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RESEARCH REPORT

EVALUATING THE CORRELATION BETWEEN SLIP RESISTANCE AND SKID RESISTANCE ON PAVEMENT MARKINGS AT CROSSWALKS

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16. Abstract

Pavement markings are crucial for ensuring the safe and efficient movement of vehicles, cyclists and pedestrians at crosswalks. They provide essential guidance in lane navigation, road sharing, and safety compliance. With growing emphasis on safety in urban areas, crosswalk markings are becoming more prevalent. The primary objectives of this project were to (i) assess slip resistance for pedestrians, PSR, and skid friction for vehicles, TSR, on crosswalk areas where pavement markings are used, and, (ii) relate vehicle pavement skid resistance to pedestrian slip resistance for a variety of conditions (i.e., wet versus dry, and/or icy conditions). The key findings of the study provided a consistent performance across both PSR and TSR measurements in dry, wet, and icy conditions. While the analysis confirmed the high repeatability of the BPT measurements, meaningful differences were observed between surface conditions (i.e., dry versus wet). All materials experienced reduced friction in wet and icy environments. Good relationships between lab and field data were established and relating the various surface conditions. Overall, this investigation provided critical insights into the relationship between pedestrian slip resistance and vehicular skid resistance. The findings suggest that Maryland's current specifications, which focus on vehicle skid resistance, could be expanded to incorporate pedestrian slip resistance requirements for improved safety at crosswalks.

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Table of Contents

List of Figures

List of Tables

Executive Summary

This study examined the relationships between pedestrian slip resistance and vehicular skid friction for pavement markings at crosswalks in Maryland, using the British Pendulum Tester (BPT). The primary aim was to evaluate the frictional properties of various pavement marking materials under different surface conditions in both laboratory (dry, wet, and icy) and field conditions (dry, wet). The tested markings considered those typically used in Maryland.

Friction was measured using two different rubber pads, pedestrian slip rubber (PSR) simulating a pedestrian's shoe sole, and tire slip rubber (TSR) representing vehicular tire interaction. The measurements and results were in British Pendulum Number (BPN), which indicate the frictional resistance of the pavement markings.

Laboratory tests involved applying selected pavement markings to concrete and asphalt samples, comparing their performance in dry, wet, and icy conditions. Field tests were conducted at multiple crosswalk locations with varying traffic conditions, assessing pavement marking friction under in-service conditions.

Key findings from the analysis showed consistent performance across both PSR and TSR measurements in dry, wet, and icy conditions. While statistical analysis confirmed the high repeatability of the BPT measurements, meaningful differences were observed between surface conditions (for example dry versus wet) and pavement marking types. In particular, preformed thermoplastic showed superior performance under dry conditions, and all materials experienced reduced friction in wet and icy environments. Good relationships between lab and field data were established and relating to the various surface conditions.

Overall, this investigation provides critical insights into the relationship between pedestrian slip resistance and vehicular skid resistance. The findings suggest that Maryland's current specifications, which focus on vehicle skid resistance, could be expanded to incorporate pedestrian slip resistance requirements for improved safety at crosswalks.

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1. Introduction

1.1 Research Need

Pavement markings are crucial for ensuring the safe and efficient movement of vehicles, cyclists and pedestrians at crosswalks. They provide essential guidance in lane navigation, road sharing, and safety compliance. Wet conditions may significantly reduce the surface friction of pavement markings.

With growing emphasis on safety in urban areas, crosswalk markings are becoming more prevalent. These markings, while effective in terms of visibility, must also meet friction standards to ensure the safety of all road users. As the adoption of preformed thermoplastic markings and other materials increases, the need to evaluate their friction performance under various conditions has become evident. The research addresses the gap in understanding the frictional properties of pavement markings and the relationship between slip resistance (pedestrian safety) and skid resistance (vehicular safety). This study aims to fill that gap through comprehensive laboratory and field testing.

1.2. Project Objectives

The primary objectives of this project were to (i) assess slip resistance for pedestrians and skid friction for vehicles on crosswalk areas where pavement markings are used, and (ii) relate vehicle pavement skid resistance to pedestrian slip resistance for a variety of conditions (i.e., wet versus dry, and/or icy conditions). To achieve these objectives the following research was undertaken:

- **Friction Evaluation of Pavement Marking Materials**: Laboratory and field testing were undertaken using the British Pendulum Tester (BPT) to assess slip and skid resistance of a select number of pavements marking materials. While the initial list of such materials included typical preformed thermoplastics, high-performance tapes, and thermoplastics used in the state, the field testing during the scoping session was focused more on preformed thermoplastics since this represents the preferred material to be used in the state as identified by the SHA project technical advisor for the project. Nevertheless, both laboratory and complementary field testing considered all three pavement marking types selected from the state suppliers list and approved by the SHA team. The laboratory testing included dry, wet, and icy conditions, while the field testing included dry and wet conditions. In both field and laboratory testing the pedestrian slip resistance (PSR) and vehicular tire skid resistance (TSR) were evaluated.

- **Statistical Analysis**: The analysis of the laboratory and field data were complemented with statistical analysis to reinforce the meaningfulness, in statistical terms, of the observed effects. For example, statistical comparisons were used to identify significant differences in slip and skid resistance values based on material types, testing conditions, and surface types. The statistical analysis focused as well on assessing the significance of differences between PSR and TSR across different pavement markings and surface conditions (D, W, I).

- **Relating Vehicle Skid and Pedestrian Slip Resistance**: Following the statistical analysis the relationships between vehicle skid friction and pedestrian slip resistance on various marking and surface conditions were examined. Furthermore, relationships between the laboratory and field measurements were obtained for both TSR and PSR under various surface conditions.

- **Recommendations for Potential Specification Revisions**: The results of this study and the relationship between vehicle skid and pedestrian slip resistance were used for providing recommendations for potential specification revisions regarding pavement markings used at crosswalks.

During the research conduct the following additional effects were considered to complement the study findings:

- **Comparison between BPT Devices**: Since a constructor and the agency may be using their own BPT units during QA and acceptance testing, it was of interest to compare alternative units. Thus, the response of two BPT units was compared to assess whether significant differences exist in their measurements of slip and skid resistance under different conditions.

- **Comparison between BPT Operators**: Similarly, alternative operators may be using the same BPT device, often reflecting different levels of training and experience. Thus, the operator-to-operator variability was examined to assess the significance of such effects on BPT measurements.

- **Potential Effects of BPT Testing Pad Wear**: The ability of the BPT to provide consistent results time after time depends on the ability of the testing pads to resist degradation. Thus, it was of interest to compare BPN values obtained using used versus new pads, as well as the potential impact of using the two opposite sides of the pad orientation (i.e., side mostly used during testing versus the complementary side not yet exposed to testing).

- **Potential Influence of Pavement Surface**: It was of interest as well to assess whether the type of pavement surface (i.e., asphalt versus concrete) where the pavement markings are applied had an influence on the BPN measurements. Thus, the pavement markings considered in this study were applied to both asphalt and concrete samples to assess any such effects for alternative surface conditions (dry, wet, icy).

1.3 Organization of the Report

This report is structured to provide a comprehensive understanding of the frictional properties of pavement markings and their effects on slip and skid resistance. Chapter 1 outlines the project objectives, detailing the study's focus on assessing both vehicular and pedestrian skid, and slip resistance on pavement markings. In Chapter 2, a summary of the literature review is provided, exploring existing research on pavement markings and their friction characteristics. Chapter 3 covers the laboratory experimental plan, while Chapter 4 focuses on the field-testing plan of pavement marking materials included in the study. Chapter 5 presents the experimental results and analysis, highlighting key findings from the British Pendulum Tester (BPT) measurements. Finally, Chapter 6 provides the conclusions and recommendations, along with suggested revisions to state specifications of pavement marking for considering pedestrian slip resistance.

2. Literature Review

Overview of Pavement Marking Materials

Pavement marking materials vary widely in their composition, application method, and performance under different environmental conditions. The most common materials used for pavement markings include paints, thermoplastics, preformed thermoplastics, and tapes. Over time various studies have focused on the performance of such materials.

Low volatile organic carbon (VOC) paints (P) are typically used for road markings because of their relatively low environmental impact compared to traditional solvent-based paints. According to Burghardt and Pashkevich, 2018, low VOC paints are used due to their compliance with environmental regulations and potential ability to reduce air pollution pertinent to their installation ease (1). These paints, available in both waterborne and solvent-based formulations, provide cost-effective solutions for low-traffic areas but have a shorter lifespan under heavy traffic or extreme weather conditions. Thus, the potential environmental benefits of low VOC paints are traded off by their lower durability as compared to the more advanced materials like thermoplastics.

Thermoplastics (T) are frequently used in the U.S. These markings are made of binders, glass beads for reflectivity, titanium dioxide (TiO_2), and fillers like calcium carbonate. They are available in two main types: alkyd-based and hydrocarbon-based. Alkyd thermoplastics are resistant to oils but are more sensitive to heat, whereas hydrocarbon thermoplastics offer greater heat stability. Typically provided in solid forms such as granules or blocks, the material is heated to over 204°C (400°F), converting it into a liquid for application through methods like spraying or extruding. On-site heating is essential for adhesion, whether applied as traditional thermoplastic or preformed segments (2,3,4). These markings have good strength and durability, making them suitable for high-traffic areas, including lane demarcations and crosswalks.

Preformed thermoplastics (E) represents a preferable pavement marking material by various states, including Maryland, due to their performance and durability among other properties.

Preformed thermoplastics (P) come as ready-made, pre-cut strips or shapes, designed for quick and precise application. These markings are placed on preheated pavement and fused to the surface using a heat source like a propane torch. Unlike traditional thermoplastics, preformed versions come pre-embedded with glass beads, ensuring immediate reflectivity and simplifying the installation process. They provide the same durability and high performance as conventional thermoplastics but are particularly advantageous for projects requiring rapid and accurate application, such as crosswalks, stop bars, and symbols (4).

High performance tape (T) consists of pre-made strips or patterns of durable reflective materials that are adhered to pavement surfaces using an adhesive backing. Commonly used for crosswalks, stop bars, symbols, and longitudinal striping in both urban and rural areas, preformed tapes are made from polyvinyl chloride (PVC) resin binders, pigments, inert fillers, extenders, and glass beads (5). While this material is more expensive than other pavement markings, it is highly durable (6, 7).

Friction of Pavement Markings & BPT

Several studies on pavement friction have predominantly focused on conventional pavement materials like, concrete and asphalt, and to a lesser degree, on pavement markings. In terms of slip resistance, early investigations have looked at slip resistance predominantly centered on laboratory-based testing and employing devices such as the BPT and the portable skid resistance tester (PSRT) (*8, 9, 10)*. While these studies focused on pavement surface texture and slip resistance, they were limited in assessing pavement materials (i.e., concrete and asphalt) rather than pavement markings. Purohit et al. and Nassiri (*11, 12*) did examine the slip resistance of thermoplastic markings. Results indicated that thermoplastic materials provide adequate slip resistance. A more recent study assessed floor slip resistance using the BPT (*13*). Another study simulated pedestrian gait on various surfaces and assessed the surface friction properties (*14*). Recent studies have also explored factors impacting slip resistance, such as driving conditions and asphalt pavement types. Fan's (*15)* investigation showed that these parameters may influence the road surface's ability to resist slipping.

Over time, several studies have used the BPT for assessing skid resistance (*16, 17*). The importance of alternative pavement markings on road safety has been recognized in Europe as well (*18*). The correlation between BPN and pavement friction have been a focal point of such studies. Research by Saito et al. (*19*) provided a good relationship between BPN values and the coefficient of friction. Thus, with the interest in alternative pavement markings, researchers have focused on assessing their impact on skid resistance. A study by Henry et al. (*20*) assessed the skid resistance of diverse alternative pavement marking materials, revealing that certain materials can furnish satisfactory levels of skid resistance. Environmental variables and surface conditions, including moisture and presence of debris, yielded a substantial influence on skid resistance. Kumar & Gupta (*21*) conducted an evaluation of factors affecting skid resistance at the tire-pavement interface under varying conditions, emphasizing the imperative of continual maintenance (such as cleanliness) to uphold skid resistance amidst changing environmental conditions. Recent studies considered the use of alternative instrumentation for field testing (17), such as the BPT and the dynamic friction tester (DFT), while laboratory experimentation explored the use of tribometer measurements (*22*). Effects of routine maintenance, including cleaning and retexturing, have been looked at as well (*23*).

