



INTERNATIONAL **M**ONORAIL **A**SSOCIATION



# **Technical Framework for Straddle Beam Type Monorail Tire-Guideway Interaction**

First Edition, 2025

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# Technical Framework for Straddle Beam Type Monorail Tire-Guideway Interaction



## Disclaimer

International Monorail Association (IMA)

'Technical Framework for Straddle Beam Type Monorail Tire-Guideway Interaction'

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## Foreword

The development of this document has been a collaborative effort involving numerous experts and organizations dedicated to advancing the field of monorail systems. The goal was to create a standardized framework that enhances the performance, safety, and durability of tire-guideway interfaces in monorail systems. This effort aims to strengthen the competitiveness of monorails as a reliable solution for mass public transportation.

We would like to extend our heartfelt gratitude to the following individuals and their respective organizations for their invaluable contributions:

- **Dr. Zoltan Rado** from Aviation Safety Technologies
- **David Jardine, Eric Berger, Mintira Suwan, and Sumeet Bhawar** from Michelin
- **Jean-Francois Blanc, Eduardo Bocci Domingues, Matthew Hofford, and Fernando Rodriguez** from Alstom Group
- **Rodolfo Szmidke** from São Paulo Metrô
- **Carlos Banchik, Lucas Bernardi, Dr. Farghal Maree and Laura Thompson** from Innova Transportation LLC
- **Jordi Revoltos Fort and Sergio Castillo Redondo** from Sener
- **Marko Kroenke** President of IMA
- **Maxim Weidner** General Manager of IMA

Additional participants in the working group were:

- **Max Brüninghold** from mageba Group
- **Nils Trachsel** from Derap AG
- **Dr. Gregor Supp** from TÜV SÜD
- **Peter E. Timan** Member of the Executive Council of IMA
- **Tarun K. Goyal** from Structure Consultants Pvt Ltd
- **Orlando Soto** from Hercules MX

Their expertise, dedication, and collaborative spirit have been instrumental in the creation of this comprehensive guideline. We are grateful for their commitment to excellence and their contributions to the advancement of monorail technology.

The IMA Executive Council, September 2025



## Executive Summary

This document presents the first industry-specific guideline dedicated to the tire–guideway surface interface in straddle-type monorail systems. Developed by the International Monorail Association (IMA) Working Group on Tire–Guideway Surface Interaction, the guideline addresses a significant gap in global transit standards by offering clear, evidence-based recommendations for the design, testing, and maintenance of concrete running surfaces used in rubber-tired monorail systems.

The document is being issued at Monorailex 2025 in Singapore, and upon review and comments by the members, it will be issued formally at Monorailex 2026 and InnoTrans 2026.

The objective of this guideline is to establish a consistent framework that ensures safety, durability, and ride quality, while minimizing lifecycle costs and environmental impact. Drawing upon international standards such as ISO 13473, ASTM E274, EN 13036, and best practices from operational systems across Asia, the Americas, and Europe, this document translates diverse global experiences into a unified set of recommendations tailored specifically to monorail applications.

Among the core recommendations is the adoption of reliable and repeatable testing methods—such as the Dynamic Friction Tester (DFT), Circular Texture Meter (CTM), British Pendulum Tester (BPT), and Sand Patch test—to evaluate surface friction and macrotexture. The guideline advocates target values in texture depth and coefficient of friction, based on methods like the International Friction Index (IFI). It also outlines requirements for acceptable concrete finishes, corrective surface treatment techniques, and inspection protocols, while emphasizing the importance of material compatibility with tire compounds used by OEMs.

Additionally, the guideline includes a detailed discussion on the functional interfaces between tires and the guideway, including safety considerations such as tire pressure monitoring systems (TPMS), environmental effects (e.g., wet surface behavior), and in-field maintainability. Sustainability is addressed through recommendations on supplementary cementitious materials (SCMs) and low-carbon concrete technologies.

The document contains four appendices, and they complement each other. Use Dr. Rado (9.1) on a theoretical basis and safety impact of friction. Use Eric Berger (9.2) on a theoretical basis and safety impacts of friction. Use Innova Surface Finishes (9.3) for benchmarking texture solutions across global projects. Use Japan Surface Practices (9.4) to validate long-term surface behavior in high-use systems.

The document is intended for a wide range of industry stakeholders. Transit agencies and operators will benefit from practical direction on maintenance and performance expectations. Civil contractors and engineering firms will find specific guidance on surface finishes and specifications. Rolling stock manufacturers and tire OEMs will be able to use this standard to inform the design of tire and suspension systems. Finally, the guideline offers a foundation for future standardization efforts at the national and international levels, and a resource for academics and researchers working in the field of tire-road interaction.

By unifying diverse perspectives and contributions from global experts, this document represents a critical first step toward improving safety, performance, and reliability across the monorail industry for straddle-type monorail systems.

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# 1 Introduction and Background

## 1.1 Purpose of the Working Group

The IMA Tire-Guideway Surface Interface Working Group was established to develop a standardized framework that ensures optimal performance, safety, and longevity of the tire-guideway interface for monorail systems, with the goal of promoting the competitiveness of monorail systems for mass public transportation. This initiative is guided by the following objectives:

### Developing a Comprehensive Guideline

- Establish a technical reference document addressing friction, durability, and maintenance of tire-guideway interfaces, integrating methodologies from ASTM E274, ISO 13473 series (pavement texture characterization), and Michelin's research on grip and wear.
- Define friction performance metrics, surface material specifications, and optimal maintenance cycles.

### Identify Best Practices and Standards

- The guideline will benchmark global best practices, leveraging ASTM STP 929, ISO 8349 (road surface friction measurements) and industry case studies from monorail manufacturers, effects of pavement texture and tire wear, ensuring optimal performance across different environmental and operational conditions. Where possible, emphasis will be placed on real-world performance data, including how surface roughness and material composition of the guideway affect tire adhesion, wear rates, and braking performance.

### Collaborating with Industry Leaders and Operators

- Close collaboration with monorail manufacturers, infrastructure operators, and tire suppliers to ensure the guideline addresses practical challenges such as environmental conditions, maintenance cycles, and long-term performance evolution. Wherever possible, insights from international projects to ensure global adaptability of friction standards, pavement surface classification, and maintenance recommendations.

## 1.2 Scope of Work

The scope of this guideline is to provide a structured approach to defining, assessing, and maintaining the tire-guideway surface interface for monorail systems. This includes the following focus areas:

### Friction and Traction Requirements

- Define minimum and optimal friction coefficients ( $\mu$ ) using ASTM E274 and ISO 8349, ensuring safety under different conditions.
- Evaluate texture on grip and wear, incorporating findings from Michelin's research and ISO 13473-1 (mean profile depth measurements).

## Surface Material and Roughness Guidelines

- Propose micro- and macro-texture parameters based on ISO 13473-2 (pavement texture analysis terminology) and ISO 13473-3 (profilometer classification).
- Establish durability benchmark for surface polishing, material degradation, and reduction of skid resistance over time, and guideway surface maintainability.

## Maintenance and Lifecycle Considerations

- Develop preventive maintenance protocols, including regular friction testing (ISO 8349), surface profiling (ISO 13473-4), and resurfacing techniques.
- Implement corrective actions such as aggregate resurfacing, and anti-polishing treatments to sustain optimal roughness.

The limitations of the work in these guidelines are as follows:

- The guideline does not provide specific material compositions for guideway surfaces or tire tread compositions but instead provides performance-based recommendations for the physical characteristics of the tire-guideway interface.
- It does not replace regulatory approvals; compliance with local transport safety laws remains the responsibility of operators.
- The study focuses on friction and wear-related factors, excluding structural load-bearing capacity of guideways.

## 1.3 Objectives and Goals

The IMA Tire-Guideway Surface Interface Working Group aims to develop a structured, performance-driven approach to defining best practices. Short term objectives are:

### Draft Technical Guidelines for Surface Friction and Texture

- Propose establishing baseline friction and surface roughness criteria using ISO 13473-1, ISO 8349, and ASTM E274.
- Propose to conduct pilot studies to compare different guideway materials and validate industry standards.
- Provide information collected from international monorail systems to illustrate common practices and propose best practices based on the collective opinion of the authors.

### Develop Testing and Measurement Protocols

- Propose to utilize ASTM STP 929 and ISO 13473-4 (spectral analysis profiles) to model long-term changes in friction properties.

The IMA Tire-Guideway Surface Interface Working Group sets the following long-term goals:

### Developing a Global Best Practices Framework

- Compile data from international monorail systems to refine best practices for guideway surface treatments.
- Align with ISO 13473-2 (texture classification) and ISO 8349 (friction evaluation) to ensure compatibility with global transit standards.

## Promote Industry Adoption and Continuous Improvement

- Engage with monorail operators, tire manufacturers, and infrastructure developers to facilitate implementation.
- Establish a review and update process, ensuring the guideline evolves based on new research and field data.

### 1.4 Key Terms and Definitions

To ensure consistency and clarity, the following technical terms are defined:

**Friction Coefficient ( $\mu$ ):** A dimensionless value representing the force resisting relative motion between two surfaces. Defined by ASTM E274 and ISO 8349, influenced by micro- and macro-texture.

**Macrotexture:** Large-scale roughness of a surface affecting water drainage and high-speed grip. Defined by ISO 13473-1.

**Microtexture:** Small-scale surface roughness related to adhesion and low speed grip. Defined by ISO 13473-2.

**Indentation Mechanism:** A friction mechanism where the tire deforms around surface irregularities, related to grip.

**Adhesion Mechanism:** The molecular bonding between tire rubber and the guideway surface in dry conditions

**Rolling Resistance:** The energy consumed due to tire deformation while moving over a surface. Measured by ASTM E274 and ISO 8349.

**Skid Resistance:** The ability of a surface to prevent vehicle sliding under braking forces. Measured using ASTM E274 methods.

**Tire Wear Rate:** The rate at which tire tread evolves due to frictional forces, influenced by surface texture, tire tread material composition and operational conditions.

**Polishing Effect:** The reduction of surface roughness over time due to tire abrasion, leading to decreased traction. Note that the system design should take into account this evolution to ensure that friction remains sufficient to ensure the traction requirements of the system through time for the targeted operating conditions i.e. potential max traction may be reduced due to polishing, but the actual traction of the system should remain acceptable if this system has been designed to take into account the effect of polishing on max traction potential for the targeted operating conditions.

**Shot Blasting:** A maintenance technique used to restore surface roughness and increase traction. See note above related in the definition of Polishing Effect.

**Mean Profile Depth (MPD):** A standardized parameter quantifying the macrotexture depth of a pavement surface, calculated from surface profile data. Defined in ISO 13473-1.

**Spectral Analysis (Frequency Domain Analysis):** An outdated method of analyzing pavement texture in terms of wavelength and amplitude used Fast Fourier Transform (FFT), enabling



identification of dominant texture features. Defined in ISO 13473-4. This method is not considered as relevant today in the field, and it is presented for information purposes only.

**Megatexture:** Surface irregularities with wavelengths between 50 mm and 500 mm that affect ride quality. Characterized using ISO 13473-5.

**Texture Wavelength:** The distance between repeating surface profile features, used in categorizing micro-, macro-, and megatexture zones (typically in micrometers to centimeters).

