	31.0	30.9

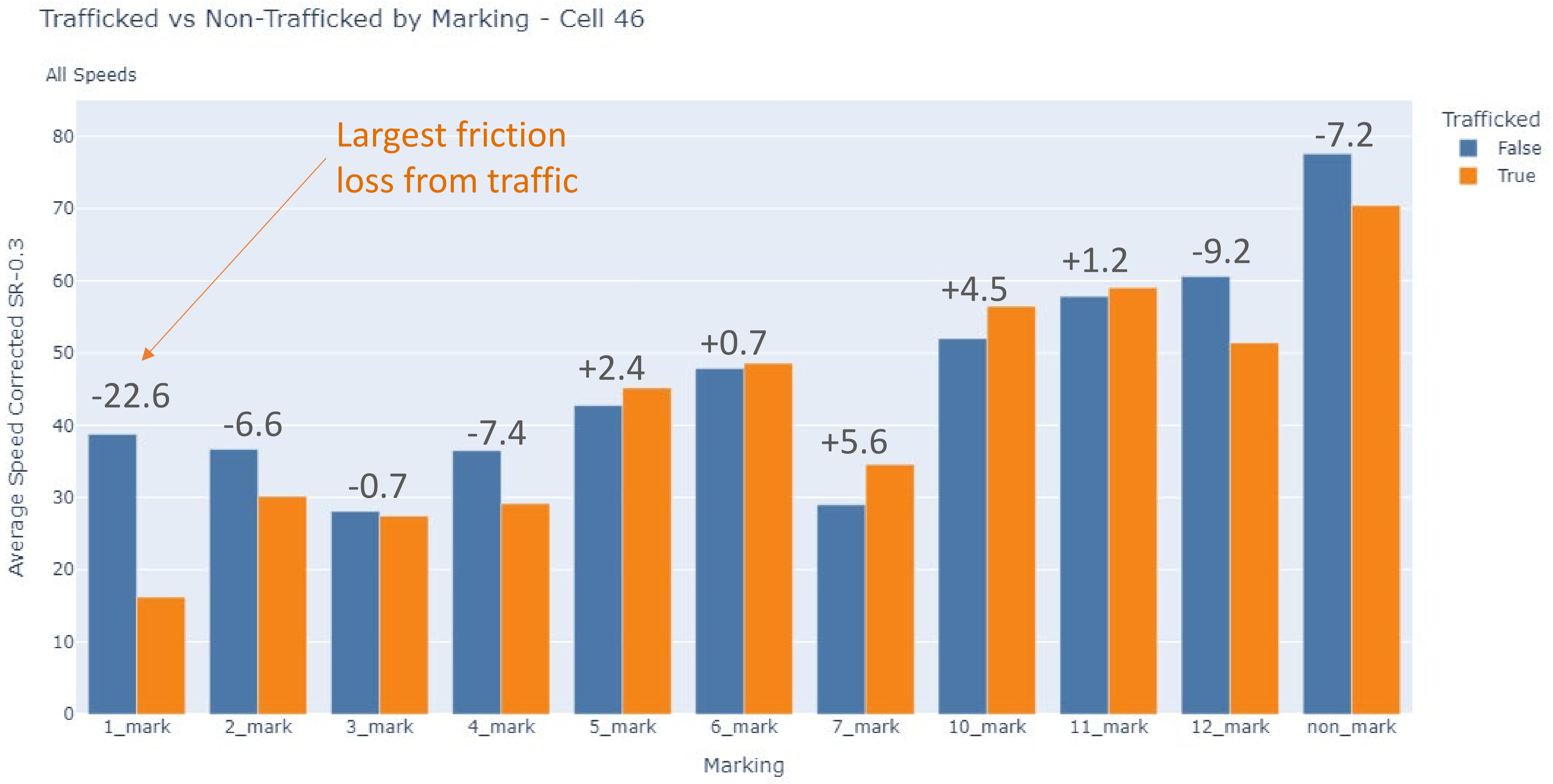
Pavement Marking Comparison – Cell 139

Pavement Marking Comparison – Cell 46

