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International Perspectives on Skid Resistance Requirements for Pavement Markings: A Comprehensive Synthesis and Analysis

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Abstract: Pavement (or road) markings play an important role in road safety, influencing the dynamics of road users through their skid resistance properties. This study provides a comprehensive synthesis and analysis of international perspectives on the skid resistance of pavement markings and their requirements. It examines marking skid test results across various regions, including North America, Europe, and other parts of the world, and emphasizes the impact of different materials and test environments on skid resistance. The study also reviews current skid resistance standards and guidelines, from North American state-level standards to European and global specifications. Furthermore, it discusses the safety implications of these standards for diverse road users, especially motorcyclists, cyclists, and pedestrians. In conclusion, this paper highlights the importance of further innovation and consistency in skid resistance testing and standards to improve road safety.

Keywords: pavement/road marking; skid resistance/friction; skid/friction number; British pendulum number; macrotexture; mean profile depth

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1. Introduction

Pavement or road markings are essential components of traffic control systems, providing guidance and safety for road users [1]. Traditionally, the performance of these markings, often enhanced with glass beads for improved retro-reflectivity, has been evaluated primarily based on visibility factors like retro-reflectivity and color. However, marking materials often fill small voids in the road surface, and the smooth, round shape of these glass beads alters the surface texture of the pavement. This leads to a reduction in skid resistance, particularly in wet conditions. On average, the skid resistance of pavement markings is 15–20% lower than that of the surrounding pavement surface [2].

While Europe [3] has long considered skid resistance a key performance requirement for pavement markings, this issue has not received the same level of attention in other regions. In the United States, for instance, the Manual on Uniform Traffic Control Devices (MUTCD) [1] acknowledges the need to minimize tripping hazards and the loss of traction but lacks clear, practical implementation guidelines. As a result, current evaluations of pavement markings tend to prioritize visibility over skid resistance, with limited research on the skid resistance of pavement markings and its safety implications.

The skid resistance of pavement markings depends on various factors, including the type of materials (such as binders and glass beads), the design of the markings (e.g., thickness and profile), the pavement surface texture, and environmental conditions like moisture and temperature. Advances in high-performance glass beads and retro-reflective technologies have enhanced visibility, particularly in low-light conditions and adverse weather [4,5]. However, the application of more drop-on glass beads increases retro-reflectivity but may reduce skid resistance [6]. While engineered anti-skid additives have been developed to improve skid resistance [7–11], achieving both high retro-reflectivity and high skid resistance remains challenging.

Concerns about the skid resistance of pavement markings arise commonly in two situations: poor friction and differential friction [12–14]. Both can lead to the loss of control, especially during turning maneuvers. Such risks are increased in high-traffic areas like intersections, where large markings such as crosswalks, letters, and arrows are common. Moreover, the advent of autonomous vehicles has led to recommendations for wider longitudinal markings [1,15]. This paper presents a comprehensive synthesis of the skid resistance of pavement markings, identifies research gaps, and discusses practical limitations, aiming to inform future studies and refine methodologies to improve roadway safety concerning the skid resistance of pavement markings. Note that, for the purpose of this paper, terms such as "road markings" and "pavement markings", as well as "friction" and "skid resistance", are used interchangeably to refer to the same concepts.

2. Pavement Markings: Types and Materials

2.1. Pavement Markings

Pavement markings consist of a binder (resin), pigments, fillers, and sometimes a dispersion medium [16]. The binder ensures adhesion and cohesion, while pigments provide color, with titanium dioxide (TiO_2) and lead chromate (PbCrO) being common for white and yellow markings [17]. Fillers, typically composed of a mixture of different materials, including calcium carbonate, sand, calcined clays, silicates, mica, barium sulfate, and other materials, enhance markings by improving moisture resistance, abrasion durability, temperature stability, visibility, and visual appearance. Some materials, like solvent-borne paints, include a dispersion medium to maintain stability, distribute components, and aid film formation.

2.1.1. Paints

Solvent-borne paints are single-component coatings consisting of binder resin, pigments, fillers, and solvents [18,19]. Their classification depends on the binder type, such as epoxy, alkyd, or acrylic. These paints contain about 30% solvent, which evaporates during application, forming a solid film. Though durable and weather-resistant, solvent-borne paints have a service life of 6–12 months and are increasingly replaced by waterborne alternatives due to environmental concerns and higher costs. They are used on clean, dry surfaces with a wet film thickness of 15 mils (1 mil = 0.0254 mm).

Waterborne paints, comprising binders, pigments, fillers, and water-based solvents, account for nearly 90% of pavement markings in the U.S. [17]. These paints dry faster, are less influenced by humidity, and offer strong adhesion to asphalt and concrete surfaces [20,21]. With a typical wet film thickness of 15–25 mils, waterborne paints last 9–36 months. While more durable than solvent-borne paints, they are best suited for low-traffic or temporary markings due to their relatively lower longevity.