**Profilometer:** An instrument used to record surface profiles of pavements, which can be contact-based (stylus) or non-contact (laser-based). Defined in ISO 13473-3.

**Polishing Resistance:** The ability of a pavement surface to retain its texture and skid resistance under traffic-induced abrasion over time.

## 2 Standards and Existing Guidelines Review

### 2.1 Overview of Related International Standards

**Summary of relevant ISO, EN, and ASTM standards related to tire-pavement interaction, skid resistance, and texture.**

This section will compile all relevant references used throughout this document, including ASTM, ISO, and industry research reports. It will provide a summary of each reference, outlining its relevance to the tire-guideway surface interface guidelines.

- **ASTM E274/E274M-15:** Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire.
- **ASTM E 303:** Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester.
- **ASTM E 965:** Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Patch Technique (Sand Patch Test).
- **ASTM E 1845:** Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.
- **ASTM E 1911:** Standard Test Method for Measuring Surface Frictional Properties Using the Dynamic Friction Tester.
- **ASTM E 2157:** Standard Test Method for Measuring Pavement Macrotexture Using a Circular Track Meter.
- **ASTM E 3145:** Standard Test Method for User-Level Calibration of Dynamic Friction Tester (DF Tester).
- **ASTM STP 929:** The Tire-Pavement Interface
- **AASHTO T 242:** Frictional Properties of Paved Surfaces Using a Full-Scale Tire
- **ISO 13473 Series (1, 3, 4, 5):** Pavement texture characterization and profiling.
- **ISO 11819 Series:** Measurement of traffic noise on different road surfaces.
- **ISO 8349:** Measurement of road surface friction.
- **BS EN 13036-1:** (BSI/CEN) Test methods - Measurement of pavement surface macrotexture depth using a volumetric patch technique.
- **DIN 51130:** (DIN Germany) Slip resistance for floors and floor coverings (inclined plane test for shod feet).
- **DIN 51097:** (DIN Germany) Slip resistance for barefoot areas (inclined plane test for barefoot).
- **UNI EN 14231:** (UNI/CEN (Europe) Determination of slip resistance of natural stone paving.
- **Michelin Research:** Roughness, grip, and wear performance studies.
- **Dr. Zoltan Rado's Studies:** Friction mechanics and braking forces in tire-road interactions.

## SUMMARY

- **ASTM E 274: Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire:** This standard outlines a procedure for measuring the skid resistance of paved surfaces by dragging a locked, full-scale automotive tire over a wetted surface at a constant load and speed, reporting the result as a Skid Number (SN). While the specific test is for roads, the principle of measuring dynamic friction under wet conditions is relevant for monorail wheel-beam interaction, requiring adaptation for monorail-specific contact mechanics.
- **ASTM E 303: Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester:** This test method measures surface frictional properties using a dynamic pendulum impact-type tester, quantifying energy loss when a rubber slider contacts a surface. It is suitable for both laboratory and field tests on flat surfaces and can measure microtexture. This method could be adapted for assessing pedestrian slip resistance on monorail maintenance walkways or for preliminary material characterization of beam surfaces.
- **ASTM E 965: Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Patch Technique (Sand Patch Test):** This is a traditional field method for quantifying pavement macrotexture by spreading a known quantity of sand in a circular pattern and measuring its diameter, which correlates to average texture depth. While simple, its manual nature and limited assessment area make it less ideal for elevated monorail beams compared to non-contact methods.
- **ASTM E 1845: Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth:** This standard defines the procedure for computing Mean Profile Depth (MPD) and Mean Segment Depth (MSD) from macrotexture data, which are indices used to quantify pavement macrotexture. This calculation practice is directly applicable to monorail beam surfaces if profile data is collected using appropriate profilometers.
- **ASTM E 1911: Standard Test Method for Measuring Surface Frictional Properties Using the Dynamic Friction Tester:** This test method covers the procedure for measuring surface frictional properties as a function of speed using a Dynamic Friction Tester (DF Tester). The DF tester uses a spinning disk with spring-loaded rubber sliders to measure torque and calculate friction. This method can be used for laboratory investigations and in-situ surfaces, making it potentially adaptable for controlled friction measurements on monorail beam materials.
- **ASTM E 2157: Standard Test Method for Measuring Pavement Macrotexture Using a Circular Track Meter:** This standard describes the use of a Circular Track Meter (CTM), which employs a laser displacement sensor to non-destructively measure pavement surface macrotexture along a circular path. It provides results that can be used to calculate Mean Profile Depth (MPD). This non-destructive, laser-based method is highly suitable for assessing macrotexture on monorail beam surfaces without direct contact.
- **ASTM E 3145: Standard Test Method for User-Level Calibration of Dynamic Friction Tester (DF Tester):** This standard describes the equipment and procedure for user-level calibration of Dynamic Friction Testers (DF Testers) to ensure uniform and accurate measurements. It covers static calibration of vertical load, friction force, and speed. This standard is crucial for ensuring the reliability and reproducibility of friction measurements obtained using DF Testers, which could be used for monorail beam surface characterization.

- **AASHTO T 242: Frictional Properties of Paved Surfaces Using a Full-Scale Tire:** This standard is a counterpart to ASTM E 274, covering the measurement of frictional properties of paved surfaces using a specified full-scale automotive tire and a locked-wheel tester methodology. Similar to ASTM E 274, its principles are relevant for understanding dynamic friction on monorail beams, but the specific test setup would need adaptation for monorail wheel-beam interfaces.

#### **ASTM E274/E274M-15(2020): Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire – Primary Focus: Vehicular Skid Resistance.**

This is included for reference, as it is not applicable to monorail. This standard establishes a methodology for measuring the skid resistance of paved surfaces using a full-scale tire, under controlled conditions.

##### **Key Aspects:**

- **Test Procedure:**
  - A standardized test tire is mounted on a specialized trailer and runs over the pavement surface.
  - A controlled amount of water is applied to simulate wet conditions.
  - The braking force generated when the tire skids at a specified speed is measured to determine skid resistance.
- **Applications:**
  - Helps assess surface friction levels for transportation safety.
  - Used in pavement maintenance planning and road safety evaluations.
  - Applicable to roads, airports, and other paved surfaces.

##### **Relevance to the IMA Document:**

- Can be adapted for monorail guideway surfaces to measure friction properties of different coatings and textures.
- Provides a benchmark for evaluating surface treatments in terms of tire adhesion and durability.

#### **ASTM STP 929: The Tire-Pavement Interface**

This commonly referred standard is included for reference, however it is not applicable to monorails. This publication compiles technical studies and research papers on the complex interactions between tires and pavement surfaces.

##### **Key Aspects:**

- **Focus Areas:**
  - **Friction & Contact Mechanics** – Analysis of forces at the tire-road interface.
  - **Pavement Surface Characteristics** – Impact of texture, roughness, and materials on traction.
  - **Tire Wear & Performance** – How different surfaces influence tire evolution and efficiency.

- **Experimental & Theoretical Studies** – Results from laboratory and field tests on tire-surface interactions.
- Applications:
  - Used for **transportation infrastructure development** to optimize friction and reduce wear.
  - Provides **guidance on material selection for pavement surfaces** to improve longevity and performance.

#### **Relevance to the IMA Document:**

- Offers technical insights on surface roughness and its effect on monorail tires.
- Supports the selection of optimal materials and surface finishes to balance durability and safety.

#### **ISO STANDARDS**

Incorporating relevant ISO standards into the **IMA Tire-Guideway Surface Interface Guidelines** ensures alignment with internationally recognized practices for evaluating pavement textures and tire-surface interactions.

#### **Key Documents:**

The following ISO standards are pertinent and are referenced in the document:

- **ISO 13473-1:2019 – Characterization of Pavement Texture by Use of Surface Profiles – Part 1: Determination of Mean Profile Depth -Primary Focus: Macrotexture Depth.**

This standard specifies a method for quantifying pavement macrotexture depth by measuring the surface profile and calculating the **Mean Profile Depth** (MPD). It is designed to be insensitive to microtexture or general unevenness and is increasingly favored for non-contact, efficient measurement of in-service road monitoring.<sup>1</sup> For monorail beams, this method could be adapted to provide a consistent metric for surface roughness.

- **ISO 13473-2:2002 – Characterization of Pavement Texture by Use of Surface Profiles – Part 2: Terminology and Basic Requirements Related to Pavement Texture Profile Analysis**

This part defines terms and expressions related to profile representations of texture, which are useful in modeling pavement characteristics such as tire/road noise emission, tire/road friction, tire rolling resistance, and tire wear. It also includes basic requirements for the use of these terms, ensuring consistency in texture profile analysis.

- **ISO 13473-3:2002 – Characterization of Pavement Texture by Use of Surface Profiles – Part 3: Specification and Classification of Profilometers – Primary Focus: Profilometer Specifications.**

This standard sets requirements for profilometers used in pavement engineering to ensure accurate measurements of micro-, macro-, and megatexture. It also classifies profilometers based on their use and accuracy.<sup>5</sup> For elevated monorail beams, non-contact, laser-based profilometers conforming to this standard would be highly advantageous for efficient and safe texture assessment without operational disruption.

- **ISO 13473-4:2024 – Characterization of Pavement Texture by Use of Surface Profiles – Part 4: One Third Octave Band Spectral Analysis of Surface Profiles – Primary Focus: Spectral Analysis of Texture**

This document details methods for performing spectral analysis of pavement surface profiles, specifically spatial frequency analysis of two-dimensional profiles. Its objective is to standardize the spectral characterization of pavement texture across various wavelengths, which is crucial for assessing characteristics like noise.<sup>9</sup> This could be applied to monorail beams to understand texture components influencing noise and vibration.

- **ISO 13473-5:2009 – Characterization of Pavement Texture by Use of Surface Profiles – Part 5: Determination of Megatexture – Primary Focus: Megatexture Measurement**

This updated standard specifies a procedure for determining pavement surface megatexture from measured profiles. It is used for predicting acoustic quality (road noise) and assessing rolling resistance.<sup>13</sup> For monorail systems, this standard could help assess operational noise, system vibration, and energy consumption related to rolling resistance.

- **ISO 11819 Series: Measurement of traffic noise on different road surfaces:**

While not directly a texture measurement standard, this series specifies methods for comparing traffic noise on different road surfaces to evaluate various road surface types. It provides a tool for establishing common practices regarding noise criteria<sup>13</sup>. This series is relevant for considering the acoustic performance of monorail beam surfaces.

- **ISO 8349:2002 – Road Vehicles – Measurement of Road Surface Friction**

This standard presents general test procedures for determining peak- and slide-braking coefficients on actual test surfaces, where the surface conditions are determined and controlled by the user at the time of testing. It aims to harmonize the results of testing on different test tracks, providing standard reference numbers indicating the friction properties of test tracks and road surfaces representative of passenger car tires.

#### **Relevance to the IMA Document:**

By referencing these ISO standards, the guidelines will be grounded in internationally accepted methodologies for assessing and managing the tire-guideway surface interface, ensuring consistency, reliability, and safety across monorail systems globally.