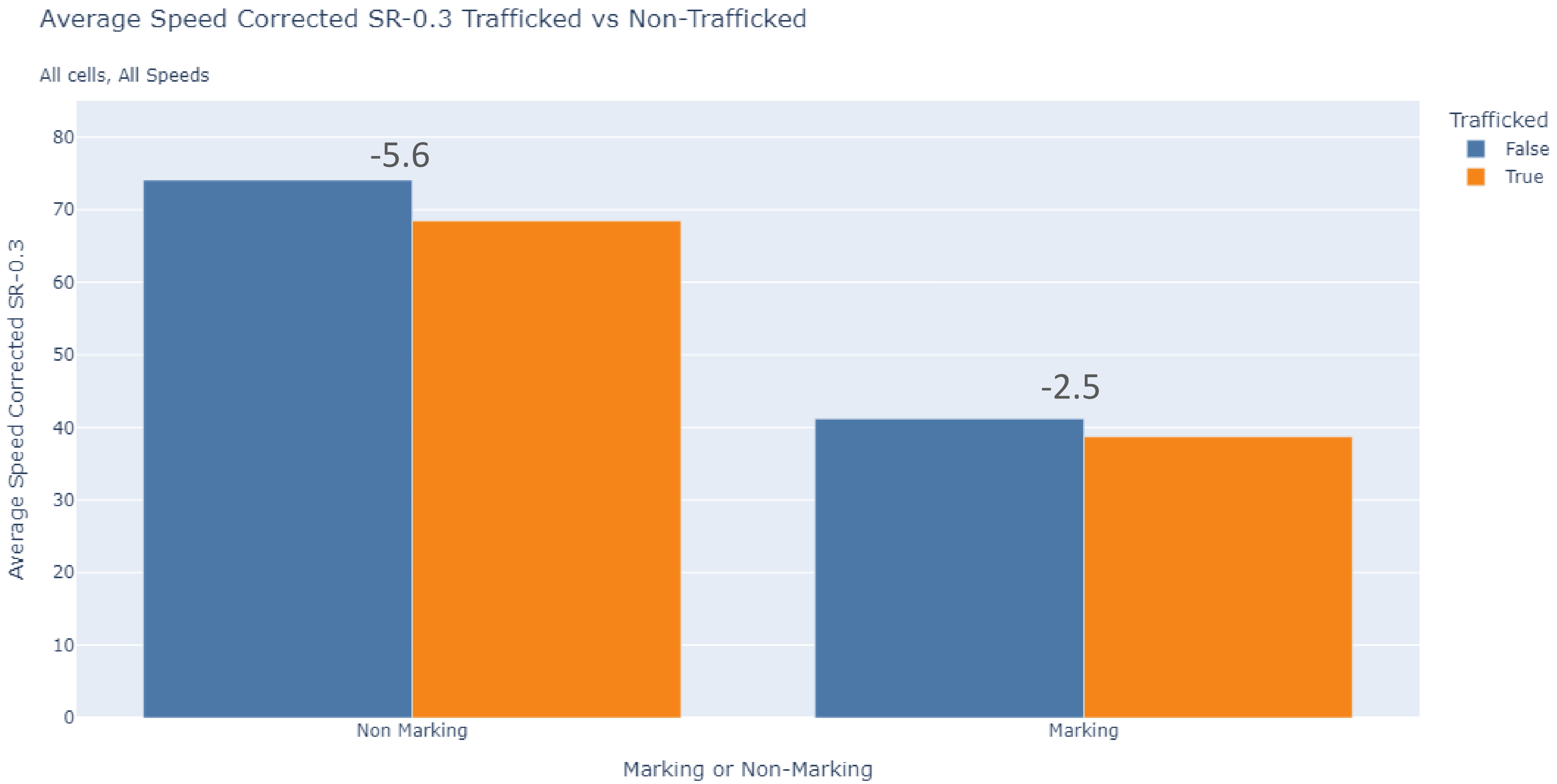


Traffic Comparison – Cell 139

Traffic Comparison – Cell 46

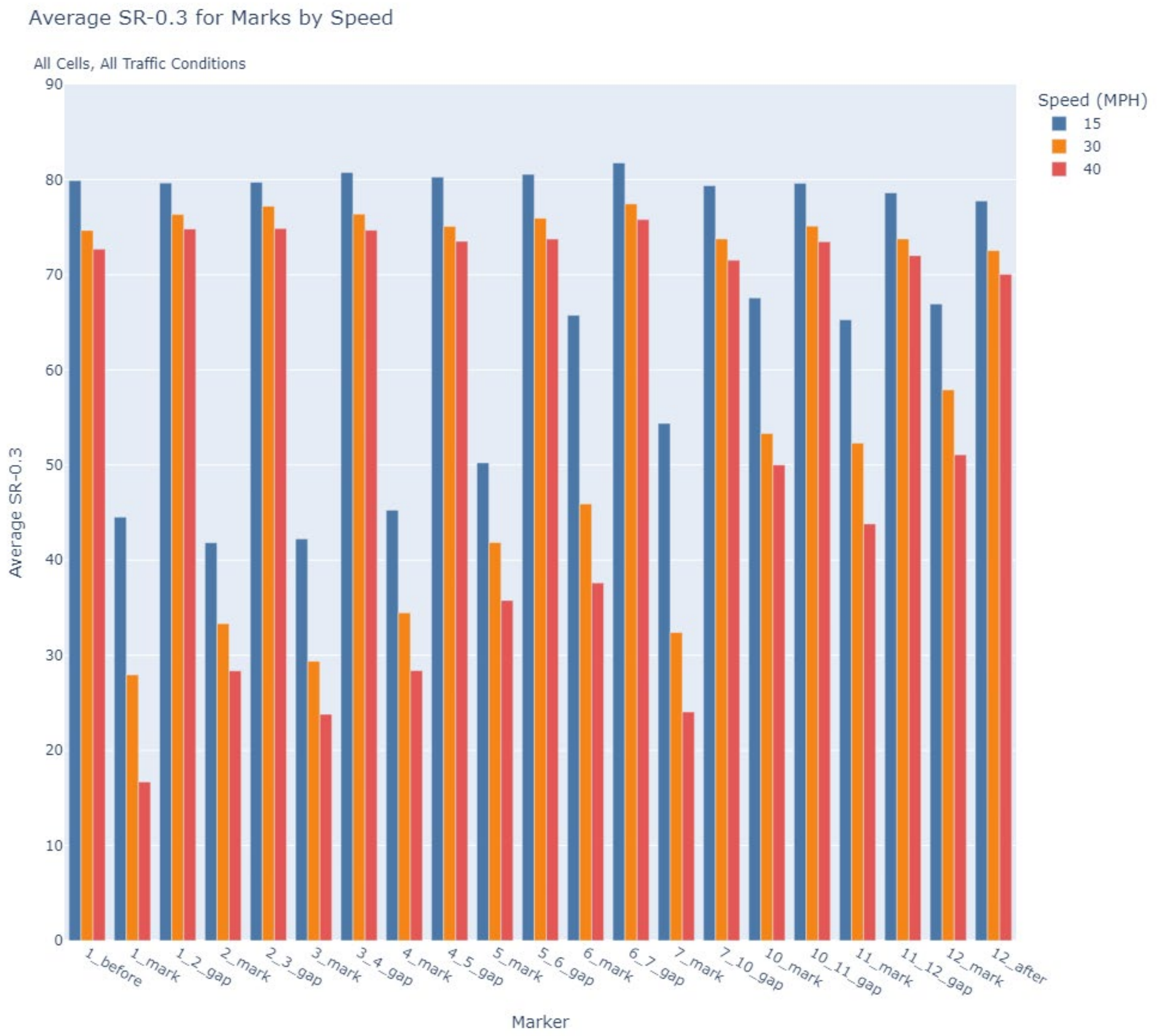