In terms of state specifications regarding pavement markings friction, the majority of the state Department of Transportation's (DOTs) focus on a minimum BPN in regard to vehicle skid resistance. While some have recognized the need to consider slip resistance, very few have considerations regarding minimum friction levels at pedestrian crossings for safety. The Maryland State Highway Administration (SHA) Manual of Standard Specifications for Construction and Materials (*24*) delineates guidelines for materials and surfaces. Notably, crosswalks are recommended to possess a minimum initial BPN of 45. Some state DOTs have adapted their friction specifications to potentially consider slip resistance at pedestrian crossings. For instance, while Caltrans does not prescribe BPN in its specifications, the practice of acknowledging a BPN of 45 as the minimum for all mixture types is widely accepted. Furthermore, Caltrans considers BPN above 55 as adequate and above 65 as exemplary (*25*). On the other hand, New York State Department of Transportation (NYSDOT) underscores the use of high-friction surface treatments (HFST) to augment pedestrian safety (*26*). In parallel, internationally various countries have revised their standards to potentially consider slip resistance at pedestrian crossings. In the United Kingdom, the highway authority provides guidance on slip resistance emphasizing a minimum pendulum test value, PTV, of 36 units (*27*). In Italy, the Decreto Ministeriale (DM) 236:1989 requirement provides recommendations for pavement slip levels at pedestrian crossings, emphasizing a PTV of at least 39 (*28*).

Overall, in terms of the most common approach for prescribing friction evaluation for slip resistance at pedestrian crossings, a minimum BPN threshold value of 45 has been suggested. Nevertheless, in recent years alternative methodologies for measuring slip resistance have been proposed. These include:

- Tribometers: Devices directly assessing the frictional properties of a surface, such as the Tortus and Portable Skid Resistance Tester (PSRT). Powers et al.'s (*29*) study attests to the accuracy of tribometers in evaluating floor slipperiness and gauging the pedestrian's risk of sliding.

- Texture depth measurement: This method evaluates the microtexture of a surface, integral to slip resistance, using instruments like the Circular Track Meter (CTM).

- Dynamic Friction Tester (DFT): Simulating a vehicle tire's interaction with the road. It measures the friction coefficient of a pavement surface.

- 3D surface profilometry: This technology furnishes detailed 3D surface maps, enabling a comprehensive assessment of surface texture and potential slipperiness.

- The portable slip simulator: A research endeavor determined the utility of a portable slip simulator in assessing sidewalk slipperiness under diverse weather conditions and evaluating various types of footwear for resistance to slippage (30).

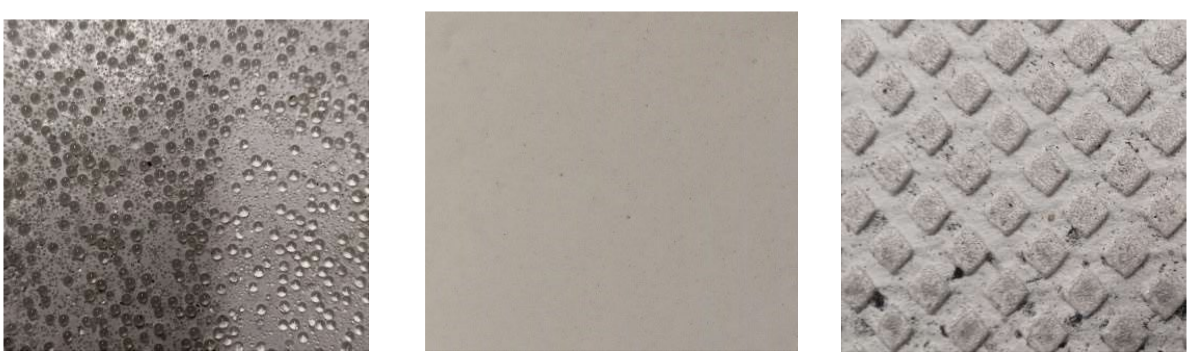
3. Laboratory Experimental Plan

Both laboratory and field testing were considered in this study to assess the slip and skid resistance of selected pavement marking materials used in Maryland. The British Pendulum Tester (BPT) was identified as the primary tool for evaluating friction following the Maryland specifications and the recommendations of the state technical group dealing with pavement markings friction assessment. The experimentation involved laboratory testing under controlled conditions and field testing at selected sites. The BPT was used to assess pedestrian slip resistance (PSR) and vehicular tire skid resistance (TSR) under different environmental conditions. These included dry (D) and wet (W) surface conditions for the field testing, and dry (D), wet (W), and icy (I) conditions for the laboratory testing.

Selection of Pavement Markings and Specimen Preparation

In consultation with the pavement markings pavement friction expert team of SHA, pavement marking materials commonly used in Maryland were reviewed and selected for this study including preformed thermoplastic (P), high-performance tape (T), and thermoplastic (Th). Although the state is moving toward adopting preformed thermoplastics for all projects, the study included the additional marking types to provide a broader assessment.

In the laboratory, the three pavement marking types were applied to both asphalt and concrete surfaces. Concrete samples were beams measuring 53.3x15.2x15.2 cm (21x6x6 in), while asphalt samples were gyratory compacted dense graded specimens measuring 15.2x6.2 cm (6x2.4 in). Figure 3.1 presents the three types of pavement markings considered in the study (Th, P, and T) and applied on both asphalt and concrete surfaces following the supplier's recommendations. For example, the application of P marking requires the use of a propane torch to be applied on asphalt samples, as per supplier recommendation, Figure 3.2.



(P) (Th) (T)

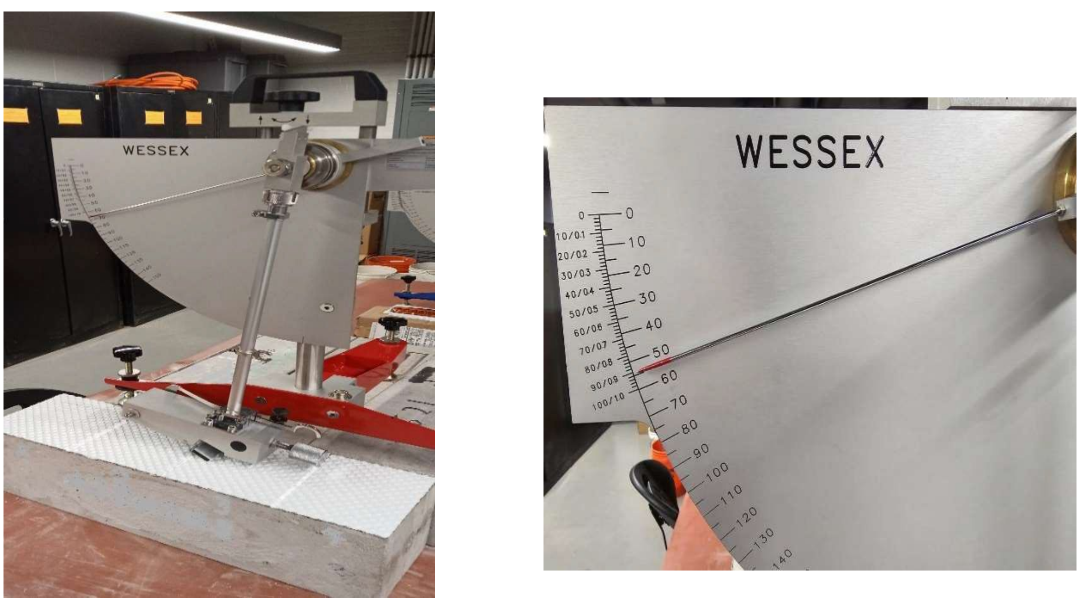
Figure 3.1: *Pavement Markings: Preformed Thermoplastic (P), Traditional Thermoplastic (Th), and High-Performance Tape (T)*

Figure 3.2: *Application of Preformed Thermoplastic on Asphalt Surfaces*

BPT Testing Protocol

The BPT was used to assess the frictional properties of each pavement marking in the lab under dry, wet, and icy conditions. The BPT uses two types of pads: the pedestrian slip rubber (PSR) to simulate pedestrian footwear and the tire slip rubber (TSR) to simulate vehicle tires. The testing followed the American Society for Testing and Materials (ASTM) E303 standards, and the BPN (British Pendulum Number) values were recorded for each sample with at least six replicate measurements for each condition.

The pendulum arm of the BPT was swung across the surface of the specimen, and the frictional resistance was measured as BPN. Figure 3.3a shows the BPT setup, while Figure 4.3b illustrates a close-up of the BPN value reading. For each test, either the PSR or TSR pad was attached to the pendulum arm, depending on the type of friction (slip or skid) being measured.



(a) (b)

Figure 3.3: *(a) BPT Instrumentation, and (b) BPN Value*

Testing Conditions

Testing was conducted under three environmental conditions: dry, wet, and icy. For the wet conditions, water was sprayed on the surface of the pavement markings to simulate moist road conditions, following recommendations and guidance from the state engineers and practices outlined in previous studies (12). For the icy conditions, an environmental chamber was used in the laboratory to replicate freezing temperatures. Samples were exposed to a temperature of 14°F (-10°C) for two hours, then submerged in a room temperature water bath for five minutes. Thus, ice crystals were formed on the surface of the pavement markings following the process recommended in past studies (12). The samples were then tested with the BPT. In addition to the environmental surface conditions, the study also included a comparison of BPT pad wear. Tests were conducted with old versus new pads as well as using the two pad orientations, one with extended use, while the second with no used conditions.

The response of two BPT units was compared to alternative pavement marking and surface conditions to assess whether significant differences exist in their measurement of slip and skid resistance under different surface conditions. These devices had the same manufacturer specifications and are shown in Figure 3.4. Similarly, alternative operators were used with the same BPT device, to assess the operator-to-operator variability and assess the significance of such effects on BPT measurements.

Figure 3.4: *Alternative BPT Instrumentation*

4. Field Experimentation

Field testing was developed with the recommendations and guidance of the SHA project technical advisory team. It primarily focused on alternative pavement site locations with preformed thermoplastic markings since this represents the preferred material to be used in the state. These 13 locations included intersection at primary and secondary roads requiring traffic control. Additional sites were considered in the study to include alternative types of pavement markings as identified in Table 4.1. These complemented field testing to include thermoplastic, paint, and high-performance tape. Field testing included both TSR and PSR evaluation in wet (W) and dry (D) surface conditions, and with at least six replicates for each determination.

Table 4.1: *Field Experimentation at Intersections with Preformed Thermoplastics*

	Pavement marking	Location
Location #1	Preformed thermoplastic	Baltimore Avenue & Campus Drive (UMD exit), Location 1: left lane, 1st crosswalk marking from left @ tire marks
Location #2	Preformed thermoplastic	Baltimore Avenue & Campus Drive (UMD exit), Location 2: left lane, 2nd crosswalk marking from left
Location #3	Preformed thermoplastic	Greenbelt Road & 48th Ave.(intersection @ stop sign), Location 1: shoulder, 1st crosswalk marking from right
Location #4	Preformed thermoplastic	Greenbelt Road & 48th Ave.(intersection @ stop sign), Location 2: main lane, 1st crosswalk marking from median
Location #5	Preformed thermoplastic	Greenbelt Road & 48th Ave.(intersection @ stop sign), Location 3: main lane, 2nd crosswalk marking from the median.
Location #6	Preformed thermoplastic	Greenbelt Road & 48th Ave.(intersection @ stop sign), Location 4: main lane, stop marking
Location #7	Preformed thermoplastic	Josephine Ave & Powder Mill Rd. (intersection @ stop sign)Location 1: main lane, stop marking.
Location #8	.Preformed thermoplastic	Josephine Ave & Powder Mill Rd.(intersection @ stop sign)Location 2: main lane, 3rd crosswalk marking from right
Location #9	Preformed thermoplastic	Hartford Ave, & Powder Mill Rd. (intersection @ stop sign).Location 1: main lane, stop marking.
Location #10	Preformed thermoplastic	Hartford Ave, & Powder Mill Rd. (intersection @ stop sign) Location 2: main lane, 4th crosswalk marking from right.
Location #11	Preformed thermoplastic	Cedar Ln. & Powder Mill Rd. (intersection @ stop sign) .Location: main lane, 3rd crosswalk marking from right.
Location #12	Preformed thermoplastic	Emack Rd. & Powder Mill Rd. (intersection @ stop sign).Location: main lane, 1st crosswalk marking from right.
Location #13	Preformed thermoplastic with beads	Campus Dr & Baltimore Ave.(vicinity of Founder's gate, right pedestrian crossing from north gate of UMD).Location: 1st crosswalk marking from the right..