- **BS EN 13036-1: Test methods - Measurement of pavement surface macrotexture depth using a volumetric patch technique:** This British and European standard describes the Volumetric Patch Test (VPT) for determining macrotexture depth, similar to ASTM E 965. It involves spreading a measured volume of material (e.g., glass beads) into a circle and calculating the average depth.<sup>1</sup> While traditional, its limitations (safety, assessment area) make laser-based methods more suitable for monorail beams.
- **DIN 51130: Slip resistance for floors and floor coverings (inclined plane test for shod feet):** This German standard evaluates the anti-slip properties of floors for pedestrian traffic with footwear. It involves an oil-lubricated floor sample on an inclined plane, with surfaces classified from R9 to R13 based on the angle of inclination at which slip occurs. This standard is highly relevant for ensuring pedestrian safety on maintenance walkways or access platforms along monorail beams.

- **DIN 51097: Slip resistance for barefoot areas (inclined plane test for barefoot):** Similar to DIN 51130, this German standard specifically sets parameters for barefoot passage on slip-resistant surfaces, such as those in swimming pools or showers. The test uses water/soap solution, and surfaces are classified from A to C.<sup>34</sup> This is relevant for monorail areas where barefoot pedestrian traffic might occur, though less common.
- **UNI EN 14231:2004: Determination of slip resistance of natural stone paving:** This European regulation defines the level of slip-resistance and friction for natural stone paving using a tilting test, often with a pendulum coefficient friction tester, for both dry and wet conditions.<sup>34</sup> This standard is applicable if natural stone is used in any pedestrian areas associated with monorail infrastructure.

### Monorail-Specific Operational and Material Insights

This section covers general concepts and specific considerations for monorail systems, including material properties, operational principles, and braking.

Category	Primary Focus
Monorail System Types and Operational Principles	Comparison of Rubber-Tired vs. Steel-Wheel Monorails
Monorail Beam Material Properties and Frictional Characteristics	Influence of Concrete and Steel Beam Materials on Friction
Monorail Guideway Friction Requirements (General)	General requirements for low-friction linear guideways and patented tracks
Monorail Braking Performance Standards	ISO 20138 for railway braking performance

### Synopsis of Monorail-Specific Operational and Material Insights:

- **Monorail System Types and Operational Principles (Rubber-Tired vs. Steel-Wheel):** Monorails primarily use rubber tires on concrete/steel or steel wheels on steel beams. Rubber-tired systems offer higher friction (e.g., rubber on dry concrete 0.6-1.0 static, 0.45-0.75 kinetic wet; rubber on steel kinetic 0.64) for better acceleration, shorter braking distances, and steeper climbing, but have higher energy consumption and tire replacement costs. Steel-wheel systems have lower friction (e.g., steel on dry steel 0.6-0.8 static, 0.4-0.5 kinetic; wet/lubricated 0.05-0.1) for high energy efficiency but poorer acceleration and longer braking distances. Understanding these differences is critical for designing appropriate beam surface properties.
- **Monorail Beam Material Properties and Frictional Characteristics:** The choice of beam material significantly impacts friction. Concrete beams for rubber-tired monorails can be engineered for enhanced friction and wear resistance, for example, by incorporating steel slag.
- **Monorail Guideway Friction Requirements (General):** Linear guideways, including those used in monorails, are designed for low-friction, precise longitudinal movement, absorbing forces from all directions. The coefficient of friction for linear guideways can be as low as 1/50th of traditional contact, enabling power savings. These insights highlight the importance of precise engineering for low friction and durability in monorail guideways.

- **Monorail Braking Performance Standards (ISO 20138):** ISO 20138 provides detailed guidelines for train braking performance, considering factors like speed, weight, brake type, and track conditions. It helps calculate braking force, optimize energy use (including regenerative braking), and prevent wheel lock-ups, ensuring trains stop accurately and predictably. While not specific to monorails, its principles for precise, predictable, and safe braking are directly transferable and crucial for monorail operational safety.

## 2.2 Analysis of Existing Practices in Monorail Systems

Existing practices in Monorail systems study tire-guideway interactions during three main activities:

- Tire offer design and evolution
- Network feasibility study
- Tire mileage limit review

### **Tire offer design and evolution:**

When a new tire offer is conceptualized or when an existing offer is modified the process to follow involves the following steps:

- Specifications are defined based on tire and vehicle manufacturer requirements;
- Tire design is defined based on reference model history, design knowledge and risk analysis;
- Based on the specifications, the tire design and the associated risk analysis, a validation plan is defined, which may include simulation, laboratory characterization and measurement, and tire and on-vehicle testing;
- Performance is evaluated versus specification and risk analysis to determine the suitability of the design for the application;
- If the design is considered suitable versus specifications and risk analysis without an additional design loop, the tire offer can be qualified for the concerned application: the tire offer is qualified, an initial tire mileage limit is set and a tire mileage review process is defined.

### **Network feasibility study:**

When conception of a new network or line is initiated the process to follow involves the following steps:

- Usage specifications are shared with the tire manufacturer;
- The tire manufacturer conducts a feasibility study to determine safety conformity;
- If conclusive, feasibility is validated; an initial tire mileage limit is set and a tire mileage review process is defined.

### **Tire mileage limit review:**

During the course of network operations, the tire manufacturer may review and redefine under their responsibility the initial tire mileage limit, depending on observed performance levels of the tires in operation, usage conditions, testing of sampled tires during the course of operation, and an evaluation of the compliance of operational practices to the maintenance rules defined by the manufacturer.

In this case, the process to follow is:

- Dismounted used tires are tested by the tire manufacturer to determine the residual endurance potential of the tire;
- Network tire reform analysis is conducted to determine the performance of the tire model on the network;
- Tire mileage limit may be redefined by the tire manufacturer upwards or downwards, or maintained at the existing level.

Adherence and wear performances are studied during these three main activities. Usage loads, usage speeds, deceleration requirements, and friction coefficient are important parameters / specifications needed for these studies. Associated tests and characterizations may include:

Adherence:

- Can be performed by tire or vehicle manufacturers at controlled environments or monorail network sites;
- Controlled environments, usually, have a different ground surface, test conditions (ex - load, speed), and ambient conditions (ex - water presence on track, wind speed, temperature) than a monorail guideway. It is important to contextualize the results of the tests;
- Can be performed under driving and braking torque;
- Tests at monorail network sites are the closest representation of true performance. They allow verification of relevant operational parameters such as stopping distance, maximum acceleration / deceleration.

Tire wear:

- A characterization of the tire-guideway contact parameters (tire slip, force, contact patch shape, contact patch forces) may be performed by the tire manufacturer in the laboratory at representative conditions of usage pressure and load;
- This characterization may be carried out on a different surface than the monorail guideway, and as such may not take into account rubber - guideway abrasion as seen during network operation.

## 2.3 Gaps in Current Standards

Identification of areas where existing standards fall short for monorail applications.

Adherence performance:

- Representativity of the diversity of system configurations and hence usage conditions to ensure safe operation in all possible operating conditions (for example: water film depth, deceleration, speed);
- Lack of adjustment of limiting conditions as a function of guideway surface evolution.

Wear performance:

- Correlation between surface characterization and acceptable wear speed due to absence of appropriate methods and equipment for substitutive evaluation of rubber – guideway abrasion, representative of real operating conditions.

## 3 Technical Framework for Tire-Guideway Interaction

### 3.1 Material Selection Guideway Surfaces

The selection of concrete materials for guideway structures in monorail systems must prioritize **long-term durability, abrasion resistance, and environmental resilience**. Drawing from past project experience, the following characteristics are mentioned below. Consult a material specialist to elaborate the appropriate concrete mix for a given climate, location, etc.

#### Concrete Grades and Application Summary (Cubic/cylinder characteristic strength):

- **C50/40 and C55/45 MPa:** Used in **precast guideway beams, deck slabs, and pier caps**, especially where **prestressing is required**. These grades balance high strength with reduced shrinkage and low chloride permeability.
- **C60/50 MPa:** Dedicated to **precast guideway beams and closure pours (joints)** between precast guideway beams, with a focus on durability and thermal control, particularly for elevated structures in high-demand areas.

#### Material and Mix Design Considerations:

- **Aggregate Durability (Abrasion Resistance):**
  - Coarse aggregate must demonstrate a maximum loss of 25% under the Los Angeles Abrasion Test, in accordance with ASTM C131.
  - **European equivalent:** EN 1097-2 (Tests for mechanical and physical properties of aggregates – Part 2: Methods for the determination of resistance to fragmentation) is recommended to verify compliance using the **Micro-Deval or Los Angeles method**.
  - Note that steel slag treated and tested for the presence of unreacted calcium oxide (free lime) and magnesium oxide could be used to increase the resistance to abrasion. When exposed to moisture, these compounds hydrate and expand significantly, sometimes by 10% or more. In a concrete pavement, this expansion is constrained, leading to immense pressure that cracks and pits the concrete. To prevent damage, steel slag must be treated and tested before it can be safely incorporated into a concrete pavement. Quality control procedures are necessary to test for expansion potential. Tests recommended by the Federal Highway Administration (FHWA) can determine if the slag is stable enough for use
- **Cementitious Materials:**
  - Use of **CEM I–III cement types** according to **EN 197-1** and **ES 4756**.
  - Admixtures must comply with **ASTM C494, C1017**, and **EN 934-2** for plasticizers, superplasticizers, and retarders.
- **Performance Requirements:**
  - Maximum **aggregate size: 20–25 mm** depending on the grade.
  - **Water/Cement ratios** range from **0.35 to 0.45**, adjusted for sulfate exposure and strength class.

- **Compressive strength classes** validated at 28 days (per **ES 1658**, **ASTM C39**, or **EN 12390-3**).
- **Shrinkage**: < 0.040% post-assembly for precast elements.
- **Chloride ion permeability**: < 1500 coulombs (per **ASTM C1202** or **EN 12390-8**) to prevent corrosion risk in reinforced and prestressed concrete.
- **Temperature and Environmental Controls:**
  - For mass concrete, control internal heat generation per **ACI 207** and **EN 13670**, especially in precast and pile-supported structures.
- **Abrasion Resistance of Concrete:**
  - For the resistance of the movement of the train, it is necessary to have a good abrasion resistance of concrete, so tests for this parameter could be done, when the composition of mixture is in elaboration. This parameter could be controlled by **ASTM C 1138-97**, or by national standards like the ones established by the Associação Brasileira de Normas Técnicas (ABNT), the Brazilian national standards organization, with standards known as "Normas Brasileiras" (NBR) **ABNT NBR 9781-13**, **ABNT NBR 12042-12**, or according to specifications of the project.

### 3.2 Surface Texture and Friction Parameters

Detailed guidelines for achieving optimal texture and friction balance on guideways.

Tires serve as the connection between the monorail vehicle and the beam, functioning as a transmission element for braking and driving torque. The ability of a tire to grip while moving involves two paradoxes: the contact patch remains motionless relative to the beam at constant speed, yet generates friction through slippage during braking, acceleration, or cornering to prevent skidding.

Each tread block of the tire entering the contact patch first shears and then slips over the beam surface. The higher the wheel slip ratio is, the slip ratio being the difference between the speed of the wheel and the speed of the vehicle, the higher is the length of slippage and the lower is the length of shear.