2.1.2. Multi-Component Paint

Epoxy is a two-component marking material consisting of two parts: component A, containing resin, pigments, extenders, fillers, and solvents, and component B, the catalyst that accelerates the curing process [16]. Proper surface preparation is critical for achieving optimal bonding when applying epoxy. The mixing ratio of component A to component B is typically 1:1 or 2:1 by volume. Once mixed, epoxy undergoes an exothermic reaction, i.e., releasing heat (or energy). Epoxy markings can be applied to either a concrete or asphalt surface. As a durable marking, the lifespan of epoxy markings exceeds four years on roads with low to medium traffic volumes [20,21]. The applied film thickness of epoxy markings typically ranges from 15 mils to 25 mils. Epoxy paints can be used for both longitudinal and transverse markings.

Polyurea is also a two-component system. Component A is a resin mixture containing pigments and fillers, while component B serves as a catalyst [16], typically mixed at a 2:1 ratio by volume. Unlike epoxy, polyurea undergoes an endothermic reaction, requiring energy input, and solidifies rapidly within seconds. Polyurea is a durable marking, with a service life of up to five years. Due to its benefits such as its fast-drying, abrasion-resistant, and high-performance properties, polyurea is a popular choice for both high-traffic and industrial environments. The recommended wet film thickness for polyurea pavement markings is 15 mils to 25 mils [21].

Methyl methacrylate (MMA) is a solvent-free, two-component system [16]. Component A contains a methyl methacrylate monomer, pigments, and fillers, and component B consists of a liquid or powder catalyst. Typical mixing ratios are 4:1 or 1:1 by volume, and 98:2 by weight, depending on the intended function of the marking. Aggregates are incorporated to enhance skid resistance. When MMA is applied to pavement surfaces, it forms a strong bond through an exothermic reaction. MMA typically lasts more over 3 years [22] and is widely used in bicycle and dedicated bus lanes. The application thickness of MMA varies according to the vendor requirements, formula, and intended use, commonly ranging from 10 to 250 mils [23].

2.1.3. Thermoplastics

Thermoplastic (TP) markings consist of a blend of resin, fillers, and pigments, with hydrocarbon and alkyd being the most used resins [16]. TP materials are solvent-free and available in two forms: dried palletized and preformed-shaped. The former requires heated extruding, where the material is melted and applied to the pavement surface, while the latter requires heating the material with a torch. TP markings are commonly melted at temperatures of 180 °C to 220 °C [17]. TP markings exhibit resistance to snowplow damage, and can be applied over existing markings, eliminating the need for prior removal. However, their application is generally limited to asphalt surfaces. TP markings can last 3 to 6 years, and their application thickness ranges from 90 mils to 125 mils.

2.1.4. Tapes

Pavement marking tapes include two types: permanent and temporary tapes. Permanent preformed tapes are typically made from plastic binder materials, with urethane and pliant polymer being the two most used binders for permanent tapes [21]. Temporary marking tapes are composed of synthetic polymer [24]. Marking tapes are typically supplied in continuous rolls and are manufactured with embedded glass beads or other particles to enhance reflectivity and retro-reflectivity. When installed correctly, permanent preformed tapes can have a service life of 4 to 8 years.

2.2. Reflective Materials and Particles

Glass beads are applied directly onto freshly applied pavement markings or, in certain cases, partially mixed into markings prior to application (pre-mixing paint) [16]. The AASHTO M247-13 specification [25] divides glass beads into six types based on gradations (see Table 1). Glass beads are available in two types: coated and uncoated. Coated (or treated) glass beads possess a surface coating that facilitates their embedding into the paint, whereas uncoated beads remain on the surface. The index of refraction (IOR) of glass beads ranges from 1.50 to 1.55. Ceramic particles, angular particles, and aggregates have also been developed to enhance the skid resistance of pavement markings [7]. Due to the absence of a standardized specification, these materials may exhibit variations in size and shape.

Table 1. Gradations of glass beads.

Sieve Size (mm)	Mass % Passing					
	Type 0	Type 1	Type 2	Type 3	Type 4	Type 5
2.35						100
2.00					100	95–100
1.70				100	95–100	80–95
1.40				95–100	80–95	10–40
1.18		100	100	80–95	10–40	0–5
1.00				10–40	0–5	0–2
0.850		95–100	90–100	0–5	0–2	
0.600	100	75–95	50–75	0–2		
0.425	90–100		15–45			
0.300	50–75	15–35	0–15			
0.180	0–5		0–5			
0.150		0–5				

As the end of this section, Table 2 summarizes the application aspects of different pavement markings reviewed above.

Table 2. Application aspects of different pavement markings from reviewed references.