Table 4.2: *Field Experimentation at Locations with Thermoplastics, Paint, Tape*

	Pavement marking	Location
Location #14	Thermoplastic marking	Exit Parking Lot 7 & Paint Branch Dr. (across J.H..Kim building @ stop sign).Location: main lane, 2nd crosswalk marking from right.
Location #15	Thermoplastic marking	Farm Dr.(north side of Atlantic building close to Cambridge Hall).Location: 3rd crosswalk marking from left.
Location #16	Paint marking	Technology Dr. & Paint Branch Dr.(north exit of A. James Clark Hall next to Biomolecular Science building).Location: 3rd crosswalk marking from left.
Location #17	Paint marking	Regents Dr& Technology Dr.(west exit of parking lot CC1 close to Manufacturing building).Location: 2nd crosswalk marking from left.
Location #18	Wet Reflective Removable Highway Marking Tape	Campus Dr & Baltimore Ave.(vicinity of Founder's gate, right pedestrian crossing from north gate of UMD). Location: At the start of the Tape.

5. Experimental Results

The experimental results from the laboratory and field testing were analyzed and presented herein. Statistical analyses were performed as well to determine the significance of testing variables and assess testing variability. These included paired t-tests for comparing slip and skid resistance and assessing effects of various conditions and materials. Analysis of Variance (ANOVA) and Multivariate Analysis of Variance (MANOVA) were used to analyze the impact of material type, surface conditions, and testing environment on slip and skid resistance. Regression analyses were then used for developing models relating laboratory and field data in regard to slip and skid resistance values, as well as relating BPN values at different surface conditions (i.e., dry, wet, and/or icy). The results are presented next.

5.1 Analysis of Laboratory Result

Effects of Pavement Surface Type on TSR and PSR of Pavement Markings

Figure 5.1 presents a sample of the laboratory results for the various pavement marking materials included in the study using the average BPN* values for TSR and PSR. These were calculated based on 108 measurements obtained from 18 distinct samples with six repetitive measurements. As expected, overall, the BPN* values for the TSR and PSR decrease from dry to wet and icy conditions.

The high-performance tape, T, marking provided the highest BPN values under dry (D) conditions for both TSR and PSR, reflecting thus a higher level of friction. As expected, in wet (W) and icy (I) conditions a decrease in BPN is observed. Preformed thermoplastic (P) and thermoplastic (Th) materials follow a similar trend but with a lower baseline in D conditions reflecting the lower inherently surface textural properties impacting the slip and skid resistance mechanisms.

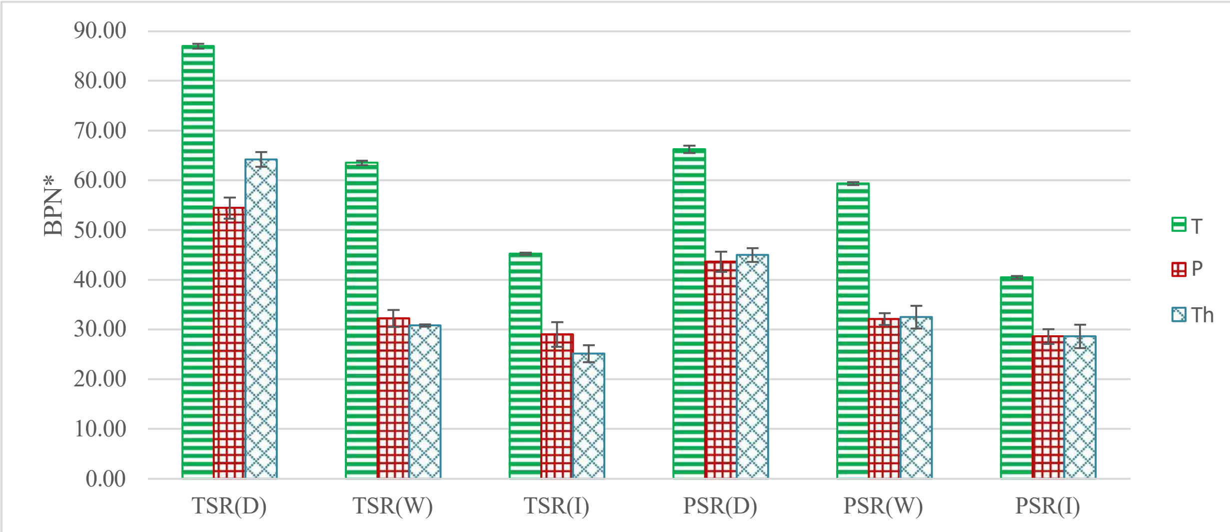


Figure 5.1: *TSR and PSR on Pavement Markings under Laboratory Conditions*

Note: BPN*average values from 18 samples and n=6 replicate measurements One standard deviation repeatability bar shown on top of each case. BPN*= Average British Pendulum Number (Wessex - SHA)

TSR= Tire Slip Rubber, PSR = Pedestrian Slip Rubber.

Analysis based on Average values (average of replicates on same marking type, and combined asphalt and concrete surfaces)

Total observations n = 108 (18 samples x 6 replicates)

Sample characteristics: 2 preformed thermoplastics on asphalt; 4 preformed thermoplastics on concrete; 2 thermoplastics on asphalt; 4 thermoplastics on concrete, 2 tapes on asphalt; 4 tapes on concrete

Following this initial assessment in BPN, the effects of alternate pavement marking and surface conditions were then examined. It was of interest to assess whether the pavement surface type that these markings are applied to have any influence of skid and slip resistance. An example of such comparison is shown in Figure 5.2 for the high-performance tape (T) applied on asphalt and concrete surfaces. As can be observed, the trends of both TSR and PSR are consistent for both pavement surfaces (i.e., asphalt and concrete) and throughout the three alternative surface conditions (D, W, I). The same result was observed for the remaining pavement markings concluding thus that pavement type does not influence the surface friction of pavement markings.

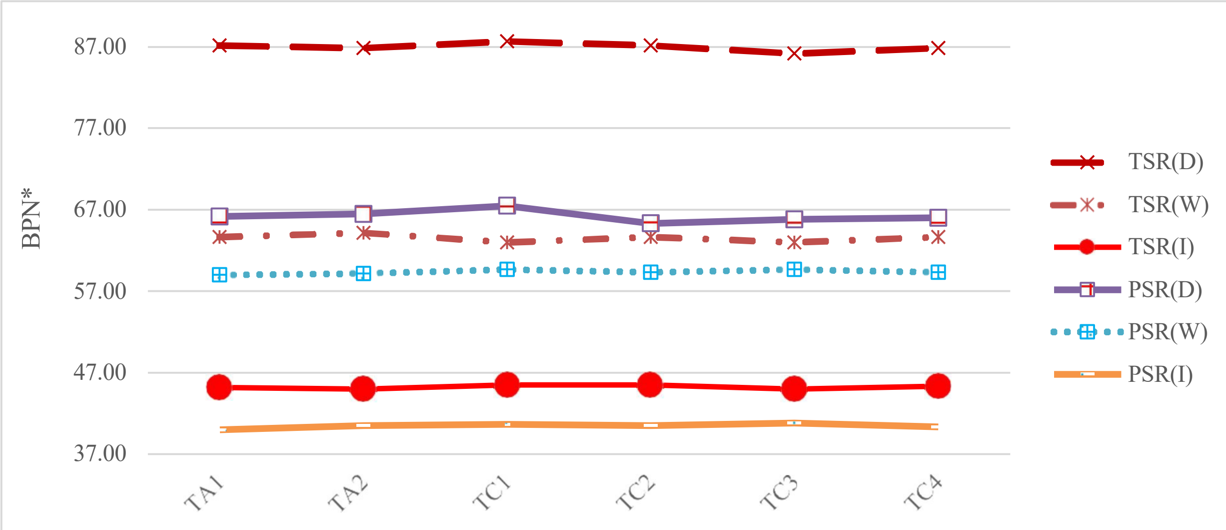


Figure 5.2: Example of effects of Pavement Surface (Asphalt vs Concrete) on TSR & PSR for Tape

Note: Average BPN* values based on n=6 repetitions
TA1, TA2, tape markings on asphalt; TC1 to TC4, tape markings on concrete.

The laboratory data were then analyzed using ANOVA/MANOVA and paired t-test. Table 5.1 provides comparative results between ANOVA/MANOVA and paired t-test on the laboratory data for evaluating the slip and skid resistance of the alternative pavement markings from the BPN measurements. The objective of these analyses was to assess at the aggregate level (i.e., independently whether they represent TSR and/or PSR measurements), if (i) the difference between D, W, and I are statistically significant, and (ii) to confirm whether the effects of alternative pavement markings on PSR were significant. The analysis dataset was based on a total of 216 observations obtained from 18 different samples with six replicates each. The samples included the three pavement marking materials, P, Th, T, and included samples on both asphalt and concrete surfaces. As can be seen from the summary results of Table 1, statistically, D, W, and I are always significant with both analyses (i.e., ANOVA/MANOVA and t-test). Also, the measurements on the alternative pavement marking, (P, Th, T) are statistically significant at the 95% confidence level. In regard to Figure 5.2, the statistical analysis confirmed that measurements on the pavement markings applied on concrete (C) and asphalt (A) are not statically different.

TABLE 5.1: *Assessment of Statistical Significance of Variables on BPN Measurements*

T-test variables	H_o	ANOVA/MANOVA variables	AS
BPN(D) vs BPN(W)	SS	BPN(D) vs BPN(W)	SS
BPN(D) vs BPN(I)	SS	BPN(D) vs BPN(I)	SS
BPN(W) vs BPN(I)	SS	BPN(W) vs BPN(I)	SS
BPN(P) vs BPN(T)	SS	BPN(P) vs BPN(T)	SS
BPN(P) vs BPN(Th)	SS	BPN(P) vs BPN(Th)	SS
BPN(Th) vs BPN(T)	SS	BPN(Th) vs BPN(T)	SS
BPN(A) vs BPN(C)	NS	BPN(A) vs BPN(C)	NS

Note: SS= statistically significant at the 95% confidence level; NS= non statistically significant. Ho = null hypothesis, average values of paired tests are equal.
AS = association between variables in ANOVA/MANOVA.

Effects of Sliding Pad Wear on BPN values

The influence of pad condition on vehicular tire slip resistance (TSR) and pedestrian slip resistance (PSR) was analyzed under dry conditions using the preformed thermoplastic marking. Figure 5.3 shows that pad wear affects the results with used pads (ONS and ORS), and in this case, each one used approximately 1,200 times for both TSR and PSR measurements, providing consistently lower BPN values compared to new pads (NNS and NRS). This suggests that surface degradation due to pad wear reduces the value of friction measurements. In contrast, pad orientation (i.e., one face versus the reverse side) has minimal impact, particularly for new pads, indicating that orientation does not significantly influence BPN measurements for either TSR or PSR. Table 5.2 supports these findings, showing statistically significant differences between worn and new pads, while differences between pad orientations (NNS vs. NRS) are not statistically significant. The analysis underscores that pad wear is the key factor affecting BPN measurements. Thus, flipping the pad after each use could be a good practice recommendation.

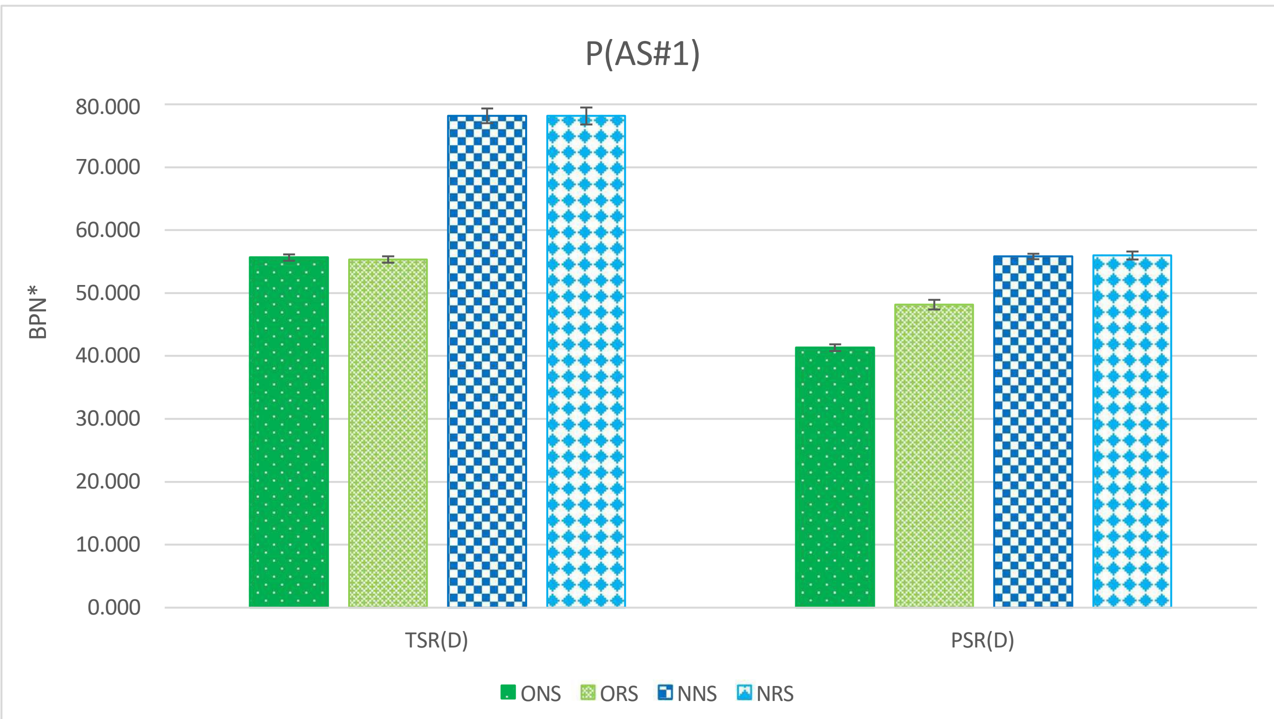


Figure 5.3: *Comparison in Testing Pad Conditions & Orientation for Preformed Thermoplastic*

Note: BPN* = Average British Pendulum Number (SHA-Wessex).
P(AS#1)= Preformed Thermoplastic, Asphalt sample1. n= 6 replicates
ONS= used pad wear side ORS= used pad reverse side NNS= new pad side 1
NRS= new pad side 2
+/- s variability bars.
Each pad is used 1,200 times for both TSR and PSR measurements.