Two stress mechanisms, indentation due to beam roughness effect and molecular adhesion, influence the relative slippage between elastomer and beam surface, with visco-elastic properties of rubber playing a crucial role in adapting to beam texture and generating reaction forces to counteract slippage:

- Tire grip is generated by the frequency-induced excitation of rubber as it slips over the beam surface. The indentation mechanism operates at a scale of millimeters, where surface indenters deform the rubber elements and, due to the hysteresis of the rubber, provide a reaction force to the deformation, generating grip. The adhesion mechanism operates on the micron scale: the molecular chains of rubber are stretched, and their deformation generates a reaction force due to the viscous properties of the rubber, generating grip. On a dry surface, the friction coefficient between the tire and the beam is commonly between 1 and 1.3.

- On a damp surface, a film of water between the rubber and the beam prevents the molecular adhesion mechanism from working unless this film is broken. However, the micro-roughness of the guideway surface can still locally pierce the film of water to ensure that the indentation mechanism, which is vital to grip, is still operational.

Therefore, the friction coefficient is lower on a wet surface compared to a dry surface and varies enormously with the type of surface, commonly from 0.1 to 0.9, micro-rough surfaces giving the best grip, and macro-roughness playing a secondary role. If the depth of water increases (wet surface), micro-roughness may become flooded. Macro-roughness continues to indent, drain and store, but there is a risk of aquaplaning at high speed.

To guarantee the transmission of acceleration and braking forces coherent with the expected service levels of the system, it is then **essential to maintain a minimum level of micro-roughness** to ensure an adequate Tire-Guideway friction coefficient.

Tire wear is influenced by several factors, upon which the most influential are:

- usage, like acceleration or braking level and frequency distribution of these levels,
- ground roughness characteristics,
- tire construction,
- vehicle characteristics and
- weather conditions.

When a tire flattens on a beam, it develops stress and strain at the interface between the rubber and the beam surface due to its toroidal shape. Moreover, when braking or driving torque is applied, tangential stress builds up from the leading edge to the trailing edge of the contact patch.

It is recognized that rubber wear is influenced by the frictional energy dissipated by these stresses. This frictional energy dissipated at the interface between rubber and beam surface increases when the friction coefficient increases, meaning that rubber wear increases when micro-roughness aggressivity increases.

Macro-roughness can also play an important role in tire wear as it will decrease the effective surface area of the contact patch, increasing the local contact pressure. For instance, the tire wear rate can vary by a factor of 3 from a macro-smooth and micro-smooth ground to a macro-rough and micro-rough ground.

A tire, regardless of its design, must perform a fundamental set of functions, which include:

- supporting load capacity;
- offering cushioning and vibration dampening;
- transmitting driving and braking torque;
- ensuring dimensional stability;
- providing low rolling resistance;
- resisting to wear and abrasion;
- in some cases, delivering cornering force and guiding the vehicle.

The tire must be able to perform these functions, whilst being capable of being produced in an industrially repetitive and economically viable manner.

In summary, the design and characteristics of the interface between the beam surface and tire should take into account:

- the expected operating temperature for the system;
- the expected service and safety levels of the system (acceleration / deceleration in normal and emergency conditions);
- the probability of presence of water, sand and other possible pollutants;
- economic considerations associated with the construction of the guideway surface and the industrial supply of tires over the system lifespan.

Depending on these usage conditions, the interface should be designed in such a way that:

- micro-roughness of the surface is sufficient to ensure grip in all usage conditions and taking account the polishing of the beam surface during the duration of the surface operational life;
- micro-roughness is nevertheless limited to avoid excessive tire wear;
- macro-roughness is sufficient to ensure evacuation and stockage of water, sand and other pollutants, according to the expected usage conditions of the system;
- macro-roughness is nevertheless limited to avoid excessive tire wear and unnecessary energetic losses;
- tread pattern and materials' choice are such that the balance of performance for the system is optimized for the expected usage conditions and economic performance of the system.

Close collaboration during the specification and design phase of a project between vehicle, infrastructure and tire designers is essential to determine the optimum design of the interface considering safety, service levels, operating cost and usage conditions.

### 3.3 Environmental Factors and Impact on Performance

The weather may affect both tire grip and wear performance:

- The **temperature and the wetness** of the surface can change the interaction between the surface roughness and the tread rubber, as explained in section 3.2.
- **Temperature** will also modify the **visco-elastic properties** of the rubber compound, depending on the tread material physical characteristics.
- **Water** interferes with **grip mechanisms** to lower the friction coefficient between tire and the beam surface.

**Sand and particles impact:** the presence of sand or other particles between the tire and guideway can impact on the adherence performance. The probability of their presence should be taken into account during the system and tire design.

## 4 Performance Testing and Evaluation Methods

### 4.1 Surface Texture Measurement Techniques

Macrotexture refers to surface irregularities with wavelengths typically between 0.5 mm and 50 mm, and amplitudes generally ranging from 0.1 mm to 20 mm. It plays a crucial role in wet-weather friction, drainage, and noise generation.

Here's a synopsis of relevant techniques:

#### 1. Circular Track Meter (CTM)

##### Operational Principles:

The Circular Track Meter (CTM), also sometimes referred to as a Circular Texture Meter, is a laser-based device used to non-destructively measure the macrotexture of a surface at a static location. It employs a laser displacement sensor mounted on a rotating arm. This arm moves the sensor in a circle (typically around 284 mm or 35 inches in diameter), collecting a high number of data points (e.g., 1024 samples per revolution). The laser measures the height of the surface, creating a precise profile. This circular profile is then divided into segments (e.g., eight equal segments), and the Mean Profile Depth (MPD) is calculated for each segment. The overall MPD for the test location is typically the average of these segment depths. High-frequency components corresponding to wavelengths less than 2.5 mm are often filtered out to reduce noise.

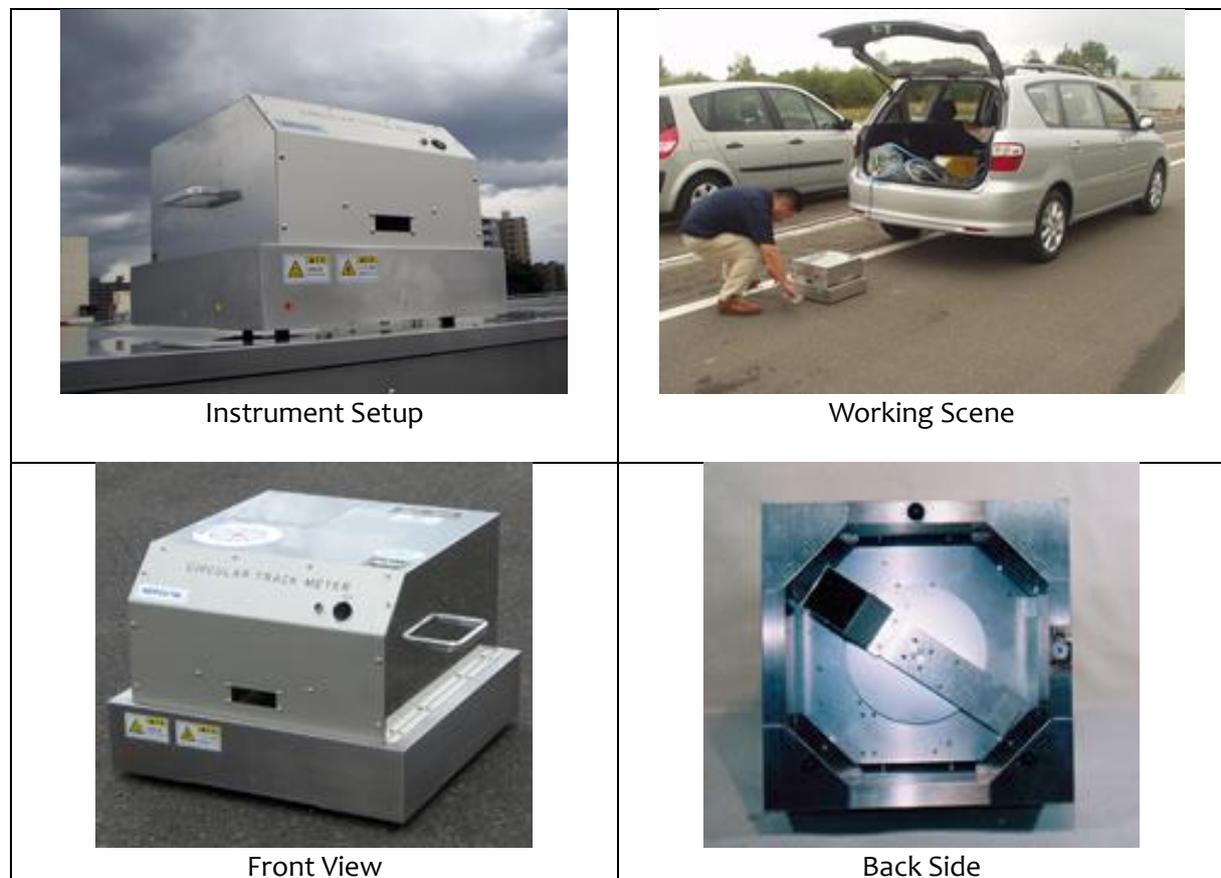


Figure 1 – Circular Test Meter (CTM)  
Source: Nippo Sangyo Co. Ltd

### Relevant Standards:

- **ASTM E2157-15:** Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter.
- **ASTM E1845-15:** Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.
- **ISO 13473-1:** Characterization of pavement texture by use of surface profiles.

## 2. Sand Patch Method

### Operational Principles:

The Sand Patch Method is a volumetric technique used to determine the Mean Texture Depth (MTD) of a surface. A known volume of dry, fine-grained material (typically uniform glass beads or sand) is poured onto a clean, dry surface to form a cone. A spreading disc is then used to carefully spread the material into a circular patch, filling the surface voids until the disc rides on the high points of the surface. The diameter of the resulting circular patch is measured at four different angles (e.g., 45-degree intervals), and the average diameter is calculated. The Mean Texture Depth (MTD) is then calculated by dividing the known volume of the material by the area of the circular patch. The principle is that a smoother surface will require a larger area to spread the same volume of material, resulting in a smaller MTD, and vice-versa.



Figure 2 -Sand Patch Method test on Guide Beams at Line 15 – Silver, São Paulo  
Source: São Paulo Metrô

## Relevant Standards:

- **ASTM E965-15:** Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.
- **EN 13036-1:** Road and airfield surface characteristics - Test methods - Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch method.

## 3. Other Relevant Measurement Techniques

While the CTM and Sand Patch Method are commonly cited for static measurements, other techniques exist, particularly for larger-scale or continuous measurements, which could be adapted for monorail beams:

- **Laser Profilometers (High-Speed/Dynamic):** These systems use rapid-firing laser range finders mounted on a moving vehicle (or, in this case, potentially a specialized inspection vehicle for monorail beams). They capture continuous 3D profiles of the surface. Algorithms then process this data to calculate macrotexture indices like Mean Profile Depth (MPD) or Sensor Measured Texture Depth (SMTD) over user-defined lengths.
  - **Relevant Standards (typically for pavements, but principles are transferable):** ASTM E1845 (for MPD), ISO 13473-1.
- **3D Laser Scanning:** This advanced technique creates highly detailed three-dimensional models of the surface. While more typically used in laboratory settings or for detailed analysis of small sections, 3D laser scanning provides comprehensive texture data from which various macrotexture parameters can be derived. It can capture both positive and negative texture features.
  - **No specific widely adopted ASTM/ISO standard solely for macrotexture from 3D scans, but data can be processed to align with MPD/MTD concepts.**
- **Outflow Meter Test:** This method measures the time it takes for a known volume of water to drain from a specific area of the surface. It provides an indication of the drainage capability, which is directly related to macrotexture. It's often more suitable for surfaces with lower texture depths.
  - **Relevant Standard:** ASTM E2380/E2380M (for pavement surface drainage).