Marking Type	Thickness (mils) [1]	Service Life	Application [2]	Advantages and Disadvantages
Solvent-borne	15	6–12 months	• Longitudinal and transverse markings; • Low traffic volume (e.g., AADT [3] < 3000).	Advantages: • Low cost; • Fast-drying; • Weathering resistance; • Suitable for asphalt and concrete. Disadvantages: • Environmental contamination risk; • Health hazards for workers; • Flammable; • Low durability.
Waterborne	15–25	9–36 months	• Longitudinal and transverse markings; • Low traffic volume (e.g., AADT < 3000).	Advantages: • Low cost; • Fast-drying; • Less affected by humidity; • Suitable for asphalt and concrete; • Environmentally friendly; • Stable properties; • Easy to apply. Disadvantages: • Low durability.
Epoxy	15–25	4 years	• Longitudinal and transverse markings; • Medium traffic volume (e.g., AADT $\geq$ 3000).	Advantages: • Suitable for asphalt and concrete; • Durable; • Environmentally friendly. Disadvantages: • Prone to yellowing or fading under UV exposure; • Incompatible with existing markings of other materials; • Slow-drying.

Table 2. *Cont.*

Marking Type	Thickness (mils) [1]	Service Life	Application [2]	Advantages and Disadvantages
Polyurea	15–25	5 years	• Longitudinal markings; • Medium traffic volume (e.g., AADT ≥ 3000).	Advantages: • Fast drying; • Resistant to abrasion, chemicals, and UV radiation; • Durable and moisture-resistant; • Applicable in freezing temperatures; • Suitable for asphalt and concrete; • Environmentally friendly. Disadvantages: • Requires specialized equipment for application.
MMA	10–250	3 years	• Bicycle and bus lanes; • Longitudinal and transverse markings; • Symbols; • Medium traffic volume (e.g., AADT ≥ 3000).	Advantages: • Durable; • Environmentally friendly; • Suitable for asphalt and concrete. Disadvantages: • Requires dry conditions for application; • Produces objectionable odor.
Thermoplastics	90–125	3–6 years	• Longitudinal and transverse markings; • Symbols; • Medium traffic volume (e.g., AADT ≥ 3000).	Advantages: • Durable; • Applicable on existing markings; • Resistant to snowplow damage. Disadvantages: • Limited to asphalt surfaces; • Requires heat or specialized devices.
Temporary Tapes	Multiple thicknesses	1–6 months	• Work zones or areas need temporary traffic control.	Advantages: • Easy to remove; • Simple application. Disadvantages: • Short service life; • High costs compared to paint.
Permanent Preformed Tapes	Multiple thicknesses	4–8 years	• Longitudinal and transverse markings; • Symbols; • High traffic volume (e.g., AADT ≥ 18,000).	Advantages: • Durable; • Suitable for asphalt and concrete surfaces; • Easy to apply; • Roads can reopen immediately. Disadvantages: • High costs.

[1] 1 mil = 0.0254 mm; [2] See reference [26]; and [3] AADT is annual average daily traffic.

3. Skid Resistance Test Results of Pavement Markings

3.1. North America

In 1975, Richard [27] conducted a two-phase study on the skid resistance of pavement markings in the U.S. Phase I tested 14 marking types in the lab using the British pendulum tester (BPT), with results ranging from a British pendulum number (BPN) of 45 for fast-dry white paint (no beads) to 14 for smooth white cold plastic. Phase II compared three marking materials on a freeway, measuring the field friction number (FN40 at 40 mph) against lab BPN data. Fast-dry beaded white paint had an FN40 of 37 and a BPN of 31, while extruded yellow hot plastic showed an FN40 of 23 and a BPN of 35. The study concluded that pavement markings generally have lower friction than road surfaces and recommended using abrasive additives to improve skid resistance.

In 1980, Anderson and Henry [12] tested 39 formulations from 11 types of marking materials, including paints, thermoplastics, cold-applied plastics, and temporary tapes, under lab and field conditions. They measured wet friction using the skid number (SN), BPN, microtexture, macrotexture, and static friction coefficients. The results showed a significant variation in wet friction among materials. Beaded materials had a consistent BPN of 50 ± 5, with little change after polishing, as beads mainly influenced friction. Unbeaded materials, like chlorinated rubber paints and thermoplastics, had lower and more variable friction. Thin materials, such as paints, lost skid resistance over time, while thick materials, like thermoplastics, did not recover skid resistance after prolonged exposure. The study highlighted safety risks from uneven skid resistance between marked and unmarked areas, especially over large zones.

In 1995, Bagot [28] tested five materials: two epoxies, two waterborne paints, and one MMA resin, at three airports to identify durable, visible options that reduce maintenance costs and meet environmental standards. Using the K.J. Law Runway Friction Tester (RFT), he found friction values ranging from 0.32 to 0.90 for epoxy, 0.44 to 0.99 for waterborne paint, and 0.31 to 0.68 for MMA, depending on the use of silica granules. The study concluded that silica additives improved skid resistance in epoxies. In 1996, Bagot [29] furthered friction tests to assess the effects of retro-reflective glass beads and silica. Adding 1.5 and 1.9 IOR beads increased initial friction from 0.54 to 0.64 and 0.63, respectively, while adding silica raised it to 0.84. Silica enhanced friction the most, but its effectiveness declined when combined with beads due to size differences.