TABLE 5.2: *Statistical Significance of Testing Pad Wear and Orientation on Preformed Thermoplastic*

Parameters	T-test variables (paired)	Difference in means (Ho)
TSR(D)	ONS Vs. ORS	NS
	ONS Vs. NNS	SS
	ONS Vs. NRS	SS
	ORS Vs. NNS	SS
	ORS Vs. NRS	SS
	NNS Vs. NRS	NS
PSR(D)	ONS Vs. ORS	SS
	ONS Vs. NNS	SS
	ONS Vs. NRS	SS
	ORS Vs. NNS	SS
	ORS Vs. NRS	SS
	NNS Vs. NRS	NS

Note: BPN* = Average British Pendulum Number (SHA-Wessex).
P(AS#1)= Preformed Thermoplastic, Asphalt sample1.
SS= statistically significant at the 95% confidence level; NS= non statistically significant n= 6 replicates
ONS= used pad wear side ORS= used pad reverse side NNS= new pad side 1
NRS= new pad side 2

Effect of Operator on BPT Measurements

The effects of using alternative operators with BPT were assessed next. Figure 5.4 provides a comparison of TSR and PSR measurements taken by two operators on preformed thermoplastic markings across both asphalt and concrete surfaces. The first operator was skilled with extensive testing in BPT, while the second one was only recently trained and with limited testing experience. As can be observed from Figure 5.4, the BPN values for both TSR and PSR are closely aligned between the two operators, with minimal variation observed across all samples. The error bars, representing testing variability, show a high degree of repeatability and consistency, indicating that the influence of the operator on the results is minimal. This consistency across both asphalt and concrete samples suggests that the process of measuring slip resistance is reliable, with negligible operator influence on the accuracy of the BPN readings.

Table 5.3 presents the statistical analysis results of the operator effect using a paired t-test. The P-values for all comparisons exceed the significance threshold ($\alpha = 0.05$), confirming that there is no statistically significant difference between the measurements from Operator 1 and Operator 2 for both TSR and PSR. This analysis reinforces that the minor variations observed between operators are not substantial enough to affect the overall results. The consistency of these findings across different surface types and slip resistance measures further highlights the reliability of the BPN measurements, regardless of operator experience.

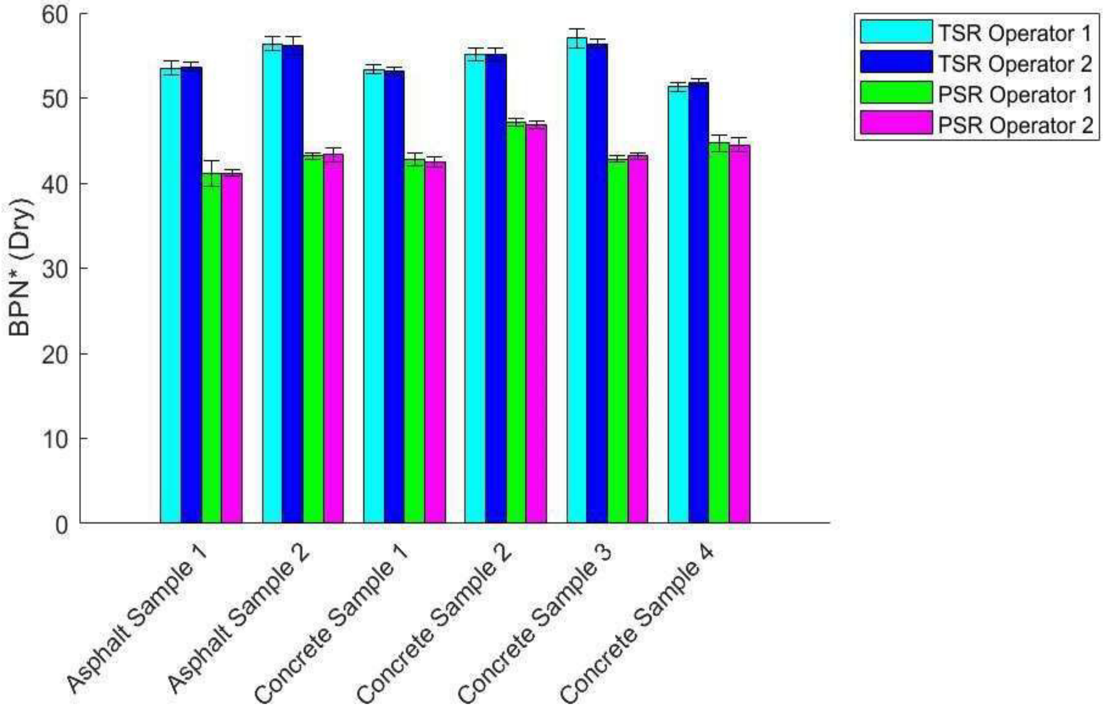


Figure 5.4: Operator Effects on TSR and PSR for Preformed Thermoplastic

Note: BPN* = Average British Pendulum Number (Cooper). n=
6 replicates
+/- s variability bars.
Sample characteristics: 2 preformed thermoplastics on asphalt, 4
preformed thermoplastics on concrete.

TABLE 5.3: *Paired t-Test for Operator Significance on TSR and PSR of Preformed Thermoplastic*

Surface Type and location	TSR-BPN(Dry) Operator 1	TSR-BPN(Dry) Operator2	PSR-BPN(Dry) Operator1	PSR-BPN(Dry) Operator2
	P-Value		P-Value	
Preformed thermoplastic, asphalt sample#1	0.695		1.000	
Preformed thermoplastic, asphalt sample#2	0.611		0.695	
Preformed thermoplastic, concrete sample#1	0.363		0.363	
Preformed thermoplastic, concrete sample#2	1.000		0.175	
Preformed thermoplastic, concrete sample#3	0.175		0.175	
Preformed thermoplastic, concrete sample#4	0.203		0.771	

Note: Confidence level = 95%; ($p=0.05$) Individual values for each sample are used.
For each sample ($n = 6$ for Operator 1 and $n=6$ for Operator 2). Null hypothesis (H_0): $\mu\_difference = 0$
Alternative hypothesis (H_1): $\mu\_difference \neq 0$
Sample characteristics: 2 preformed thermoplastics on asphalt; 4 preformed thermoplastics on concrete.

Comparison of BPT Devices on TSR & PSR

Two different BPT units were compared for assessing potential impact on BPV values. These devices have the same supplier specifications, Figure 3.4. For the comparison of the two BPT units a total of 216 BPV measurements were used using 18 asphalt and concrete samples with the three pavement marking types (P, T, Th), tested at three surface conditions (D, W, I) and with six replicate measurements in each case. Table 5.4 presents an example of the comparison of the BPV measurements obtained from the two devices on the high-performance tape (T) at dry (D), wet (W), and/or icy (I) conditions for both the tire slip resistance (TSR) and pedestrian slip resistance (PSR). Table 5.4 presents the average values of the BPV measurements on the asphalt (T, A) and concrete samples (T,C) with six replicates, the standard deviation (SD) and the coefficient of variation (CV%). As can be observed, the average TSR values on asphalt samples (T, A) between the two units at each of the three surface conditions (D, W, and I) were very close. Furthermore, in terms of testing variability a significantly low CV% was observed, in the range 0.6% to 1.67 %. Similar results were obtained for the PSR values on the asphalt samples as well as in concrete (T, C). The same effects were observed for the remaining two pavement marking materials (P, Th). Furthermore, as mentioned earlier, the statistical analysis with both ANOVA/MANOVA and paired t-test confirmed that measurements on the pavement markings applied on concrete (C) and asphalt (A) were not statically different.

An example comparison of the average PSR and TSR values for T for all three surface conditions (D, W, I) and for the two units on an asphalt sample is shown in Figure 5.5, as can be observed from the results the two units provide consistent values in all cases. The interval lines at the top of the bars in the graph represent the one standard deviation for each case, reflecting a low variability between repeated measurements, and at comparable levels for both units.

TABLE 5.4: *Example Results of TSR and PSR on High Performance Tape, T, with Two BPT Units*

Pavement Marking	BPN	Statistic	BPN1 (Dry) Unit 1	BPN2 (Dry) Unit 2	BPN1 (Wet) Unit 1	BPN2 (Wet) Unit 2	BPN1 (Icy) Unit 1	BPN2 (Icy) Unit 2
T, A	TSR	SD	0.55	0.75	0.52	0.52	0.52	0.75
		Mean	86.50	87.17	63.67	63.67	45.33	45.17
		CV%	0.63	0.86	0.81	0.81	1.14	1.67
	PSR	SD	0.52	0.41	0.98	0.89	0.52	0.63
		Mean	66.33	66.17	58.83	59	40.33	40
		CV%	0.78	0.62	1.67	1.52	1.28	1.58
T, C	TSR	SD	0.52	0.52	0.98	0	0.41	0.55
		Mean	87.67	87.67	62.83	63.00	44.83	45.50
		CV%	0.59	0.59	1.56	0	0.91	1.2
	PSR	SD	0.75	0.55	0.75	0.52	0.52	0.52
		Mean	67.17	67.50	58.83	59.67	40.33	40.67
		CV%	1.12	0.81	1.28	0.87	1.28	1.27

Note: BPN average values, n=6 replicates.

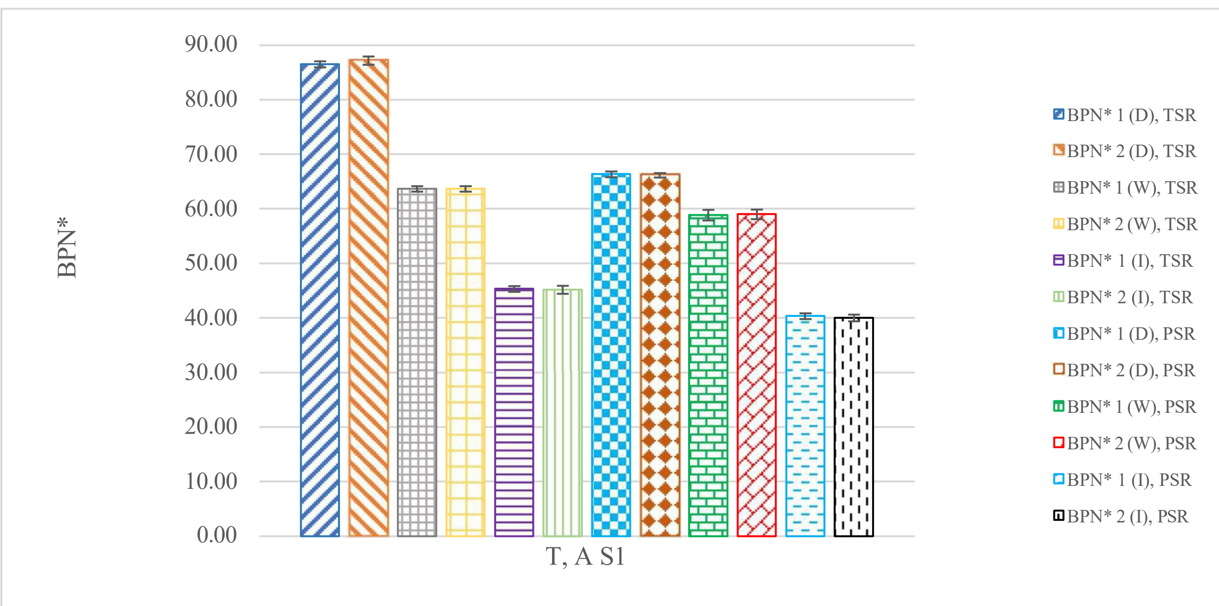


Figure 5.5: *Effect of Testing Devices on TSR & PSR on T(A) Based on Average Values*

Note: T, AS1 = High-Performance Tape on Asphalt Sample 1; BPN*1 = average value for BPT unit 1, with n= 6 replicates.