## Necessary Reliability and Accuracy

The CTM generally offers significantly higher reliability and accuracy compared to the Sand Patch Method and other manual or older volumetric techniques due to several key factors:

### 1. Operator Dependence and Subjectivity:

- **Sand Patch Method:** This method is highly susceptible to operator influence. The spreading of the sand, the determination of the patch's edge, and the measurement of its diameter are all manual processes, leading to considerable

variability between operators and even for the same operator on repeated tests. The subjective judgment of when the disc "rides on top of the high points" can vary. This leads to poor repeatability and reproducibility.

- **Other Manual/Volumetric Methods:** Similar issues arise with any method requiring manual spreading or observation of material.

## 2. Accuracy and Precision:

- **CTM:** As a laser-based system, the CTM provides objective, precise digital measurements of the surface profile. It captures thousands of data points within a small area, allowing for a detailed and quantitative assessment of the texture. The vertical resolution of CTMs can be very fine (e.g., 3  $\mu\text{m}$ ), and sample spacing is consistent (e.g., 0.87 mm). This inherent precision leads to highly repeatable and reproducible results.
- **Sand Patch Method:** The reliance on volumetric calculations from a measured diameter introduces potential for error. The assumption that the sand forms a perfect cylinder is a simplification that may not accurately represent the complex geometry of a real surface texture. The reproducibility of the sand patch test has been reported to be as high as 24% to 41% of the mean, whereas the CTM typically has a much lower coefficient of variation (e.g., 2.3% within-lab and 4.2% between-lab for two averaged readings).

## 3. Data Resolution and Detail:

- **CTM:** Provides a detailed profile of the surface, allowing for the calculation of not just MPD but also other parameters like Root Mean Square (RMS) of the profile, which can offer further insights into the texture characteristics. The data can be analyzed in segments, providing localized texture information.
- **Sand Patch Method:** Only provides a single average texture depth value (MTD) for the tested area. It doesn't capture the intricacies of the surface profile or variations within the patch.

## 4. Efficiency and Practicality:

- **CTM:** Tests are quick (often less than a minute) and relatively easy to perform, requiring minimal surface preparation (dry and clean). It's portable and generates data instantly.
- **Sand Patch Method:** While simple in principle and low-cost, it is a slow, manual process. Each test represents only a small area, making it impractical for continuous or large-scale assessment. It often requires stopping traffic or operations if used on active surfaces, which might be a significant concern for monorail beams.



## 5. Environmental Factors:

- **Sand Patch Method:** Requires the surface to be dry and free of debris. Wind can also affect the spreading of the material.
- **CTM:** While also requiring a dry and clean surface, it is generally less susceptible to minor environmental variations compared to the manual spreading of sand.

## 4.2 Surface Friction Measurement Techniques for Monorail Beams

Friction is a critical surface characteristic for monorail beams, influencing the traction of the monorail vehicle, braking performance, and overall safety, especially under varying environmental conditions (e.g., wet, icy). It measures the resistance to motion between two surfaces in contact.

Here's a synopsis of relevant techniques for measuring friction:

### 1. Dynamic Friction Tester (DFT) from Nippo Sangyo

#### Operational Principles:

The Dynamic Friction Tester (DFT) is a portable device designed to measure the dynamic friction coefficient of a surface under wet conditions. It simulates the slip behavior of a tire on a wet surface. The DFT consists of a spinning disc with three rubber sliders (typically specified as Standard Reference Friction Material or SRFM) positioned at a fixed radius. The disc is brought into contact with the test surface while rotating at a controlled speed (e.g., 20-80 km/h peripheral speed). Water is applied to the test surface just before the sliders make contact. As the sliders move over the wet surface, the tangential forces (friction) and vertical forces (load) are continuously measured by sensors. The dynamic friction coefficient is calculated as the ratio of the tangential force to the vertical force. The rotational speed of the rubber sliders are gradually reduced by the frictional forces to zero. The equipment measures the friction coefficient as a function of the speed of the rubber sliders and records it in graphical and tabular formats. The measurements can be used to calculate the International Friction Index (IFI).

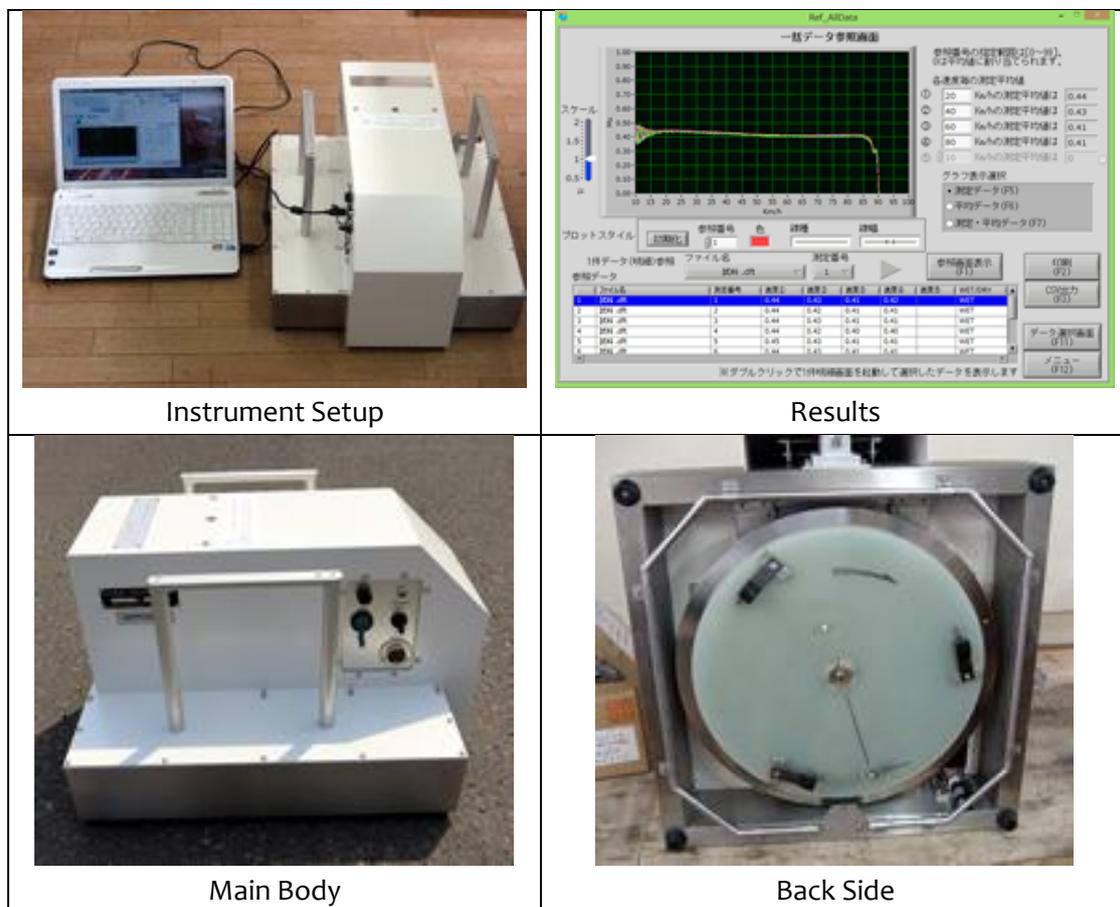


Figure 3 - Dynamic Friction Tester (DFT)  
Source: Nippo Sangyo Co. Ltd

## Relevant Standards:

- **ASTM E1911-19:** Standard Test Method for Measuring Pavement Friction Using the Dynamic Friction Tester (DFT). (Note: While primarily for pavements, the principles and application are directly transferable to other surfaces like monorail beams).
- **ASTM E1960-07:** Standard Practice for Calculating International Friction Index of a Pavement Surface. This standard outlines the methodology for calculating the International Friction Index (IFI), which uses DFT measurements as a key component. The IFI harmonizes friction measurements from different equipment to a common calibrated index, typically expressed by two parameters:
  - **F60:** The calibrated wet friction at a slip speed of 60 km/h.
  - **Sp:** The speed constant of wet pavement friction, which describes how friction changes with speed and is often related to macrotexture measurements (e.g., Mean Profile Depth from a CTM). The DFT, particularly its measurements at specific speeds like 20 km/h, is often considered the standard reference device for calibrating the IFI.

## 2. British Pendulum Tester (BPT)

### Operational Principles:

The British Pendulum Tester is a portable, pendulum-type instrument that measures the "skid resistance" of a surface, often referred to as the British Pendulum Number (BPN). It is a measure of dynamic friction in a specific, standardized low-speed sliding condition. The device consists of a pendulum arm with a spring-loaded rubber slider at its end. When released from a horizontal position, the pendulum swings down, and the rubber slider makes contact with the test surface over a specified length (typically 126 mm). The energy lost due to friction between the slider and the surface causes the pendulum to swing less high on the rebound. The BPN is read directly from a calibrated scale, which indicates the loss of energy. A higher BPN indicates higher skid resistance. The test is typically performed under wet conditions, with water applied to the surface.



Figure 4 - British Pendulum Test on Guide Beams at Line 15 – Silver, São Paulo  
Source: São Paulo Metrô

#### Relevant Standards:

- **ASTM E303-93 (Reapproved 2018):** Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester.
- **EN 13036-4:** Road and airfield surface characteristics - Test methods - Part 4: Method for measurement of slip/skid resistance of a surface - The pendulum test.

#### 3. Other Relevant Friction Testers

- **Continuous Friction Measuring Equipment (CFME) / Friction Trailers:** These are typically tow-behind or self-contained vehicles equipped with a continuously slipping or locked wheel that measures friction as the vehicle moves at speed. They apply a constant vertical load to a test tire (often a ribbed or smooth tire) and measure the braking or cornering forces. Water is sprayed in front of the tire to simulate wet conditions. CFME provides a continuous record of friction over long sections of a surface.
  - **Relevant Standards (typically for pavements, but principles transferable):** ASTM E274 (locked-wheel), ASTM E2340 (side-force coefficient). While usually large for pavements, smaller, specialized versions could be envisioned for monorail inspection.

- **Static/Portable Skid Resistance Testers (beyond BPT):**
  - **Drag Testers:** These devices measure the force required to pull a weighted block with a standard rubber pad across a surface at a very low, constant speed. The coefficient of friction is calculated from the measured force and the known weight. Examples include specialized "sled" type testers. These are more for static or very low-speed friction.
  - **Inclined Plane Testers:** Used primarily in laboratories, these involve placing a material sample on an inclined plane and increasing the angle until a second material (or a slider) begins to slide. The angle at which sliding occurs relates to the static coefficient of friction. Not typically field-applicable for monorail beams.
- **Tribometers (Laboratory-based):** A broad category of instruments used to measure friction, wear, and lubrication in controlled laboratory environments. They come in various configurations (pin-on-disc, block-on-ring, etc.) and can precisely control load, speed, temperature, and environmental conditions. While not field-deployable for monorail beams, they are crucial for material characterization and understanding fundamental friction mechanisms.