Rodin et al. [22] investigated the safety of different marking materials for motorcyclists and bikers in 2018. Three types of markings, including waterborne paint, TPs, and preformed tape, were assessed for friction in dry, wet, and iced conditions. In the laboratory, beaded paint exhibited the highest BPN at 100, and beaded TPs exhibited the lowest BPN at 62 in dry conditions, and, in wet conditions, preformed tape exhibited the highest BPN at 64, and beaded TPs exhibited the lowest BPN at 40. The results also showed that the wet BPNs measured with a pedestrian slip rubber and a tire slip rubber are very close.

Fanijo et al. [30] evaluated waterborne paint, MMA, and TP markings for bicycle lanes under simulated wear conditions in 2023. Friction measurements included the mean texture depth (MTD) and the international friction index (IFI). The results showed that TP markings had a higher MTD (1.20 mm) than beaded paint (0.90 mm), unbeaded paint (0.59 mm), and MMA (0.62 mm). Before polishing, MMA had the highest IFI at 0.40, while unbeaded waterborne paint had the lowest IFI at 0.18. The test results also showed that friction decreased for MMA and slightly increased for the waterborne paint, after polishing.

The latest research by Bao et al. (2024) examined the skid resistance of six beaded markings [31]. Laboratory tests revealed the following mean profile depth (MPD) and BPN values: beaded waterborne (MPD 0.31–1.26 mm, BPN 40.0–62.5), preformed tapes (MPD 1.08 mm, BPN 40.8), epoxy (MPD 0.42–0.75 mm, BPN 33.8–35.5), polyurea (MPD 0.37–1.55 mm, BPN 34.0–42.5), MMA (MPD 0.34 mm, BPN 47.5), and thermoplastics (MPD 0.25–0.26 mm, BPN 30.5–32.5).

3.2. Europe

In the United Kingdom (UK), Reid et al. (1962) [32] studied white-line road markings and light-colored surfaces. Laboratory tests showed that TP markings with glass beads had a skid resistance of 37–58 BPN without gritty aggregate and 48–90 BPN with it. A survey of 100 road sites found that all TP markings had a skid resistance of at least 55 BPN, with most exceeding 65 BPN, while three paints fell below 55 BPN. TP markings were the most durable and skid-resistant. Purohit et al. (2020) [33] assessed preformed 3D TP markings on asphalt and concrete. On Day 1, MTD values were 4.0 mm on asphalt and 2.8 mm on concrete, with slight reductions after a year. The initial BPN values on asphalt were 84.2 (dry) and 69.0 (wet), dropping slightly to 81.3 (dry) and 68.0 (wet) after a year. On concrete, the initial BPN values were 90.4 (dry) and 73.0 (wet), decreasing to 82.5 (dry) and 69.0 (wet) after a year. The markings maintained a stable texture and high friction over 12 months.

In Italy, Pasetto and Manganaro (2006) [9] studied the impact of surface texture saturation on skid resistance for solvent-based paints with glass beads and anti-skid granules (80:20 weight ratio) applied at a depth of 300 μm. The markings had skid resistance tester values (SRT) of 41–55 and an MTD of 0.51–0.91 mm. Skid resistance decreased by 15–20%, and macrotexture by 10%, with greater effects on surfaces with an initially high texture. Asdrubali et al. [34] evaluated road markings at 28 sites using various materials, including paint, TP, two-component, and preformed markings. Tests conducted in 2010 and 2012 showed SRT values ranging from 31–63 in 2010 and 32–68 in 2012.

Lundkvist and Isacsson (2007) carried out wet nighttime measurements in three test-fields, two in Sweden and one in Demark [35]. Skid resistance and texture were measured on 130 flat TP road markings. The results showed that the MPD ranged between 0.15 mm and 2.35 mm, and the SRT ranged from 0.63 to 0.92. The findings indicated that a dry texture could predict wet skid resistance using models validated through regression analysis.

Coves-Campos et al. (2018) [7] tested 18 road marking types on a rural highway in Spain using styrene acrylic paint, four types of glass beads (125–1180 μm), and two anti-skid aggregates (marble sands and calcium-sodium granules). Initial SRT values ranged from 49.0 to 55.1 for markings with glass beads alone, 58.0–63.0 with 80% glass beads and 20% marble sands, 52.0–55.2 with 80% glass beads and 20% granules, and 53.0–58.5 for double-layer systems using beads or granules. After 18 months, SRT values declined to 41.2–45.1, 44.0–49.0, 43.0–46.5, and 43.5–48.5, respectively. Glass beads offered better visibility but lower durability, anti-skid aggregates improved skid resistance at the cost of visibility, and double-layer systems demonstrated the best overall durability.