Traffic Comparison – Markings vs Non Markings

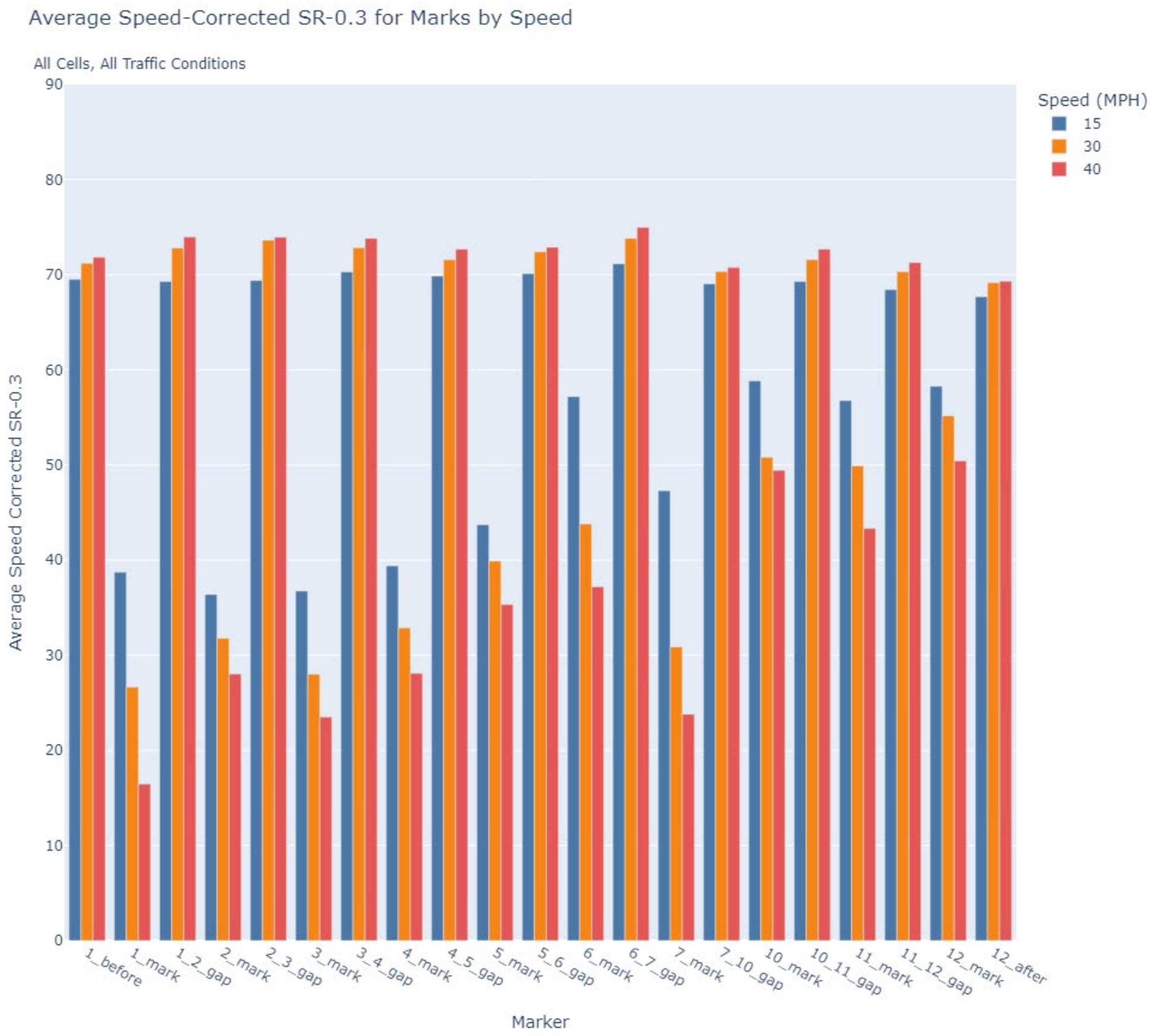


Speed Comparison

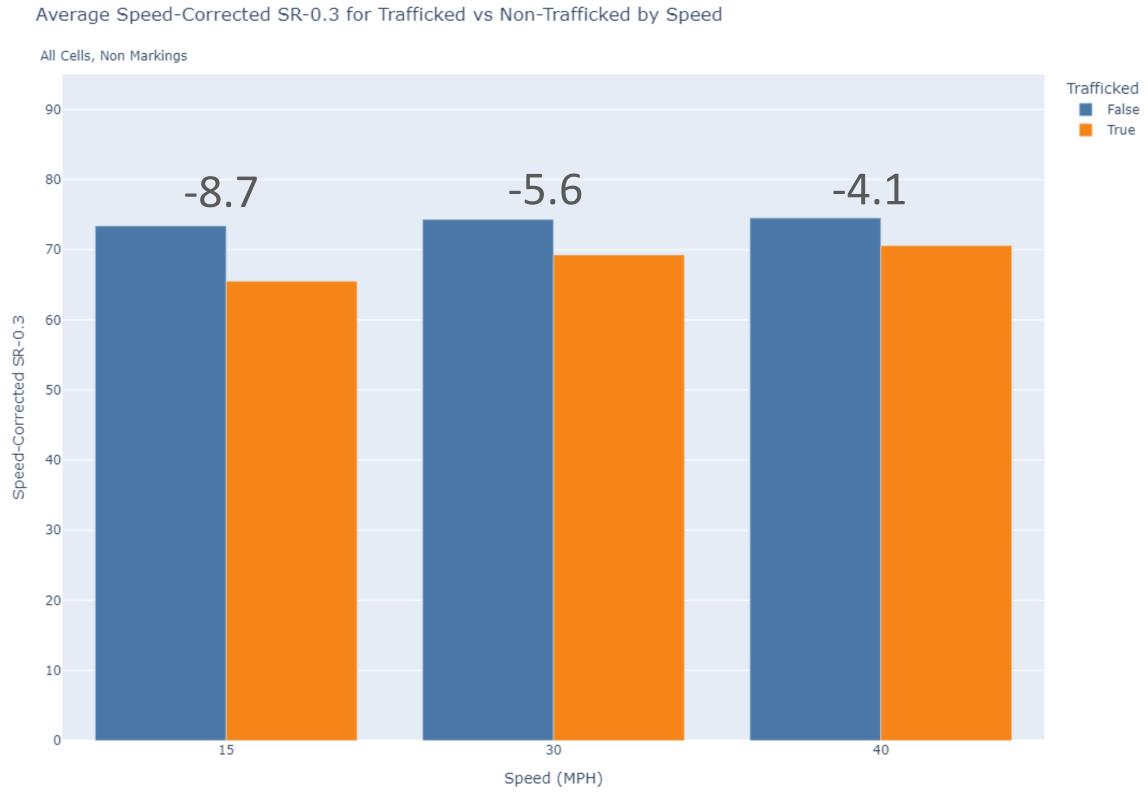