Table 5.5 presents the results of the statistical analysis using paired t-test, Analysis of Variance (ANOVA) and Multivariate Analysis of Variance (MANOVA) on all 216 BPV observations. The measurements obtained between the two BPT units were first paired for each pavement marking material for paired t-test analysis. Both asphalt and concrete samples were used in the analysis. As can be observed from Table 5.5, there was no statistical difference between the TSR and/or PSR measurements obtained between the two BPN units on measurements obtained on each of the three pavement markings (P, Th, T). Similarly, when the measurements in each of the surface conditions (D, W, I) were paired for the two BPT units, no significant difference was statically observed. This was the case for each of the TSR and PSR measurements at the corresponding surface conditions (D, W, I). Thus, based on the t-test analysis, the two BPT units statically provide the same measurements.

In the ANOVA/MAROVA analysis, all 216 BPV observations were used. In these analyses, the TSR values for both units at any pavement marking material and surface condition were compared. Similarly, the PSR values between the two units were examined as well. The ANOVA/MANOVA statical analysis confirmed as well that both BPT units provide statically the same response, for each of the three pavement markings (P, Th, T) and at each surface condition (D, W, I). Thus, the use of alternative BPT units with same design specifications provide consistent measurements.

TABLE 5.5: *Statistical Results of BPV Measurements Between Two BPT Units*

Analysis	Pavement Markings	Variables	Observations	Outcome
Paired t-test	P/A/C	TSR	72	NS
	Th/A/C	PSR		
	T/A/C	BPN 1(D) vs BPN 2(D)		
		BPN 1(W) vs BPN 2(W)		
		BPN 1(I) vs BPN 2(I)		
ANOVA/ MANOVA	APM	BPN 1(TSR) vs BPN 2(TSR)	216	
	APM	BPN 1(PSR) vs BPN 2(PSR)		

Note: Th/A/C=Thermoplastic on Asphalt and Concrete; T/A/C=High-Performance Tape on Asphalt and Concrete; P/A/C=Preformed Thermoplastic on Asphalt and Concrete; APM=All Pavement Markings with all Surface Conditions; NS=Differences not Statistically Significant.

Relating TSR and PSR & Surface Conditions

The next step in the analysis was to develop relationships between PSR and TSR under different conditions: dry (D), wet (W), and icy (I). Among various models considered, the standardized linear model offered the best fit:

$$BPN_{\text{Response}} = \alpha + \beta BPN_{\text{Predictor}} \qquad (1)$$

where BPN_{Response} is the dependent variable, α is the intercept (set to zero for all cases), and β is the slope coefficient relating to the predictor variable $BPN_{\text{Predictor}}$. The models were evaluated with a 95% confidence interval, calculating R^2 and the root mean square error (RMSE) to measure the fit of the model. A total of 1,296 observations were used from the laboratory experiments, encompassing 18 samples (six P, six Th, six T), three surface conditions (D, W, I), two devices, and two pads (TSR, PSR), each with six replicate measurements. As shown in Table 5.6, for the preformed thermoplastic (P) material, the model fit the data very well, with high R^2 and low RMSE values across all conditions, providing reliable relationships between vehicle skid resistance (TSR) and pedestrian slip resistance (PSR). Figure 5.6 provides an example of the predictive relationship between TSR and PSR under dry conditions. Similar results were observed for the other marking materials, Th and T and surface conditions.

TABLE 5.6: *Models Relating TSR and PSR for Various Conditions on Pavement Markings*

Marking Type	Data Comparison	β	R^2	P-value	RMSE
P	D: (TSR & PSR)	1.25221	0.99	0.000	0.587
	W: (TSR & PSR)	1.00972	0.99	0.000	0.542
	I: (TSR & PSR)	0.99861	0.99	0.000	1.178
	D vs W (TSR)	1.65898	0.99	0.000	1.866
	D to I: (TSR)	1.8901	0.99	0.000	2.613
	W to I: (TSR)	1.14224	0.99	0.000	0.756
Th	D: (TSR & PSR)	1.42801	0.99	0.000	1.143
	W: (TSR & PSR)	0.95068	0.99	0.000	1.188
	I: (TSR & PSR)	0.86412	0.99	0.000	0.618
	D vs W (TSR)	2.06361	0.99	0.000	1.144
	D to I: (TSR)	2.5839	0.99	0.000	3.200
	W to I: (TSR)	1.25260	0.99	0.000	1.431
T	D: (TSR & PSR)	1.31404	1	0.000	0.566
	W: (TSR & PSR)	1.06874	1	0.000	0.345
	I: (TSR & PSR)	1.12287	1	0.000	0.233
	D vs W (TSR)	1.36629	1	0.000	0.448
	D to I: (TSR)	1.92235	1	0.000	0.476
	W to I: (TSR)	1.39882	1	0.000	0.303

Note: Linear regression model: $BPN_{\text{Response}} = \alpha + \beta BPN_{\text{Predictor}}$
BPN_{Response} dependent variable. 95%
Confidence level
RMSE= root means square error
α is the model intercept, set to zero. β is
the slope coefficient
D=Dry, W=Wet, and I =Icy.
BPN = British Pendulum Number.
PSR= Pedestrian slip rubber, and TSR= Tire slip rubber.
P=Preformed Thermoplastic, Th=Thermoplastic and T=High Performance Tape.
# of observations= 1296 in total, 18 samples (6P+6Th+6T) x 6 replicates x 3 surface conditions x 2 devices x 2Pads (TSR&PSR)

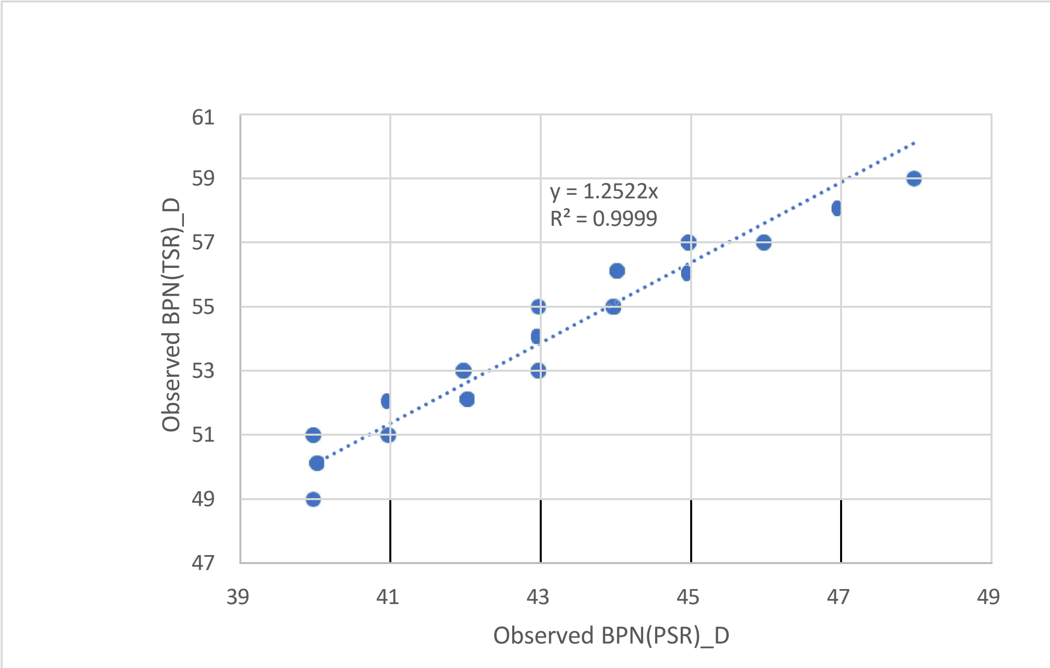


Figure 5.6: *Example of Relationship Between TSR and PSR for Preformed Thermoplastic – Dry conditions*

5.2 Analysis of Field-Testing Results

Effects of Wear, Marking Types, and Surface Conditions on PSR and TSR

As mentioned previously, Maryland is considering moving towards the use of preformed thermoplastic (P) pavement markings. Thus, the first group of field sites (13 out of 18) included in the field experimentation of this study featured preformed thermoplastic, Table 4.1. The data on these sites were collected at two different times and thus subjected to increasing traffic levels, resulting in varying degrees of wear and tear. Figure 5.7 illustrates the comparison of TSR and PSR under dry (D) and wet (W) conditions at these sites. Over time, friction measurements tend to show degradation in performance, particularly in wet conditions, as shown by the decreasing TSR and PSR values between the first (10.25.2023) and the second data collection (4.19.2024). The consistent pattern across locations indicates that both TSR and PSR values tend to decrease over time, suggesting that the surface friction of preformed thermoplastic pavement markings deteriorates under the influence of environmental conditions and traffic exposure. While both TSR and PSR exhibit location specific BPN values across locations due to these factors, TSR values in dry conditions generally maintain a higher threshold, except at Location #10, where the TSR values are lower. This discrepancy might be attributed to unique site conditions affecting testing variability due to local conditions pertinent to lack of regular maintenance such as surface cleanliness. The statistical analyses of these observations are presented in Table 5.7, confirming that surface condition (D vs. W), location, and the date of field data collection measurement significantly impact BPN values, with statistical significance ($P < \alpha$) across all parameters for both TSR and PSR.

Figure 5.8 presents the field results for the additional testing sites (LC14 to LC18) regarding TSR and PSR on thermoplastic, paint, and tape. The results follow a similar trend with decreasing values over time, especially in wet conditions. The statistical analyses are presented in Table 5.8, further reinforcing the above findings and considering additional field data collection dates for these sections.

All the field data collected on the various pavement markings included in the study were aggregated and statistically compared. Table 5.9, as can be observed, the ANOVA/MANOVA analysis confirms that statistically dry and wet conditions for TSR and PSR across different pavement markings (preformed thermoplastic, thermoplastic, paint, and tape) are statistically significant different. Also, marking type and field data collection dates (i.e., wear from environment and traffic) are significant as well for all cases.

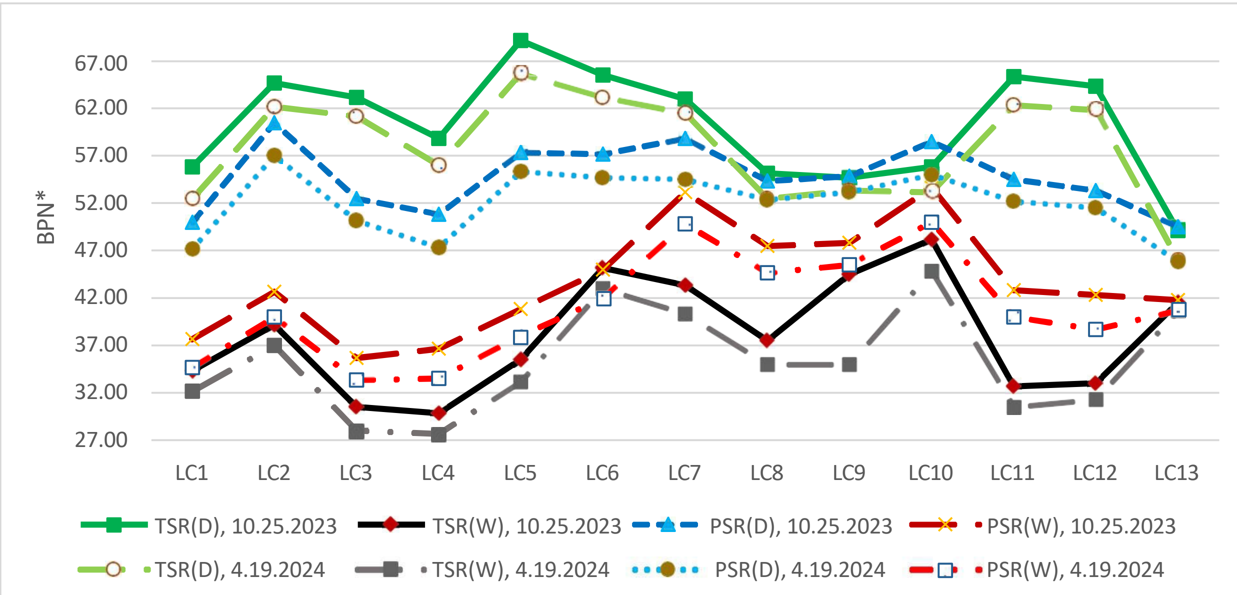


Figure 5.7: *BPN Over Time for Various Locations & Surface Conditions (D, W) for Preformed Thermoplastic*