In Austria, Burghardt et al. (2023) [8] studied how glass beads and anti-skid particles affect the skid resistance of pavement markings. They tested five setups: bare asphalt, paint only, paint with glass beads, paint with glass beads and 10% corundum, and paint with anti-skid particles. Waterborne paints, 400 μm thick, were applied as transverse stripes on a road with low-speed traffic (400 trucks and 200 cars daily). The initial and 10-month SRT values were as follows: asphalt (49.0 to 47.0), paint only (35.0 to 36.0), paint with glass beads (44.0 to 41.0), paint with glass beads and corundum (50.0 to 42.0), and paint with anti-skid particles—corundum (48.0 to 45.0), glass granulates (65.0 to 44.0), cristobalite (53.0 to 46.0), and bauxite (61.0 to 49.0). The study found that adding anti-skid particles is critical to reducing slipperiness in thin markings.

3.3. Other Regions

Thew and Dabic (2000) evaluated the skid resistance of three paints and adjacent road surfaces in Australia [36]. The results exhibited that waterborne paints with Type C beads demonstrated a skid resistance that was 9–13 BPN lower than that of the adjacent road surface, while alkyd markings exhibited a skid resistance that was 19–22 BPN lower than that of the surrounding road surfaces. Drop-on glass beads increased the skid resistance, typically from 25–30 BPN to 35–38 BPN.

In South Africa, Naidoo and Steyn (2018) [37] tested various road marking materials, including white and yellow waterborne, 1.2 mm TP, 1 mm cold plastic, and 3 mm screed materials. Skid resistance was evaluated using test markings on plates in the lab. White waterborne, 1 mm cold plastic, and both white and yellow 1.2 mm TPs had an SRT value greater than 50. Other materials had SRT values between 35 and 45. The study suggested that road marking applicators should increase the amount of anti-skid aggregate to improve skid resistance.

Siyahi et al. (2015) [38] studied the effect of additives (ground waste glass, silica, and Lika powders) on the properties of a two-component acrylic paint used in Iran. They applied 800-micron thick paint samples on asphalt slabs. Skid resistance for the paint without additives was 33 BPN, and it increased by 46%, 33%, and 25% when 5% Lika, silica, and waste glass powders were added, respectively. Hadizadeh et al. (2020) [39] evaluated MMA-based cold plastic traffic paints under simulated conditions, with samples applied to degreased steel panels. Skid resistance ranged from 48 to 74 BPN using two different aggregates of silica.

In Mainland China, Wang et al. (2023) [40] evaluated tire-road wear using a two-wheel accelerated wear test with three specimens: 13 mm hot mix asphalt, unbeaded solvent-based paint, and beaded solvent-based paint. Initial BPN values were 54 for asphalt, 35 for unbeaded paint, and 70 for beaded paint. After 150 min, the BPN values changed to 61, 53, and 54, respectively. Chen et al. (2020) [10] tested traditional and modified hot-melt paints with glass beads, using a four-wheel accelerated polishing machine. The initial BPN was 65 for traditional paint and 68 for modified paint. After 10,000 cycles, the BPN decreased to 51 and 54. Yang (2020) [11] also reported a high-performance highway marking with a BPN of 65.

In Taiwan, Chiu et al. (2017) [41] studied heat-treated polyester markings on two highways. White beaded longitudinal markings, 15 cm wide, were applied to new asphalt pavements. The initial BPN values ranged from 45 to 68 at 18 test points, but half of the points showed a drop below 50 BPN after one year. Su et al. (2021) [42,43] assessed the skid resistance of marking materials, focusing on those with 65 BPN or higher. At real intersections, 65 BPN markings, aggregate markings, and cold plastic markings were tested. The initial BPN for 65 BPN markings was 60, dropping to 43 after 400 days and increasing to 58 after 575 days. Aggregate markings started at 52 BPN after 65 days and rose to 79 after 340 days. Cold plastic markings began with 95 BPN and dropped to 55 after one year. Lab tests showed that 65 BPN markings started at 71 BPN, decreasing to 59 after 150,000 polishing cycles.

4. Skid Resistance Requirements for Pavement Markings

4.1. North America

The MUTCD recommends selecting pavement marking materials that reduce the risk of tripping or losing traction for all road users, including pedestrians, cyclists, and motorcyclists. Florida Department of Transportation (DOT) [44] mandates a minimum skid resistance of 35 BPN for pavement markings, and 55 BPN for bicycle markings and crosswalks. Texas DOT [45] requires high-build paints to have an initial skid resistance of at least 45 BPN. Georgia DOT [46] sets a minimum of 35 BPN for preformed plastic markings. Illinois DOT [47] requires at least 45 BPN for Types B and D materials (both with patterned surfaces, intermixed glass beads with IOR $\geq$ 1.50, and top-coated ceramic particles with IOR between 1.80 and 1.70) and 55 BPN for Type C. The surface of blackout pavement marking tape must also have a minimum of 45 BPN. Other state DOTs [48–51] require at least 45 BPN for preformed tapes and TP markings. Municipal agencies [52–54] require preformed TP markings to have an initial BPN of 55 or 60 and maintain at least 45 BPN.