### Reliability and Relevancy

The Dynamic Friction Tester (DFT) is generally considered more reliable and provides a more representative measure of real-world friction compared to the British Pendulum Tester (BPT) and many other static or low-speed friction measurement techniques, particularly for applications like monorail beams where dynamic interactions are key. Here's why:

#### 1. Dynamic vs. Static/Low-Speed Measurement:

- **DFT:** Measures dynamic friction at controlled, higher slip speeds (simulating vehicle tire slip). This directly correlates with the friction experienced by a monorail vehicle during operation, braking, or acceleration. The ability to vary the test speed (e.g., 20-80 km/h) allows for the assessment of the friction-speed gradient, which is crucial for understanding friction performance at different operational speeds.
- **BPT:** Measures friction at a very low, instantaneous sliding speed (around 10 km/h at the point of contact, rapidly decreasing). This "low-speed" or "micro-texture" sensitive friction may not accurately represent the friction available at higher monorail operating speeds. Surfaces can exhibit significantly different friction characteristics as speed increases (e.g., "rubber-reversion" or "viscous hydroplaning" effects).
- **Static/Drag Testers:** These measure static or very low-speed kinetic friction, which is often much higher than the dynamic friction at operational speeds. They provide little insight into the actual friction experienced by a moving vehicle.

## 2. Continuous vs. Spot Measurement:

- **DFT:** Provides a continuous profile of friction along a circular path, allowing for the detection of localized variations in friction within the test area. It takes numerous readings during a single test.
- **BPT:** Provides a single, discrete spot measurement. To assess a larger area, multiple individual tests are required, which is time-consuming and still might miss localized low-friction spots between test points.

## 3. Operator Dependence and Reproducibility:

- **BPT:** Highly dependent on the operator's technique, including the correct calibration, release of the pendulum, and precise reading of the scale. Slight variations in these actions can significantly affect the results, leading to lower reproducibility between different operators or even the same operator on different days. Correct preparation of the slider is also critical and can be subjective.
- **DFT:** Being largely automated and instrumented, the DFT reduces operator variability significantly. The measurement process (spin-up, contact, data capture) is controlled by the device, leading to more consistent and reproducible results. Calibration procedures are also more standardized and less prone to manual error.

## 4. Measurement Principle and Data Quality:

- **DFT:** Directly measures tangential and vertical forces using sophisticated sensors, providing a quantitative coefficient of friction. The digital data acquisition allows for precise calculation and analysis.
- **BPT:** Relies on the principle of energy loss, which is then converted to a BPN. While standardized, it's an indirect measure, and the BPN scale is empirically derived. The "frictional heating" of the slider and surface during the brief contact can also influence results.

## 5. Applicability and Realism:

- **DFT:** Offers a more realistic simulation of tire-surface interaction under wet conditions. The controlled slip ratio and water film thickness more closely mimic real-world scenarios.
- **BPT:** While useful for general "skid resistance" and microtexture assessment, its direct correlation to actual vehicle braking or traction at higher speeds is often limited. It's better suited for pedestrian areas or low-speed applications.

## International Friction Index (IFI)

The International Friction Index (IFI), as defined by **ASTM E1960**, is a standardized system for reporting pavement (or in this adapted context, monorail beam) surface friction properties. Its primary goal is to harmonize friction measurements obtained from various devices, allowing for a

common reference scale. This is achieved by accounting for both the surface macrotexture and the friction-speed relationship.

The IFI consists of two parameters:

1. **F60:** The calibrated wet friction at a slip speed of 60 km/h. This parameter represents the friction level of the surface.
2. **Sp:** The speed constant of wet pavement friction. This parameter describes how the wet friction changes with speed, and it is largely influenced by the macrotexture of the surface.

The IFI is typically reported as **IFI(F60, Sp)**.

### Procedure to Calculate IFI (Simplified from ASTM E1960)

The calculation of IFI involves two main measurements: a macrotexture measurement (typically Mean Profile Depth, MPD) and a wet friction measurement (often from a Dynamic Friction Tester, DFT). ASTM E1960 recommends using the Circular Track Meter (CTM) for MPD and the DFT at 20 km/h for the friction measurement as standard reference devices for calibrating the IFI.

Here's a simplified outline of the procedure and the core equations:

#### Step 1: Measure Macrotexture

- Obtain the Mean Profile Depth (MPD) of the surface using a device like the Circular Track Meter (CTM) or a laser profiler.
- **Relevant Standard:** ASTM E1845 (for MPD calculation).

#### Step 2: Calculate the Speed Constant (Sp)

- The speed constant, Sp, is primarily determined from the macrotexture measurement (MPD). The relationship is generally linear.
- Equation for Sp (from ASTM E1960, based on PIARC findings and CTM/MPD):

$$S_p = a + b * MPD$$

Where:

- Sp = Speed constant of wet pavement friction (km/h)
- MPD = Mean Profile Depth (mm)
- a and b are constants specific to the texture-measuring device used to measure MPD. For the CTM, these are established values (e.g., a=14.2 and b=89.7 for MPD in mm).

So, specifically for MPD from a CTM:

$$S_p = 14.2 + 89.7 * MPD$$

### Step 3: Measure Wet Friction at a Specific Speed

- Obtain a wet friction measurement (FRS) at a known slip speed (S) using a friction-measuring device, such as the Dynamic Friction Tester (DFT).
- **Relevant Standard:** ASTM E1911 (for DFT measurements).
- For the DFT, a common reference speed is S=20 km/h, yielding DFT<sub>20</sub>.

### Step 4: Convert Measured Friction to Friction at 60 km/h (FR<sub>60</sub>)

- The measured friction at speed S (FRS) is converted to an estimated friction at 60 km/h (FR<sub>60</sub>) using the calculated Sp. This equation accounts for the speed dependency of friction.
- Equation for FR<sub>60</sub>:

$$FR_{60} = FRS * e^{\frac{S-60}{Sp}}$$

Where:

- FR<sub>60</sub> = Estimated friction at 60 km/h
- FRS = Friction measurement obtained from the specific device at slip speed S
- S = Slip speed of the measurement (km/h)
- Sp = Speed constant calculated in Step 2
- e = Euler's number (the base of the natural logarithm, approximately 2.71828)
- Specific for DFT<sub>20</sub>: If you use DFT measurement at 20 km/h (DFT<sub>20</sub>), then S=20:

$$FR_{60} = DFT_{20} * e^{\frac{20-60}{Sp}}$$

$$FR_{60} = DFT_{20} * e^{\frac{20-60}{Sp}} = DFT_{20} * e^{\frac{-40}{Sp}}$$

### Step 5: Calculate the Calibrated Friction Number (F<sub>60</sub>)

- The estimated FR<sub>60</sub> is then transformed into the calibrated F<sub>60</sub> using a linear regression equation with device-specific constants. These constants are determined through extensive correlation experiments involving various friction devices and reference surfaces.
- Equation for F<sub>60</sub>:

$$F_{60} = A + B * FR_{60}$$

Where:

- F<sub>60</sub> = Calibrated wet friction at 60 km/h
- A and B are constants specific to the friction-measuring device used to obtain FRS.

- For DFT, these constants have been established through international experiments. For example, some sources indicate values like  $A=0.081$  and  $B=0.732$  when using DFT<sub>20</sub> to calculate FR<sub>60</sub>.
- So, combining with the FR<sub>60</sub> from DFT<sub>20</sub>:

$$F_{60} = 0.081 + 0.732 * DFT_{20} * e^{\frac{-40}{S_p}}$$

### Step 6: Report the IFI

- The International Friction Index is then reported as IFI ( $F_{60}$ ,  $S_p$ ).

For some rolling stock manufacturers, the monorail surface assessment purposes, the Frictional constant of the IFI ( $F_{60}$ ) is further modified to represent a ribbed commercial tire frictional behavior on the monorail beam surfaces known as Skid Number at 65 kmph, SN<sub>65</sub>:

### Step 7: Report SN<sub>65</sub>

$$SN_{65} = \frac{F_{60} + 0.023 - 0.098 \cdot MPD}{0.607 \cdot e^{\frac{65-60}{S_p}}}$$

### Summary of Core Equations (using CTM MPD and DFT<sub>20</sub> as standard inputs):

#### Key Points about IFI:

- **Harmonization:** The IFI allows for a common language for friction properties, enabling comparison of data from different measurement devices and locations worldwide.
- **Speed Dependency:** By incorporating  $S_p$ , the IFI provides insight into how friction changes with speed, which is crucial for safety analysis, especially at higher operating speeds.
- **Macrotexture and Microtexture:** The IFI implicitly acknowledges that friction is a function of both macrotexture (influencing  $S_p$ ) and microtexture (influencing  $F_{60}$ ).
- **Reference Devices:** The DFT and CTM are often considered the "gold standard" reference devices for establishing the A, B, a, and b coefficients for other friction and texture measurement equipment. Other devices can be calibrated to provide IFI values.
- **Limitations:** ASTM E1960-07 typically specifies the valid range for MPD (e.g., 0.15 to 1.5 mm) and friction values for which the IFI model is validated. It might not be as appropriate for very smooth or extremely rough surfaces beyond these ranges without further validation.

As an example of acceptable values, we offer two samples below by Alstom and Hitachi, however, values might vary based on project and rolling stock requirements:

Alstom recommended

MPD between 0.6 and 0.8	ACCEPTABLE
DFT20 between 0.45 and 0.55	ACCEPTABLE
SN65 between 0.35 and 0.43	ACCEPTABLE

Hitachi in Line 3 of Panamá recommended:

Coefficient of Friction:	$0.3 \leq CF$
Rugosity:	250 $\mu$ m

## 5 Maintenance and Inspection Guidelines

### 5.1 Routine Maintenance Practice

Guidelines for regular inspection and maintenance of guideway surfaces to ensure consistent performance.

Along the life cycle of the structure of the guideway line, the surface that was predicted at the project will lose the rugosity by continuous friction of the train tires. The project will assess the probable durability of the beam surface roughness.

The durability along a guideway beam can be different from place to place due to concrete mix and texture type, presence of repairs, precast concrete vs. cast-in-situ, even weather conditions.

The guideway routine maintenance needs to be provided by the Operation Manual, with a specific chapter related to the inspection of the guideway surface, with acceptance criteria.

The guideway surface inspection routine requires different solutions, depending on the condition of the monorail line and the presence or absence of maintenance walkways next to the guideway beams.

In monorail lines that have maintenance walkways, the inspection can be made by employees walking along the extension of the line, verifying the condition of the surface of the guideway.

Another way to perform inspections is to use equipment like the MIV (Maintenance and Inspection Vehicle), lifting platforms, or drones.

Environmental conditions are important to be considered while doing visual inspections, some inspections can only be made at night, hence they require good lighting equipment. Also, it's important that the inspections take place without rain, since dry surfaces are easier to see and assess.

To do the visual inspection, there is a need to have a reference surface to compare. This reference surface can be a photo or a piece of concrete surface that can be carried along the inspection.