Note: BPN* = Average British Pendulum Number (SHA-Wessex).
TSR= Tire Slip Rubber, PSR = Pedestrian Slip Rubber
Average values per location, n= 6 replicates
LC= Location

TABLE 5.7: *Statistical Results of BPN for Location-Specific Effects & Surface Conditions (D, W) for P*

Variable(s)	Condition	Effect ANOVA/MANOVA	Results
BPN(TSR)	Location	SS	P< α (0.05)
	Dry vs Wet	SS	P< α (0.05)
	Date	SS	P< α (0.05)
BPN(PSR)	Location	SS	P< α (0.05)
	Dry vs Wet	SS	P< α (0.05)
	Dry vs Wet	SS	P< α (0.05)
BPN(TSR), BPN(PSR)	Location	SS	P< α (0.05)
	Dry vs Wet	SS	P< α (0.05)
	Date	SS	P< α (0.05)

Note: BPN = British Pendulum Number (SHA-Wessex), based on average values for each location TSR = Tire Slip Rubber, PSR = Pedestrian Slip Rubber.
Site-specific effects/conditions: 13 Location (L1 to L13)
Data collections: (10.25.2023) and (4.19.2024)
SS=Statistically Significant
Surface Condition: Dry, Wet
Based on average BPN values for each location
Total number of 312 observations (n = 13 sections x 6 replicates x 2 conditions x 2 dates)

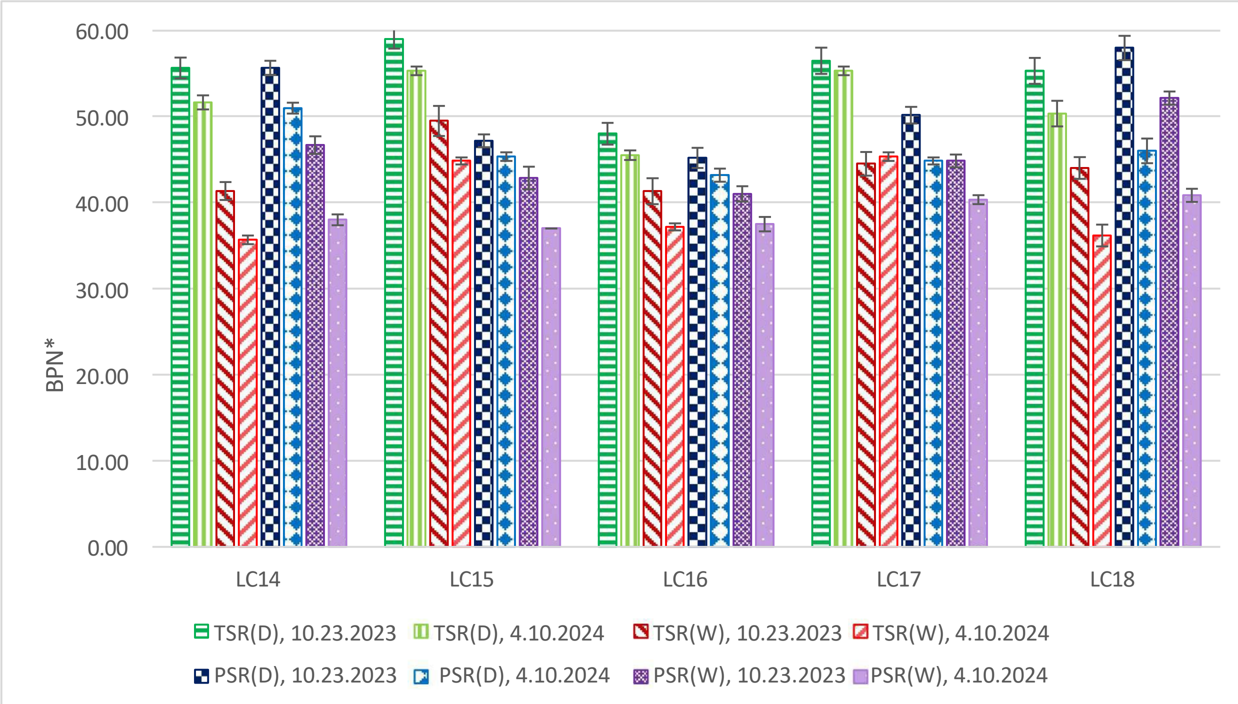


Figure 5.8: *BPN Over Time for Various Locations & Surface Conditions (D, W) for Thermoplastic, Paint, and Tape*

Note: BPN* = Average British Pendulum Number (SHA-Wessex).
TSR= Tire Slip Rubber, PSR = Pedestrian Slip Rubber
Average values per location
n= 6 replicates LC=
Location
+/- s variability bars.

TABLE 5.8: *Statistical Results of BPN for Surface Condition (D, W) of Pavement Marking Types*

Pavement Marking	Difference in means T-test (paired) Ho	Variable Effect	Significance Level
Thermoplastic	TSR, BPN(Dry) vs TSR, BPN(Wet)	SS	P< α (0.05)
	PSR, BPN(Dry) vs PSR, BPN(Wet)	SS	P< α (0.05)
Paint	TSR, BPN(Dry) vs TSR, BPN(Wet)	SS	P< α (0.05)
	PSR, BPN(Dry) vs PSR, BPN(Wet)	SS	P< α (0.05)
Tape	TSR, BPN(Dry) vs TSR, BPN(Wet)	SS	P< α (0.05)
	PSR, BPN(Dry) vs PSR, BPN(Wet)	SS	P< α (0.05)

Note: Total observations(N)= 240+180= 420
Locations: #14 and 15 (thermoplastic); #16 & #17 (Paint); #18 (wet reflective removable tape); SS=Statistically Significant
For TSR Each location tested 4 times (10.8.2023, 10.20.2023, 10.23.2023, 4.10.2024)
For PSR Each location tested 3 times (10.20.2023, 10.23.2023, 4.10.2024)
BPN paired measurements for 3 or 4 data collections and surface conditions (D,W)
Total number (TSR) of 240 observations (5 sections x 4 collections x 6 replicates x 2 surface conditions)
Total number (PSR) of 180 observations (5 sections x 3 collections x 6 replicates x 2 surface conditions)

TABLE 5.9: *Significance of Surface Condition (D, W) & Wear on All Pavement Markings*

Parameter	Variables	Variable Effect ANOVA/MANOVA	Significance Level
BPN(TSR)	Wet vs Dry	SS	P< α (0.05)
	Marking type	SS	P< α (0.05)
	Date	SS	P< α (0.05)
BPN(PSR)	Wet vs Dry	SS	P< α (0.05)
	Marking type	SS	P< α (0.05)
	Date	SS	P< α (0.05)
BPN(TSR), BPN(PSR)	Wet vs Dry	SS	P< α (0.05)
	Marking type	SS	P< α (0.05)
	Date	SS	P< α (0.05)

Note: TSR = Tire Slip Rubber, PSR = Pedestrian Slip Rubber; Surface Condition: 2 levels (Dry, Wet)
Pavement Marking Material: 4 types (Preformed thermoplastic, Tape, Thermoplastic, Paint).
SS=Statistically Significant
Total observations(N)= 312+240+180= 732
Preformed thermoplastic: 13 Locations (L1 to L13) tested 2 times (collections): (10.25.23) and (4.19.2024); Number of 312 observations (n = 13 sections x 6 replicates x 2 conditions x 2 collection dates)
Remaining Pavement Markings. Locations: #14 and 15 (thermoplastic); #16 & #17 (Paint); #18 (wet reflective removable tape); For TSR Each location tested 4 times (repetitions): 10.8.2023, 10.20.2023, 10.23.2023, and 4.10.2024. Total number (TSR) of 240 observations (5 sections x 4 collections x 6 replicates x 2 surface conditions); For PSR Each location tested 3 times (collections): 10.20.2023, 10.23.2023, and 4.10.2024; Total number (PSR) of 180 observations (5 sections x 3 collections x 6 replicates x 2 surface conditions)

Effect of Traffic/Wheel Path Overtime

Since the degree of wear from traffic is expected to influence the surface friction of pavement markings, it was of interest to assess such aspect. Figure 5.9 presents a comparison of slip and skid resistance on preformed thermoplastic (P) at two locations, LC1 and LC2, where one is located directly on the tire marks (wheel path), and the other is positioned away from it. As shown, both TSR and PSR values are consistently lower in the wheel path for both dry and wet conditions, indicating the significant impact of traffic wear. The small standard deviations at the top of each bar, based on repeated measurements (n=6), provide confidence that the BPN values effectively capture this difference. Figure 5.10 expands this comparison across shoulder (Sh), wheel path (WP), and off-wheel path (NWP) locations, showing that BPN values are higher in areas with less direct traffic exposure (shoulder and off-wheel path), with TSR generally providing higher values than PSR in dry conditions. The statistical results in Table 5.7 further supported these findings, demonstrating that location, surface condition (dry vs wet), and time (i.e., traffic exposure) are significant factors in pavement marking performance.

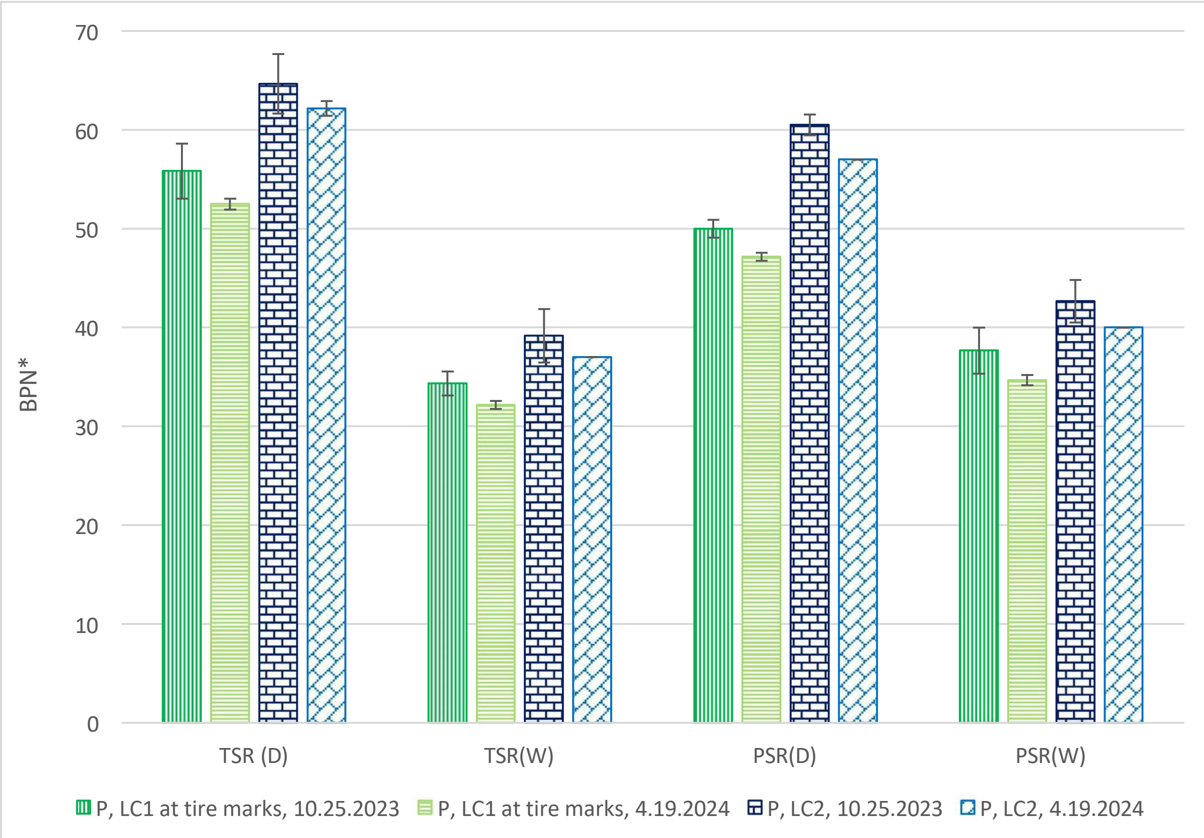


***Figure 5.9**: Effect of Traffic on BPN (dry, wet) for Preformed Thermoplastic*

Note: BPN*= Average British Pendulum Number. n=6 replicates
+/- s variability bars.
P, LC1(Preformed Thermoplastic, Location 1) = R1 at tire marks (UMD entrance). P, LC2(Preformed Thermoplastic, Location 2) = R2 marking (UMD entrance).
PSR= Pedestrian slip rubber. TSR= Tire slip rubber.