4.2. Europe

The EN standard, EN 1436 [3], which addresses marking performance, serves as the basis for establishing skid resistance requirements for road markings in EU member states. The skid resistance of pavement markings is measured as the skid resistance tester value (SRT) that is divided into six classes of S0 to S5. Class S0 denotes situations where no SRT is requested or when the SRT cannot be measured, while Classes S1 to S5 denote markings with SRT $\geq$ 45, 50, 55, 60, and 65, respectively. The permitted skid resistance classes range from S1 to S5.

In the UK [55], the minimum skid resistance is 55 for critical areas and 45 for non-critical areas. In France [56], the Decree of 10 May 2000 sets a minimum Class S1 (SRT $\geq$ 45) for all markings, with a recommended Class S3 (SRT $\geq$ 55) for areas requiring higher grip, such as pedestrian crossings. Nordic countries [57] require friction values of at least 0.52 for type I and II markings, temporary markings, and durable markings; 0.65 for hand-applied retro-reflective markings; and 0.71 for hand-applied non-retro-reflective and anti-skid markings. Poland [58] requires SRT values of 50 for motorways and express roads and 45 for other roads.

4.3. Other Regions

In New Zealand, NZTA M7 [59] requires a minimum BPN of 45 for markings with a thickness <0.9 mm and 50 for markings with a thickness $\geq$0.9 mm. NZTA M20 [60] requires a skid resistance of 50–65 BPN for long-lasting markings one hour after application and beyond. In Australia, the skid resistance is specified for TP markings (at a minimum of 45 BPN) [61] and high-performance markings [62], which are classified into three categories: no requirement (SK0), 45–60 BPN (SK1), and over 60 BPN (SK2).

In Mainland China, the initial skid resistance for all markings must be at least 45 BPN [63], with an upcoming revision [64] to set 45 BPN for conventional markings and 55 BPN for anti-skid markings. Taiwan's specifications require a minimum initial BPN of 50 for TP markings [65] and classify markings into six classes [66], requiring a minimum SRT of 45. Tung (2020) [67] reviewed the skid resistance specifications and found that many countries, including Singapore, Vietnam, Malaysia, Indonesia, and India, set the minimum BPN threshold at 45.

5. Discussion and Analysis

5.1. Safety Demand

Pavement markings are installed on road surfaces, so skid resistance requirements for markings often align with those for the road. Kummer and Meyer (1967) [68] recommended a minimum pavement friction of 37 SN40R (test speed: 40 mph, rib tire). Zhao et al. (2020) [69] linked the AASHTO [70] deceleration threshold (3.4 m/s^2) to a minimum friction coefficient of 0.35. Shuo et al. (2021) [71] found that 37 SN40R equals 20 SN40S (smooth tire) and that setting a minimum above 20–23 SN40S could raise maintenance costs significantly.

Friction demand and handling differ significantly for four-wheel and two-wheel vehicles. Four-wheel vehicles, with larger tire footprints, are more stable, whereas motorcycles are more affected by pavement friction. Research [72,73] has mainly focused on motorcycle sliding friction for accident reconstruction rather than the friction at the moment of a crash. Bicycles, with unique dynamics, generally require less friction than motorcycles but need enough for safe stopping and control. In the U.S., AASHTO [74] specifies friction coefficients of 0.32 (dry) and 0.16 (wet) for bicycle lanes. South Australia [75] mandates a grip number (GN, where GN = 0.01 $\times$ BPN) of 0.40 for bikeways, Korea [76] requires a 40 BPN, and Andalusia [77] sets a 0.25 friction coefficient for safe stopping distances on paved roads.

Pedestrians, though not as speed-dependent as motorcycles and bicycles, still require sufficient friction to avoid slips and falls, especially in busy areas or adverse conditions. ASTM D2047 [78] recommends a static friction coefficient of 0.50 for floor surfaces. However, slip risks on roads, floors, and work surfaces vary due to differences in the environment, users, and consequences. In Japan, Yamada et al. [79] suggested a slip friction coefficient of 0.34 (31 BPN) for wet conditions. Tanaka and Uchida [80] identified surfaces with 40 BPN or lower as slippery. Miyata et al. [81] found no significant benefit above 40 BPN, proposing it as the standard, and that a BPN of 30 is a critical safety threshold, with values below 30 indicating risk and 20 considered hazardous.

Table 3 summarizes pavement marking performance requirements from various global roadway agencies, as discussed in Section 4. Most standards or specifications prioritize retro-reflectivity and color for visibility, while skid resistance requirements are absent in the U.S., Japan, and Korea standards. Note that the two main BPT test methods, EN 13036 [82] and ASTM E303 [83], show slight differences [41]. Seemingly, a minimum skid resistance of 40 BPN may be acceptable for low-speed, low-traffic areas like residential streets or rural roads. However, for high-speed, high-traffic, or critical areas such as crosswalks, intersections, or regions prone to wet or icy conditions, a minimum of 45 BPN or higher is recommended to ensure sufficient skid resistance.