When the inspector finds some location that do not conform, there is a need to register the location and perform a local test to verify the conditions, using equipment, like the sand patch, British Pendulum, of friction testing equipment and circular track meter described earlier.

Possible issues on concrete surfaces include cracks, breakages, and early wear. On the steel guideway or particularly at finger plates a, problems may involve peeling of the protective layer, rust, and loosened bolts.

#### Tire pressure maintenance

Tire pressure should be set and maintained using nitrogen gas during service life according to the manufacturer's recommendations for the system. Monitoring of tire pressure should be carried out using homologated equipment & methods to ensure appropriate detection of anomalies versus the manufacturer's recommendations. Inflation pressure maintenance should be carried out using equipment and according to the safety recommendations prescribed by the manufacturer.

### Regular inspection of tires

Tires in service must be inspected at regular intervals defined by the manufacturer, typically between 15,000 km and 30,000 km  $\pm$ 2,000 km, depending on system type and usage.

These inspections aim to confirm compliance with the manufacturer's mileage limits and to identify any maintenance indicators – such as deformation, tearing, separation, splitting, or cuts – in line with the manufacturer's maintenance manual.

Based on the assessment, appropriate measures should be taken, including either continued use or removal of the tire.

## 5.2 Repair and Replacement Protocols

Procedures for repairing or replacing worn tires and guideway surfaces.

### Guideway surfaces

According to the possibility and necessity of re-establishing the roughness conditions of the surface of guideway, some different solutions can be applied:

- Intervention using groove;
- Intervention to replace or add material on the guideway surface;

The **intervention using groove** is a solution that probably will change the characteristics of the surface roughness, and the new type of surface needs to be verified with the project and the interaction of the train tires to approve the surface. It's important to verify the loss of concrete coverage thickness to the structure steel, because of the reduction of the durability of the structure. If the groove intervention affects this parameter, another solution needs to be evaluated.

The **intervention to replace or add new material to the guideway surface**, the first thing that will need to be considered regarding the process of repairing the guideway surface is a material requirement from the project, with some tests before the application on the guideway line. These tests will homologate the material to the monorail guideway line condition, with long and thin concrete beams that are submitted to dynamic efforts from the train operation. One of the most important parameters that will need to be verified is the adhesion of the new material to the substrate. It's recommended to have a prototype of the guideway to make the tests, with the same or at least as close as possible the original material of the guideway.

It recommended the repair material meets the requirements of EN 1504 standard, in Class 4.

The total time available to do the repairing process needs to be considered, once time that the resistance of the material needs to be the minimum to allow the passage of trains in low ages, if the repair will be made at night access.

The procedure of the repair needs to have at least these chapters:

- Demolition of the old surface (if the surface will be replaced);
- Preparation of the substrate;
- Materials and methods to do the new surface;
- Control quality requirements;
- Cure cares;

- Inspection of the repair;
- Security and environmental aspects at the work;

While the surface finish is being executed, the leveling of the repair must be monitored to ensure compliance with the project's defined tolerances. This verification must occur before the repair is finalized. Any section that does not meet the specified tolerances must be reconstructed to achieve conformity.

For the metallic surface and/or components, the materials that will be applied also need to conform with the required roughness parameters.

Proposed remediation measures may involve the application of a new coating, replacement of components (e.g., finger plates), or the implementation of galvanization or other approved surface treatments. Regardless of the selected solution, quality control measures must be implemented to verify treatment thickness, product specification, adhesion performance, and durability in accordance with project requirements.

### Tires

No matter how well any tire is constructed, punctures, impact damage, improper inflation, improper maintenance, or service factors may cause tire failure creating a risk of property damage and serious or fatal injury. It is recommended that the system operator provides a program to train all employees who service wheels in the hazards involved in servicing those wheels and the safety procedures to be followed. The operator should ensure that no employee services any wheel unless the employee has been trained and instructed in correct procedures for servicing the type of wheel being serviced and should establish safe operating procedures for such service. The tire manufacturer can support to define and provide appropriate training related to their tires.

Following the inspection protocol defined by the tire manufacturer, tires should be removed from the vehicle when the first of any of the following conditions is met:

- When the tire reaches the limit of its service life **in terms of mileage or age** as defined by the manufacturer, irrespective of the remaining tread depth available or the general appearance of the tire.
- When the tire presents a type of maintenance criteria identified in the manufacturer's maintenance guide for which the manufacturer has classified the maintenance criteria as requiring a decision to remove the tire from service.
- An operator has a doubt concerning the decision to take and asks the manufacturer for advice. In this case, the manufacturer may request the removal of the mounted assembly for further inspection by the manufacturer's technicians as a precaution. Following this further inspection, the manufacturer may recommend that the mounted assembly be placed in service again, or request that the tire be scrapped depending on the identified maintenance criteria.

The design of the bead of metro tires is reinforced to manage the high pressure and loading conditions that metro tires encounter during service. This reinforcement leads to the bead zone undergoing high levels of stress and deformation during the mounting and dismounting process, requiring these processes to be carried out by personnel qualified by the manufacturer, according to protocols and using equipment recommended by the manufacturer. Even in these conditions,

the bead zone may suffer damage during the demounting process, either externally visible (cuts / aggression of the rubber) or invisible (initiation of separation within the bead structure). For this reason, **metro tires should not be remounted after partial or full dismounting**, due to the safety risk of service operation with damaged beads related to dismounting, and the risk of loss of mileage traceability (essential for managing the respect of the tire service life limits defined by the manufacturer).

The performance of a metro tire depends on the balance between the tire architecture (including the tread pattern), the properties of its components and the cohesion of the interfaces between the different parts of the tire. Given the severity of the solicitations that a metro tire encounters during service (high load, high pressure, high acceleration and deceleration) and mounting / dismounting, **metro tires should not be repaired nor retreaded**, as these operations will alter the performance balance of the original tire design in such a way as to no longer satisfy safe performance in the operating conditions of the system.

In many cases, the useable service life of a metro tire is defined by the fatigue resistance of the tire structure, rather than the wear of the tread. The tread pattern and groove depth are designed to provide optimum adherence, energy efficiency and longevity performance over the service life of the tire structure. For these reasons, metro tires are not designed to be regrooved and should not be regrooved, as this would expose the tire structure to risks of damage and possible safety issues, expose the casing to mileages over the designed maximum operating mileage limit of the tire, and lose traceability of mileage (essential for managing the respect of the tire service life limits defined by the manufacturer). As such, **metro tires should not be regrooved**.

In all cases, the tire manufacturer's prescriptions should be referred to and adhered to.

### 5.3 Documentation and Record-Keeping

Requirements for maintaining records of maintenance activities, inspections, and replacements.

#### Guideway surfaces

The routine of inspection of the guideway line needs to be recorded, to have a material of consulting for verifying the history of some part of the guideway, all the interventions that region suffered, and the evolution of the parameters of roughness. With this record, it will be possible to start map the regions of the guideway that will need some intervention first, and a maintenance program can be elaborated with this information.

The maintenance team can create a digital data sheet with all the inspections, or an application to put this information and share it with all staff. Some of data of inspection activities that could be created are the data and time of inspection, the stretch of the guideway that was verified, the Wheeler conditions, tools and equipment's used, if there are some pathological manifestations and, which is, eventual emergency intervention, the tests that was made.

When some repairs are made, all the weather conditions need to be registered like the temperature, wind conditions, humidity. The information of the repair product like the batch, name, expiration date, and all the tests fixed at the procedure will be registered.

The verifications of the attendance of level tolerances and the roughness of the surface will be recorded.

### Tires

Records of tire maintenance activities should be kept for all tires in service, to ensure traceability and allow for performance analysis.

The following parameters should be recorded at every inspection:

- Tire, train and mounting position identification;
- Fitment date, maintenance inspection date, removal date;
- Mileage and tread depth;
- Observed maintenance criteria (classification & severity, according to the manufacturers' maintenance guide).

## 6 Safety and Risk Assessment

### 6.1 Safety Standards for Tire-Guideway Systems

Although it is a basic interface between the rolling stock and the track, there are no specific regulations focusing on the interface between the tire and the guideway in monorails, others than those specified by the Rolling Stock manufacturers. The following functional factors are usually covered for the application of monorails, but are not limited to these:

- I. **Adequate Adhesion and Friction between Load and Guide Tires of the Rolling Stock and the Guideway.** The lack of adhesion and friction between the load and guide tires of the rolling stock and the guideway can, in more severe cases, violate the safe braking distance of the rolling stock and increase the risk of accidents. We can highlight, but not limit, the following:
  - a. **Consideration of Climatic Conditions:** For example, precipitation, which is the loss of adhesion between the tire and guideway due to rain, can cause tire slippage during deceleration.
  - b. **Integrity of the Guideway Surface:** The integrity of the guideway surface is crucial to maintain adequate tire adhesion. Irregular or damaged surfaces on the guideway can compromise tire adhesion.
  
- II. **Wear and Durability of Rolling Stock Load and Guide Tires.** Excessive adhesion and friction between the rolling stock load and guide tires and the guideway can, in more severe cases, cause tire rupture and loss of rolling stability, compromising the operational safety of the monorail. We can highlight, but not limit, the following:
  - a. **Excessive Heat and/or Pressure:** Excessive heat and/or pressure on the tires can cause excessive wear or even tire rupture.
  - b. **Inadequate Monitoring and Maintenance:** Inadequate monitoring and maintenance of the tires can cause excessive, irregular wear or even tire rupture.
  
- III. **Contact Pressure of Rolling Stock Load and Guide Tires with Guideway Elements** It is important to maintain a controlled and uniform pressure on the rolling stock load and guide tires when moving over the guideway. Rapid oscillations in tire profiling on the guideway can cause premature and irregular tire wear and, in more severe cases, tire rupture and loss of rolling stability, compromising the operational safety of the monorail. We can highlight, but not limit, the following:
  - a. **Misalignment between Guideway Surfaces and Finger Plates**
  - b. **Misalignment between precast beams and cast-in-place sections**
  - c. **Misalignment between Guideway beams and Structural Beam of the Switch Apparatus**

## 6.2 Risk Analysis and Mitigation

Preliminary risk analysis in the project and necessary mitigation actions are essential to ensure the final safety and efficiency of the interfaces between the tires and the guideway. The following points should be highlighted, but not limited to:

- I. **Materials and Design.** The determination of loads and dynamics of the rolling stock over the constructive boundary limitations of the guideway should be taken into account in the selection of materials and design of the tires for the monorail. The following should be considered, but not limited to:
  - a. Selection of Tires with Adequate Lifecycle: Tires should offer good operational cost-benefit, considering durability and wear resistance.
  - b. Development of Tires: Tires should meet the adverse climatic conditions of the monorail, ensuring adhesion and safety in different environments.
  
- II. **Regular Maintenance.** Adequate system maintenance is fundamental to identify and correct problems before they become failures. The main components evaluated between the tire and guideway interface during maintenance are:
  - a. Tire Monitoring: Verification of tire pressure and external condition during maintenance to ensure adequate conformity. Worn or damaged tires can compromise availability and, in the worst case, operational safety. The inspection should include checking for irregular wear, cuts, cracks, and adequate pressure.
  - b. Guideway Surface Inspection and Maintenance: Maintenance of the guideway surface aims to avoid irregularities that could compromise the tire-guideway interface. Irregular or damaged surfaces on the guideway can compromise tire adhesion and, in the worst case, cause tire failures.
  