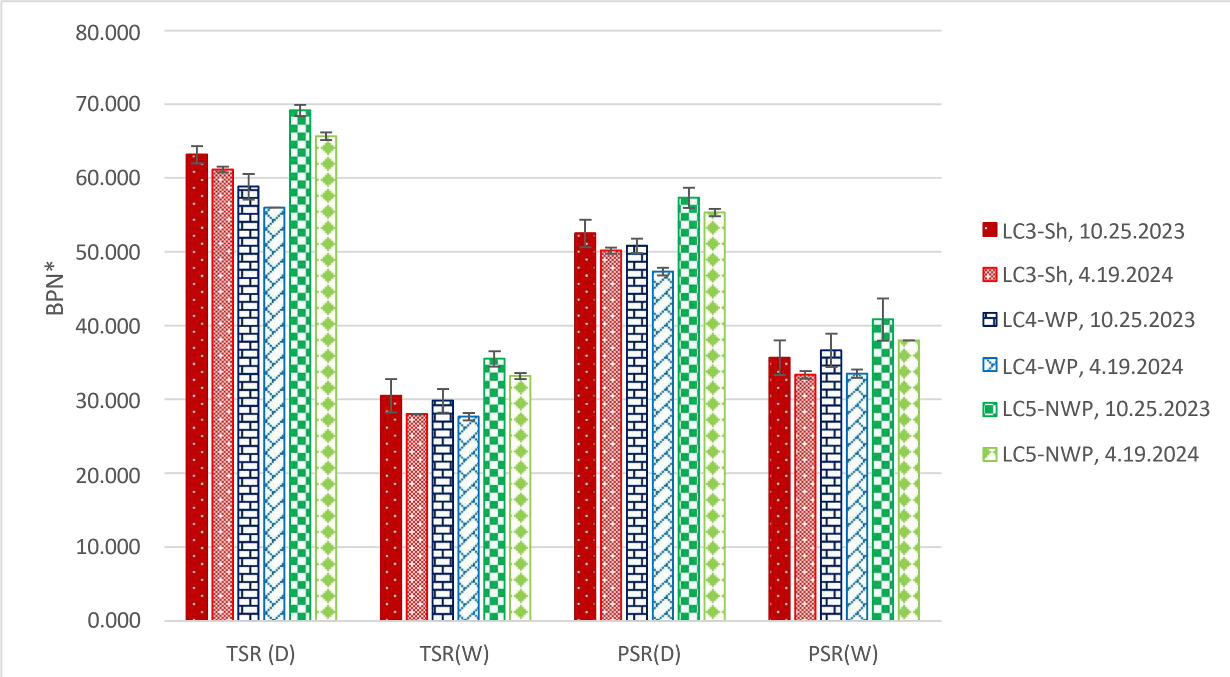


Figure 5.10: *BPN Over Time for Preformed Thermoplastic at Wheel Path, Off-Wheel Path, and Shoulder*

Note: BPN*= Average British Pendulum Number (SHA-Wessex). n=6 replicates
+/- s variability bars.
LC=Location.
Sh= shoulder; WP= wheel path; NWP= off-wheel path PSR= Pedestrian slip rubber, and TSR=Tire slip rubber. D=Dry, W=Wet.

Relating TSR and PSR from Field Observations

As in the case for the laboratory data, field observations were used for relating TSR and PSR under different conditions (D, W) and using 984 observations collected from 18 field sites. The tests were conducted either two or three times, with six repetitions for each site. Three types of pavement markings were analyzed: preformed thermoplastic (P), thermoplastic (Th), and high-performance tape (T). As with the laboratory data, a standardized linear model was used to assess the relationships between TSR and PSR for each surface condition. The results for preformed thermoplastic (P) are presented in Table 5.10, where a strong relationship between TSR and PSR was obtained with high R^2 values and low RMSE. Figure 5.11 presents an example of such field relationship between TSR and PSR for dry conditions. These predictive models can be used to estimate PSR from PSR field measurements for pavement marking under different surface conditions (D, W), and thus may reduce the extent of required field testing. Similar results were observed for the other pavement marking materials, Th and T, Table 5.10. Furthermore, strong relationships were obtained relating to dry and wet conditions for each pavement marking regarding TSR and PSR, Table 5.10. These relationships further reduce the need for extensive field testing for assessing BPV values for both D and W conditions. Since state specifications are typically based on identifying the minimum PSR threshold value under dry conditions, such relationships can be very helpful in assessing potential implications due to an observed reduction in this value and related reductions in TSR and or wet conditions without the need of further field testing.

TABLE 5.10: *Models Relating TSR and PSR for Various Conditions on Pavement Markings*

Marking Type	Data Comparison	β	R^2	P-value	RMSE
P	D: (TSR & PSR)	1.10847	0.99	0.000	1.931
	W:(TSR & PSR)	0.87087	0.99	0.000	1.229
	D to W:(TSR)	1.59439	0.99	0.000	4.073
	D to W: (PSR)	1.25283	0.99	0.000	3.560
Th	D: (TSR & PSR)	1.09005	0.99	0.000	2.208
	W:(TSR & PSR)	1.06299	0.99	0.000	2.441
	D to W:(TSR)	1.2870	0.99	0.000	4.742
	D to W: (PSR)	1.2579	0.99	0.000	3.066
T	D: (TSR & PSR)	1.0247	0.99	0.000	3.589
	W:(TSR & PSR)	0.84576	0.99	0.000	1.278
	D to W:(TSR)	1.3570	0.99	0.000	3.525
	D to W: (PSR)	1.12033	0.99	0.000	0.892

Note: Linear regression model: $BPN_{\text{Response}} = \alpha + \beta BPN_{\text{Predictor}}$
BPN_{Response} dependent variable. 95%
Confidence level
RMSE= root mean square error β is
the slope coefficient
α is the model intercept, set to zero for all cases.
D=Dry, W=Wet.
BPN = British Pendulum Number.
PSR= Pedestrian slip rubber. TSR= Tire slip rubber.
Total observations(N)= 624+360= 984
Preformed thermoplastic: 13 Locations (L1 to L13) tested 2 times (collections): (10.25.23) and (4.19.2024); Number of 624 observations (n = 13 sections x 6 replicates x 2 conditions x 2 collection dates x 2Pads (TSR&PSR))
Remaining Pavement Markings. Locations: #14 and 15 (thermoplastic); #16 & #17 (Paint); #18 (wet reflective removable tape); tested 3 times (collections): 10.20.2023, 10.23.2023, and 4.10.2024. Number of 360 observations (n = 5 sections x 6 replicates x 2 conditions x 3 collection dates x 2Pads, TSR&PSR)

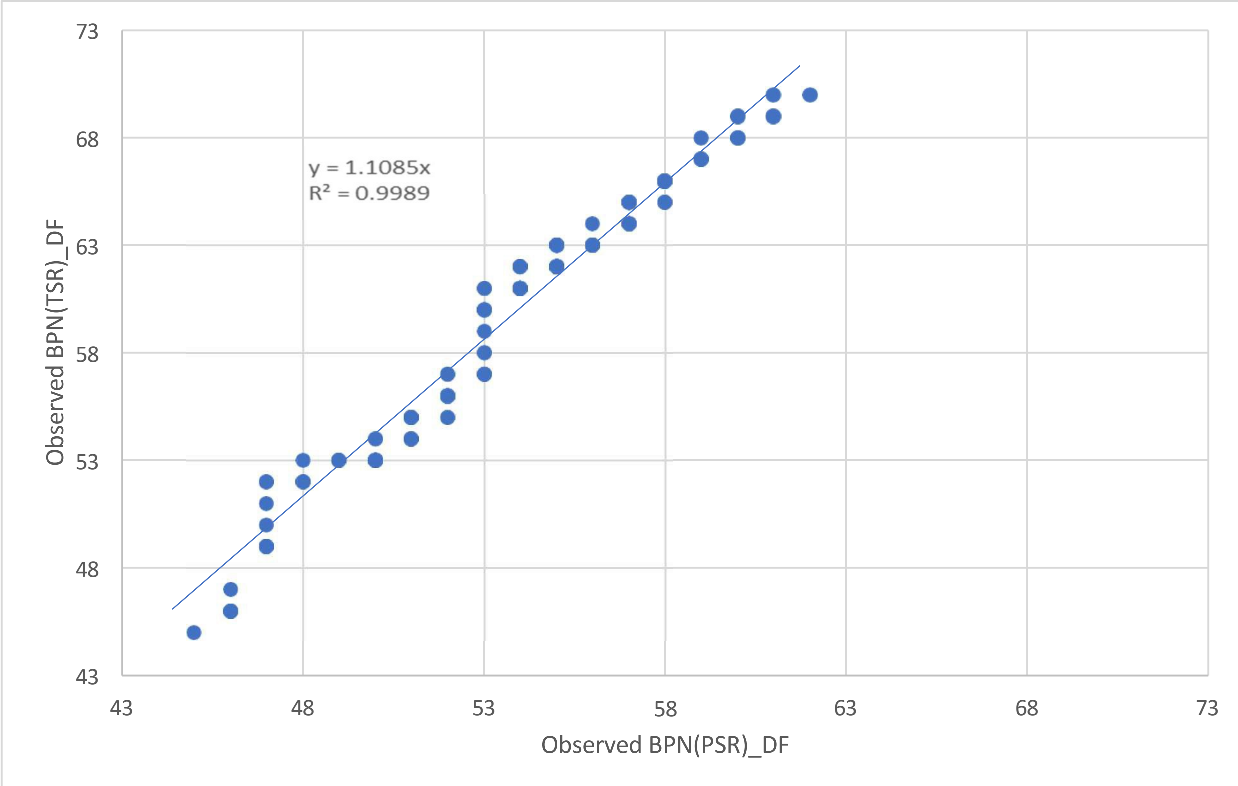


Figure 5.11: Example of Field Relationships Between TSR and PSR, for Preformed Thermoplastic – Dry Conditions

Note: DF- dry field; (individual values)

5.3 Relationship Between Laboratory and Field Results

It was also of interest to explore whether it is possible to relate laboratory and field measurements, recognizing potential limitations pertinent to the multiple variables affecting field conditions versus the lab-controlled testing conditions. In the lab measurements are based on new pavement marking conditions while in the field the same materials may be exposed to different degrees of degradation, as well as surface conditions in terms of wear and cleanness. In this study 1,848 observations were analyzed, combining both lab and field data for TSR and PSR across different conditions (D, W). A linear model was used to compare field (F) and laboratory (L) results, as shown in Table 5.11. The preformed thermoplastic (P) material demonstrated strong relationships between lab and field results, in both dry and wet conditions, providing high R^2 values and low RMSE. These relationships indicate ensure that laboratory tests can provide accurate field predictions, reducing thus the need for field testing. Strong relationships between lab and field data were also obtained for the remaining pavement marking materials, Th and T.

TABLE 5.11: Models Relating Field and Laboratory BPN Measurements for Various Conditions and Pavement Markings

Marking Type	Data Comparison	β	R^2	P-value	RMSE
P	TSR: F to L (D)	0.98724	0.9994	0.000	1.376
	TSR: F to L (W)	0.96307	0.9994	0.000	0.802
	PSR: F to L (D)	1.15429	0.9998	0.000	0.780
	PSR: F to L (W)	1.15302	0.9994	0.000	0.945
Th	TSR: F to L (D)	0.9208	0.986	0.000	7.170
	TSR: F to L (W)	1.4562	0.9887	0.000	4.916
	PSR: F to L (D)	1.2085	0.9820	0.000	7.442
	PSR: F to L (W)	1.3147	0.9947	0.000	3.216
T	TSR: F to L (D)	0.6780	0.9789	0.000	8.900
	TSR: F to L (W)	0.6869	0.9852	0.000	5.492
	PSR: F to L (D)	0.8642	0.9804	0.000	8.352
	PSR: F to L (W)	0.8808	0.9762	0.000	8.217

Note: Linear regression model: $BPN_{\text{Response}} = \alpha + \beta BPN_{\text{Predictor}}$
BPN_{Response} dependent variable. 95%
Confidence level
RMSE= root mean square error β is
the slope coefficient
α is the model intercept, set to zero for all cases. D=Dry,
W=Wet, and I =Icy.
F=Field, and L=Lab.
BPN = British Pendulum Number.
PSR= Pedestrian slip rubber. TSR= Tire slip rubber. # of
observations= 864+984= 1848 in total.
Lab observations = 864 in total, 18 samples (6P+6Th+6T) x 6 replicates x 2 surface conditions x 2 devices x 2 Pads (TSR&PSR)
Field observations =984

6. Conclusions and Recommendations

The primary objectives of this project were to assess slip resistance for pedestrians on crosswalks where pavement markings are used and to relate vehicle pavement skid friction to pedestrian slip resistance. Based on the study findings and the relationship between vehicle skid and pedestrian slip resistance, it was the aim of this study to provide recommendations for potential specification revisions regarding pavement marking friction at crosswalks. The key findings and recommendations of the study are summarized next.