Table 3. Minimum requirements for pavement marking performance from reviewed references.

Source	Reflection	Retro-Reflection	Color	Durability	Skid Resistance [1]
US: MUTCD [1]	No	Yes	No	No	No
INDOT [84]	No	Yes	Yes	Yes	No
Canada: Ontario MTO [85]	No	Yes	Yes	Yes	No
UK: BSI [86]	Yes	Yes	Yes	Yes	45 (55 [2])
EU: EN 1436 [3]	Yes	Yes	Yes	Yes	45
New Zealand: <0.9 mm thick [59]	Yes	Yes	Yes	Yes	45
≥0.9 mm thick [59]	Yes	Yes	Yes	Yes	50
Long-life [60]	Yes	Yes	Yes	Yes	≥50 and ≤65
Australia: Paints [87,88]	Yes	Yes	Yes	Yes	No
Thermoplastic [61]	Yes	Yes	Yes	Yes	40 (initial)
High-Performance [62]	Yes	Yes	Yes	Yes	No/45–60/>60
Mainland China: GB/T 16311 [63]	No	Yes	Yes	No	45
GB/T 16311 pending [64]	No	Yes	Yes	No	45/55
Taiwan: T.E. Specs. [65]	Yes	Yes	Yes	Yes	≥50 (TP)
CNS 15834 [66]	Yes	Yes	No	No	45~65
Japan: JCASM [89]	Yes	Yes	Yes	No	No
Korea: KS M6080 [90]	Yes	Yes	Yes	No	No

[1] Skid resistance is in BPN or SRT; and [2] Required for critical locations.

5.2. Engineering and Technical Feasibility

Establishing minimum friction requirements for pavement markings involves balancing material science, engineering, and economics. The choice of materials, such as TPs, epoxy resins, high-friction aggregates, and additives, is key to ensuring durability and adequate texture for marking skid resistance. Application methods like spraying, rolling, or using preformed tape influence the texture and performance, each with its pros and cons. Moreover, regular maintenance helps maintain skid resistance over time. While the initial costs may vary significantly by material (see Table 4), the long-term safety benefits and reduced accidents can justify the investment.

Table 4. Bid price ranges for marking materials [91].

Materials		Paint	Epoxy	Polyurea	MMA	Thermoplastic	Tape
Price ($/ft)	4 in.	0.05–0.22	0.3–1.32	0.56–1.32	1.25	0.11–0.91	1.94–3.78
	6 in.	0.11–091	0.54–0.69	0.8	0.79–0.8	0.16–1.08	2.08–5.62

Table 5 summarizes the skid resistance test results of all pavement markings cited in Section 3 of this paper, including detailed material and glass bead information, and shows substantial variability based on marking type, binder, and test environment. Clearly, there are more lab studies than field studies. Adding anti-skid additives can greatly increase the skid resistance, especially for epoxy and TP markings. A direct comparison of the test results can lead to the following general guidelines for minimum skid resistance requirements, which ensure sufficient safety and performance across various road conditions and traffic volumes:

- 40 BPN (new markings) for low-traffic application areas;

- 45–50 BPN (new markings) for typical roads with moderate-traffic applications;
- 60 BPN or higher (new markings) for skid-prone and safety-critical locations.

Table 5. Summary of skid resistance test results from reviewed references.