No Speed Correction

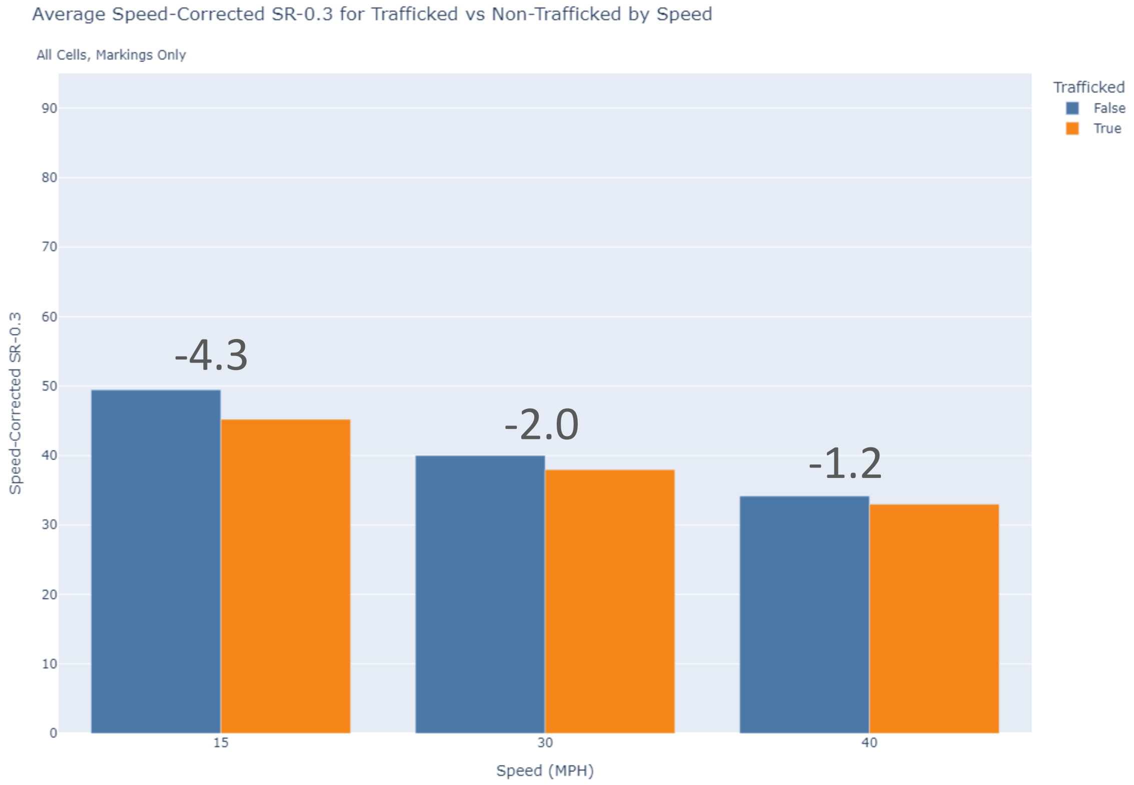


Speed Correction



Traffic x Speed Comparison





Questions or Feedback

If you have any questions about the methodology or the data, feel free to contact me.

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