6.1 Key Research Findings & Conclusions

- **BPN Repeatability:** Both laboratory and field test results showed high repeatability for BPN measurements under dry, wet, and/or icy conditions for vehicular tire slip resistance (TSR) and pedestrian slip resistance (PSR), with a coefficient of variation (CV) of around 3-5%.

- **Pavement Surface Type:** No statistical differences in BPN values were observed between markings applied on asphalt versus concrete. This finding indicates that the friction characteristics of pavement markings are independent of the surface type.

- **Comparison between BPT Devices:** There was no statistical difference between the two BPT devices used in the study regarding BPN measurements across dry, wet, and icy conditions, nor between TSR and PSR. This indicates that alternative BPT devices meeting the same design specifications can be reliably used for BPN testing.

- **Effects of Pad Wear:** Pad orientation (i.e., one face versus the reverse side) has minimal impact, particularly for new pads, indicating that orientation does not significantly influence BPN measurements for either TSR or PSR. However, the comparison between worn pads (used for about 1,200 times) and new pads provided significantly different BPN values for both PSR and TSR.

- **Operator Effects:** No meaningful differences between BPN measurements taken by two different operators were observed for both TSR and PSR. Statistical analysis through paired t-tests confirmed that the operator effect was not significant.

- **Impact of Pavement Marking Surface Conditions (D, W, I):** Surface conditions had a significant effect on both TSR and PSR values. The BPN values in wet conditions were consistently lower than the dry conditions providing thus lower friction and slip resistance. Similarly, the icy conditions in the lab provided the lowest values compared to dry and wet conditions. Such effects were statistically meaningful for both lab and field measurements.

- **Traffic Wear:** The effect of traffic over time on pavement marking was meaningful, representing the degree of wear in terms of friction reduction. Also, the specific traffic lane locations were examined, with the wheel path areas providing lower friction values for TSR and PSR as compared to off-wheel path and shoulder areas. This indicates the importance of accounting for differential wear in wheel path areas.

- **Comparison of TSR and PSR Measurements:** TSR (D) was consistently higher than PSR (D) by around 5 BPN units in field tests and between 5-10 BPN units in lab tests. However, in wet conditions, PSR (W) was higher than TSR (W) by about 5-10 BPN units, reflecting the different frictional behaviors of pedestrian and vehicular interactions in wet surfaces. Strong predictive relationships were obtained between TSR and PSR in both lab and field conditions.

- **Relating Lab and Field Measurements:** Strong predictive relationships were established between TSR and PSR from lab and field measurements for dry and wet surface conditions.

6.2 Study Recommendations and Potential Revisions to State Specifications

- **Revisions to Pavement Markings' Specifications:** Based on the study findings, the current Maryland's acceptance specifications for pavement markings may be revised to consider thresholds reflecting pedestrian slip resistance (PSR) in relation to the current vehicular tire skid resistance (TSR) minimum threshold values.

- **MD 951.06 Preformed Thermoplastic Pavement Markings Spec:** The current acceptance specification for preformed thermoplastic pavement markings considers a minimum average skid resistance value of 50 BPN determined according to ASTM E 303 with the TSR in dry conditions. Based on the monitoring of the 13 field sites with preformed thermoplastic markings included in this study, Figure 5.7, an average of about +/- 5 BPN units was observed between PSR and TSR under dry conditions. Thus, if the specification is to be revised to include considerations regarding pedestrian slip resistance, the minimum threshold value should be set to 55 BPN units as tested by ASTM E 303. This implies that no separate BPN testing is needed for pedestrian and vehicles friction evaluation. To be mentioned that the 13 field sites included in this study had already experienced 1-2 years of in-service traffic (i.e., pavement markings installed in 2022) and thus the minimum threshold value of 55 BPN units should be easily attained during installation of the new preformed thermoplastic markings.

- **MD 951.02 Pavement Marking Tape Spec:** The current acceptance specification for tape pavement markings considers a minimum average skid resistance value of 45 BPN as determined with ASTM E 303. This study included only one site with marking tape (#18) where TSR and PSR in dry conditions were comparable, yet in one testing date one was higher than the other, and vice-versa for the following field-testing date, Figure 5.8. While the laboratory testing results provided conclusive trends between TSR and PSR in dry conditions, Figure 5.1, further assessment is needed to identify conclusive trends in the field between PSR and TSR for tape in dry conditions, and thus determine potential recommendations for the acceptance specification of this pavement marking material.

- **Monitoring Pavement Marking Friction Over Time:** Based on the study findings, the effect of traffic in time has an impact on TSR and PSR reduction. Furthermore, the concentration of traffic on wheel paths further reduces slip and ski resistance. Thus, it is recommended that monitoring of friction levels over time for assessing safe conditions at pavement marking should be focused on the wheel path locations where the lowest BPN values are expected.

- **Wear of TSR and PSR Pads:** As it was identified in this study the wear of sliding TSR and PSR pads may have a significant impact on BPN measurements. Thus, frequent pad replacement is recommended for consistent measurements over time. Comparing used pads to the values obtained using new TSR and PSR pads may provide an assessment of their ability to provide consistent values over time and degree of wear, as well as when to replace used pads.

- **Predicting Pavement Marking Friction:** The good predictive relationships between TSR and PSR from the lab and field measurements can be used to estimate and/or predict slip and skid resistance of pavement marking by limiting the amount of testing needed. In other words, measuring one of the two friction resistance parameters could lead to a good estimate of the other. This could be particularly helpful, for example when new pavement marking materials are supplied by the producers that need to be assessed for meeting the minimum TSR specification acceptance threshold values. Another example of the potential use of such predictive relationships is when the TSR values are monitored in the field under one surface condition (i.e., dry) and it is of interest to either identify the other (i.e, PSR), and/or the BPN under wet conditions for safety related considerations of the traveling public and pedestrians.

References

[1]. Burghardt, T. E., & Pashkevich, A. (2018). Emissions of volatile organic compounds from road marking paints. *Atmospheric Environment*, *193*, 153-157.

[2]. Carlson, P., Park, E. S., Pike, A., Porter, R. J., Miles, J., Boulanger, B., Ealding, W. (2013). *Pavement marking demonstration projects: state of Alaska and state of Tennessee* (No. FHWA-HRT-12-048). United States. Federal Highway Administration. Office of Safety Research and Development.

[3]. Wang, S. (2010). *Comparative analysis of NTPEP pavement marking performance evaluation results* (Master's thesis, University of Akron).

[4]. Mohamed, M., Abdel-Rahim, A., Kassem, E., Chang, K., & McDonald, A. G. (2020). Laboratory-based evaluation of pavement marking characteristics. *Journal of Transportation Engineering, Part B: Pavements*, *146*(2), 04020016.

[5]. Martin, P. T., Perrin, J., Jitprasithsiri, S., & Hansen, B. (1996). *A comparative analysis of the alternative pavement marking materials for the state of Utah*. Department of Civil and Environmental Engineering, University of Utah.

[6]. Montebello, D., & Schroeder, J. (2000). *Cost of pavement marking materials*. Minnesota Department of Transportation.

[7]. Cuelho, E., Stephens, J., & McDonald, C. (2003). A Review of the Performance and Costs of Contemporary Pavement Marking Systems.

[8]. Kim, I. J., Smith, R., & Nagata, H. (2001). Microscopic observations of the progressive wear on shoe surfaces that affect the slip resistance characteristics. International Journal of Industrial Ergonomics, 28(1), 17-29.

[9]. Strautins, C. J. (2008). Sustainable slip resistance: an opportunity for innovation. Proceedings of Qualicer.

[10]. Vermol, V. V., Kamsah, K., Hassan, O. H., & Anwar, R. (2011, December). A study on porcelain anti slip tile design. In 2011 IEEE Colloquium on Humanities, Science and Engineering (pp. 121-124). IEEE.

[11]. Purohit, K., Rahman, M., Price, A., & Woodside, A. (2020). Assessment of Preformed 3D- Thermoplastic Road Markings for Long-Term Durability, Skid Resistance and Texture Functionality. In Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9 (pp. 965-974). Springer International Publishing.

[12]. Nassiri, S. (2018). Evaluation of Motorcyclists' and Bikers' Safety on Wet Pavement Markings.

[13]. Cui, X., Guo, W., Fwa, T. F., & Chu, L. (2022). Improved Interpretation of British Pendulum Test Measurements for Evaluation of Floor Slip Resistance. Journal of Testing and Evaluation, 50(3), 1403-1414.

[14]. Chimich, D. D., Al-Salehi, L., Elkin, B. S., & Siegmund, G. P. (2022). Contaminant film thickness affects walkway friction measurements. Frontiers in public health, 10, 915140.

[15]. Fan, T. (2023). Research Status of Anti Slip Characteristics of Asphalt Pavement for Vehicle Turning and Braking Stability. International Core Journal of Engineering, 9(7), 339-344.

[16]. Kumar, A., Tang, T., Gupta, A., & Anupam, K. (2023). A state-of-the-art review of measurement and modelling of skid resistance: The perspective of developing nation. Case Studies in Construction Materials, e02126.

[17]. Chu, L., Cui, X., Zhang, K., Fwa, T. F., & Han, S. (2019). Directional skid resistance characteristics of road pavement: Implications for friction measurements by British pendulum tester and dynamic friction tester. Transportation research record, 2673(10), 793-803.

[18]. Mosböck, H., & Burghardt, T. E. (2016, October). The importance of road markings for road safety and modern traffic management. In Proceedings of the 1st European Road Infrastructure Congress, Leeds, UK (pp. 18-20).

[19]. Saito, K., Horiguchi, T., Kasahara, A., Abe, H., & Henry, J. J. (1996). Development of portable tester for measuring skid resistance and its speed dependency on pavement surfaces. Transportation Research Record, 1536(1), 45-51.

[20]. Henry, J. J., Anderson, D. A., & Hayhoe, G. F. (1981). Skid Resistance of Pavement Marking Materials Volume 1 (No. FHWA-RD-80-199). United States. Department of Transportation. Federal Highway Administration.

[21]. Kumar, A., & Gupta, A. (2021). Review of factors controlling skid resistance at tire-pavement interface. Advances in Civil Engineering, 2021, 1-16.

[22]. Powers, C. M., Brault, J. R., Stefanou, M. A., Tsai, Y. J., Flynn, J., & Siegmund, G. P. (2007). Assessment of walkway tribometer readings in evaluating slip resistance: a gait-based approach. Journal of forensic sciences, 52(2), 400-405.

[23]. Ostrofski, A. (2004). High pressure water retexturing/cleaning of bituminous surfacings. In Road System and Engineering Technology Forum, 2004, Brisbane, Australia.

[24]. MDOT-SHA, Maryland Department of Transportation State Highway Administration. (2023). Standard specifications for construction and materials.

[25]. Ongel, A., Lu, Q., & Harvey, J. (2009, February). Frictional properties of asphalt concrete mixes. In Proceedings of the Institution of Civil Engineers-Transport (Vol. 162, No. 1, pp. 19-26). Thomas Telford Ltd.

[26]. New York State Department of Transportation. (NYSDOT). Highway Safety Improvement Program Procedures and Techniques (aka 'Red Book'). https://www.dot.ny.gov/divisions/operating/osss/highway-repository/RedBook.pdf

[27]. Sudoł, E., Szewczak, E., & Małek, M. (2021). Comparative analysis of slip resistance test methods for granite floors. Materials, 14(5), 1108.

[28]. Queipo de Llano Moya, J., & Frías-López, E. (2016). Spanish Pre-regulatory Research in Slip Resistance. Journal of Applied Safety Research, 47(4), 508-520.

[29]. Powers, C. M., Brault, J. R., Stefanou, M. A., Tsai, Y. J., Flynn, J., & Siegmund, G. P. (2007). Assessment of walkway tribometer readings in evaluating slip resistance: a gait-based approach. Journal of forensic sciences, 52(2), 400-405.

[30]. Aschan, C., Hirvonen, M., Rajamäki, E., Mannelin, T., Ruotsalainen, J., & Ruuhela, R. (2009). Performance of slippery and slip-resistant footwear in different wintry weather conditions measured in situ. Safety science, 47(8), 1195-1200.