Source	Marking Materials		Skid Resistance [1]	Test Environment
	Binder	Beads		
Richard (1975) [27]	Paints	Glass	30~32 (38~45)	Lab
	Cold plastic	Glass	14~38	Lab
	Extruded hot plastic	Glass	30~38	Lab
	TP tape	Glass	36~38	Lab
Anderson & Henry (1980) [2]	Paints	Glass	47~61 (28~59)	Lab
	Cold plastic	Glass	45~58 (46~57)	Lab
	Hot extruded TP	Glass	40~47 (21~39)	Lab
	Hot sprayed TP	Glass	46~63 (19~45)	Lab
Bagot (1995–1996) [28,29]	Waterborne	Silica	RFT: 0.77~0.90 (0.44~0.47)	Field
	Epoxy	Silica	0.60~0.90 (0.32~0.40)	Field
	Methacrylic resin	Silica	0.77~0.90 (0.44~0.47)	Field
	Methacrylic resin	Silica+Glass	0.42~0.52	Field
Rodin et al. (2018) [22]	Waterborne	Glass	52	Lab
	Preformed fused TP	Glass	40	Lab
	Patterned surface tape	Micro-ceramic	64	Lab
Fanijo et al. (2023) [30]	Waterborne	Glass	MTD: 0.90 (MTD: 0.62; IFI: 0.18)	Lab
	Thermoplastic	Glass	IFI: 0.19; MTD: 1.20	Lab
	MMA	Intermix glass	IFI: 0.40; MTD: 0.62	Lab
	Waterborne	Glass+&-ceramic	MPD: 0.31–1.26; BPN: 40.0–62.5	Lab
	Preformed tape	Micro-ceramic	MPD: 1.08; BPN: 40.8	Lab
Bao et al. (2024) [31]	Epoxy	Glass	MPD: 0.42–0.75; BPN: 33.8–35.5	Lab
	Polyurea	Glass+&-ceramic	MPD: 0.37–1.55; BPN: 34.0–42.5	Lab
	MMA	Glass+Corundum	MPD: 0.34, BPN: 47.5	Lab
	TP	Glass+Micro-ceramic	MPD: 0.25–0.26; BPN: 30.5–32.5	Lab
Reid et al. (1962) [32]	TP	Glass	37~58	Lab
	TP	Glass+Gritty agg.	48~90	Lab
	TP	Reflectorized	44~70	Field
Purohit et al. (2020) [33]	Preformed TP	Glass	69~73; MTD: 2.8~4.2	Field
Pasetto & Manganaro (2006) [9]	Solvent-based paints	Glass+Anti-skid granules	SRT: 41~55; MTD: 0.51~0.91	Field
Lundkvist & Isacsson (2007) [35]	TP	Glass	SRT: 0.63~0.92; MTD: 0.15~2.35	Field
Coves-Campos et al. (2018) [7]	Styrene acrylic paints	Glass±Anti-skid agg.	SRT: 49~63	Field
Burghardt et al. (2023) [8]	Paints	Glass	SRT: 44 (35)	Field
	Paints	Glass+Corundum	50~55	Field
	Paints	Andi-skid agg.	48~65	Field
Thew & Dabic (2000) [36]	Waterborne	Intermix Type C glass	46~70	Field
Naidoo & Steyn (2018) [37]	Waterborne	Glass	SRT: >50	Lab.
	Cold plastic	Glass	>50	Lab.
	TP	Glass	>50	Lab.
	Others	Glass	35–45	Lab.
Siyahi et al. (2015) [38]	Acrylic paints	Glass	41~48 (33)	Lab.
Hadizadeh et al. (2020) [39]	MMA	Silica	48~74	Lab.
Wang et al. (2023) [40]	Solvent-based paints	Glass	70 (35)	Lab.
Chen et al. (2023) [10]	Hydrophobic hot-melt paint	Glass	65	Lab.
	Traditional paint	Glass	68	Lab.
Yang (2023) [11]	High-performance paint	Glass	65	Lab.
Chiu et al. [41]	Heat-treated polyester	Intermix glass	45~68	Field
Su et al. (2021) [42]	TP (BPN $\geq$ 65)	Glass+Anti-skid agg.	60 or 71	Field or Lab.
	TP	Anti-skid agg.	52 (at 65 days)	Field
	Heat-treated polyester	Anti-skid agg.	95	Field

[1] Unless otherwise specified, skid resistance is in BPN, MPD is in mm, and values in brackets refer to unbeaded markings.

Note that thermoplastic and epoxy markings commonly require anti-skid additives to ensure adequate skid resistance. Moreover, the skid resistance of pavement markings may deteriorate over time due to factors such as traffic wear, environmental exposure, material quality, and substrate characteristics. This degradation increases the risk of skidding, especially at intersections and curves in wet conditions. Localized proactive measures to address these effects can enhance road safety and optimize maintenance efforts.

6. Conclusions

This paper presents a comprehensive synthesis of the global variability in materials and skid resistance requirements for pavement markings. The diverse thresholds for skid resistance, ranging from 45 BPN to over 60 BPN, reflect the need for region-specific strategies. Areas with high traffic volumes, extreme weather conditions, or safety-critical locations (such as intersections and crosswalks) may require higher skid resistance. To adapt to local conditions, highway agencies should consider factors such as road users, materials, weathers, traffic wear, and maintenance needs.

The paper also identifies a key challenge: non-uniformity in testing methodologies. Variations in testing methods can lead to inconsistent skid resistance evaluations. Standardizing test methods, such as EN 13036 SRT and ASTM E303 BPN tests, would allow for more consistent and comparable results across different regions, ensuring that pavement markings perform as expected in various environments.

Moreover, the addition of anti-skid aggregates, such as glass beads and corundum, significantly improves skid resistance, particularly in thermoplastic and epoxy markings. However, the choice of additives should be made according to local environmental factors and road conditions.

Finally, future efforts should focus on long-term performance data for pavement markings under diverse real-world environmental conditions and traffic patterns. More detailed studies on the influence of variables like temperature, traffic load, and age on skid resistance would support the development of more robust safety standards. In short, adapting to regional needs, standardizing testing methods, and further investigating the long-term impacts of marking materials will help enhance the skid resistance and safety of pavement markings globally.

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