- III. **Continuous Monitoring.** Keeping the rolling stock continuously monitored during monorail operation is essential to ensure adequate mitigation actions for the system and its regular and safe operation with passengers. The following should be highlighted, but not limited to:
  - a. Implementation of Sensors on Tires: Sensors to monitor usage conditions such as temperature and pressure in real-time allow quick actions on the system in case of failures and also contribute to preventive actions on the system.
  - b. Operator Training: Operators should be trained and qualified for quick action if detection systems observe component failures that could compromise commercial operation. This monitoring depends on the contracted system, where the most common are performed by the operational control center in case of driverless operation or by drivers located on the trains in case of driven operation.

## 6.3 Compliance with Regulatory Standards

### I. Safety Standards

- a. EN 50126: Standards to ensure the safety and reliability of transport systems, including the tire-guideway interface. Compliance with safety standards is essential to ensure safe and efficient operation.
- b. ISO 9001: Quality certification for tire and guideway maintenance and manufacturing processes. Quality certification helps ensure that processes are carried out according to high standards.

### II. Operational Procedures

- a. Operator Training: Certification and continuous training to ensure operators are prepared to deal with adverse conditions. Well-trained operators are essential for the safe operation of the system. Training should include emergency simulations and regular updates on safety procedures.
- b. Emergency Procedures: Detailed plans for quick response in case of failures in the tire-guideway interface. Well-defined emergency procedures help minimize the impacts of failures and accidents. This includes creating quick response protocols and conducting emergency drills.

### III. Maintenance Procedures

- a. Maintenance Team Training: Periodic verification of tire and guideway conditions to ensure compliance with safety standards. Regular inspections are essential to identify and correct problems before they become dangerous. It is crucial that staff involved in these activities have knowledge of the system and its particularities to prevent failures.
- b. Preventive and Predictive Maintenance: Implementation of preventive and predictive maintenance programs to avoid failures and prolong the life of components. Preventive and predictive maintenance helps ensure continuous and safe operation of the system.

## 7 Sustainability and Environmental Considerations

### 7.1 Sustainable Material Options

Reference 5 refers to an article outlining the state of the art on sustainable concrete. It presents a detailed current exploration of strategies and industry advancements focused on reducing the environmental footprint of concrete production, particularly in relation to carbon dioxide (CO<sub>2</sub>) emissions. As concrete is a major contributor to global CO<sub>2</sub> emissions due to the production of Portland cement, the authors outline the urgent need for sustainable practices in construction.

To minimize CO<sub>2</sub> emissions, the article emphasizes multiple approaches. One of the foremost strategies involves the reduction of Portland cement content in concrete mixes. Portland cement is identified as the largest source of CO<sub>2</sub> in concrete production, and its substitution with supplementary cementitious materials (SCMs) such as fly ash, slag cement, and silica fume significantly lowers emissions. These SCMs not only reduce the reliance on traditional cement but also enhance certain performance characteristics of concrete.

Another method involves optimizing concrete mix designs to use the least amount of cementitious material necessary to achieve the required strength and durability. This performance-based approach prioritizes efficiency and functionality over prescriptive standards, allowing for innovative use of materials and proportioning.

The use of carbon capture and utilization technologies is also discussed. These emerging technologies capture CO<sub>2</sub> either during the cement production process or through curing methods that incorporate CO<sub>2</sub> into the concrete itself, effectively sequestering it.

Additionally, the authors note that greater sustainability can be achieved by sourcing materials locally to reduce transportation-related emissions, extending the service life of concrete structures to delay replacement and demolition, and recycling concrete materials. The concrete industry's adoption of environmental product declarations (EPDs) and life cycle assessment tools also helps quantify and reduce environmental impacts in a measurable, transparent way.

Overall, the article provides a comprehensive look at how material choices, technological innovation, and lifecycle thinking contribute to more sustainable concrete construction, all while maintaining safety, performance, and structural integrity.

## 8 References and Resources

### 8.1 Bibliography of Standards and Guidelines

Comprehensive list of all referenced standards, guidelines, and publications.

- **ASTM E274/E274M-15:** Skid resistance testing methodologies.
- **ASTM STP 929:** Tire-pavement interface studies.
- **ISO 13473 Series:** Pavement texture characterization and profiling.
- **ISO 8349** – Measurement of road surface friction.
- **Structural Engineering Institute (SEI)-Structure Magazine, December 24, Navigating Sustainable Concrete**
- **ASTM C 1138-97:** Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)
- **ASTM E1911-22:** Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester
- **ASTM E1960-07 (2023):** Standard Practice for Calculating International Friction Index of a Pavement Surface
- **ASTM E2157-09 (2021):** Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter
- **ASTM E965-15:** Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique
- **ASTM E303-22:** Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester
- **EN 1504-1 (2005):** Products and systems for the protection and repair of concrete structures. Definitions, requirements, quality control and evaluation of conformity Definitions
- **EN 1504-4 (2004):** Products and systems for the protection and repair of concrete structures. Definitions, requirements, quality control and evaluation of conformity Structural bonding
- **EN 50156:** Electrical equipment for furnaces and ancillary equipment - Requirements for application design and installation.
- **ISO 9001:** Quality management systems - Requirements for establishing, implementing, maintaining, and improving a quality management system.

### 8.2 Areas Warranting Further Studies

- 1) Mechanical Methods to provide concrete riding surface reliably consistently.
- 2) Types of steel surface texturing to improve performance of riding surfaces

## 9 Appendices

Four documents are presented and they complement each other:

- Use Dr. Rado (9.1) for theoretical basis and safety impact of friction.
- Use Eric Berger (9.2) for theoretical basis and safety impacts of friction.
- Use Innova Surface Finishes (9.3) for benchmarking texture solutions across global projects.
- Use Japan Surface Practices (9.4) to validate long-term surface behavior in high-use systems.

### 9.1 Friction of a Rolling Tire v2, by Dr. Z. Rado

#### Summary:

This technical presentation outlines the science of tire-road friction with a focus on **vehicle braking dynamics, surface texture, and environmental influence**. Dr. Rado defines friction as a **process involving tire structure, braking hardware, road texture (micro and macro), and environmental factors**. He compares conventional braking with ABS systems and highlights the impact of **friction coefficient ( $\mu$ ) on stopping distances**.

Key insights include:

- Friction potential is dictated by **tire-surface interaction** and **vehicle speed**.
- A **decrease in  $\mu$  by just 0.1** can increase stopping distance by 51.8m (171 ft) at high speed.
- Emphasis on the importance of **macrotexture** (hysteresis) and **microtexture** (adhesion) for achieving optimal grip.
- Provides baseline equations and comparative friction curves (e.g., PIARC) for engineering applications.

#### Relevance:

This document provides **critical background** for defining acceptable surface roughness and friction properties for monorail guideway surfaces and validates the need for tight control of surface texture during finishing.

# Subjects for understanding Friction

## ➤ Tire



- Design
- Material
- Pressure
- Carcass ... etc.

## ➤ Road

- Material
- Construction
- Geometry
- Surface ... etc.

## ➤ Environment

- Weather
- Speed of vehicle
- Maneuver ... etc.

1

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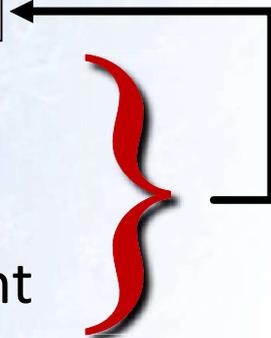
# Friction is a PROCESS

## ➤ Areas of interest



- Brake
- Tire
- Surface
- Environment

User

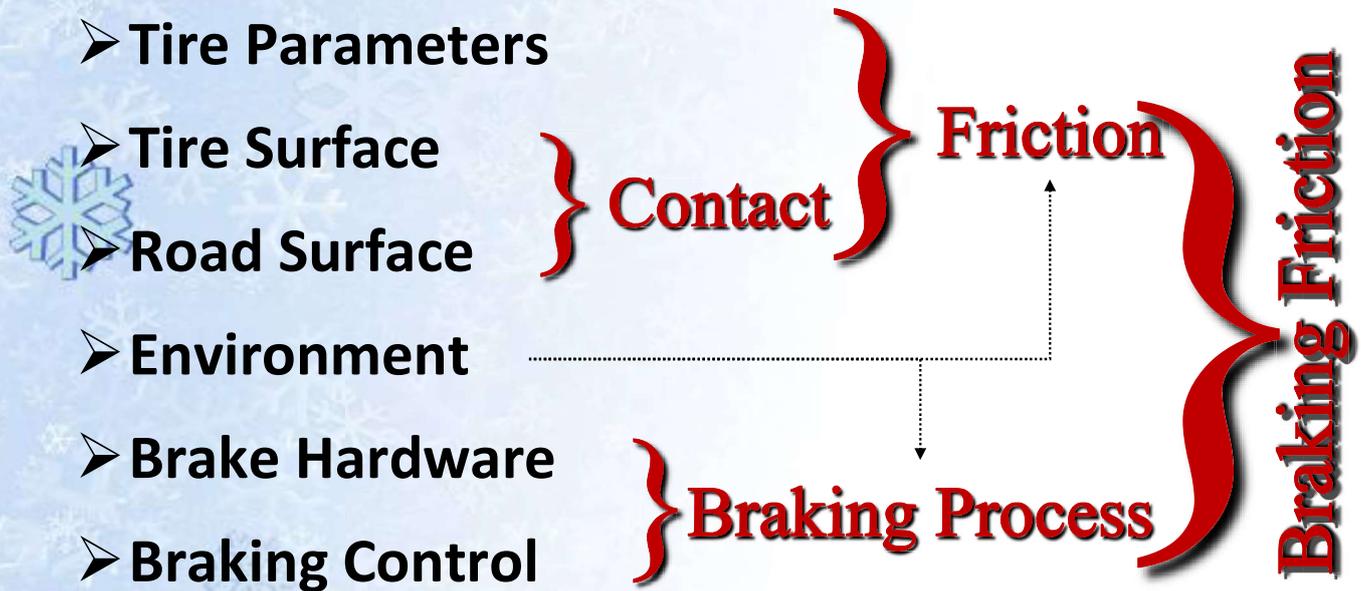


**The generation of frictional forces is a PROCESS**

2

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## Understanding the process

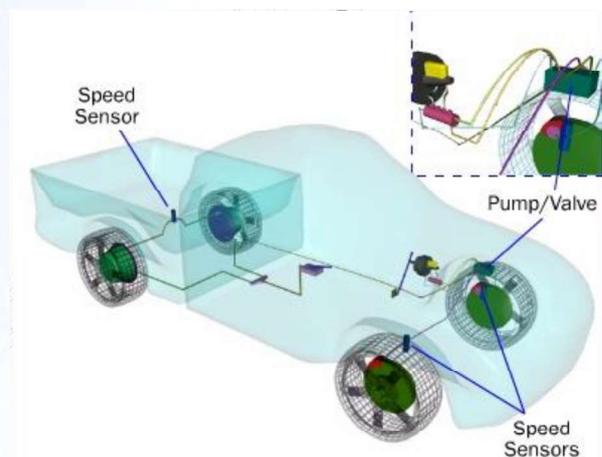


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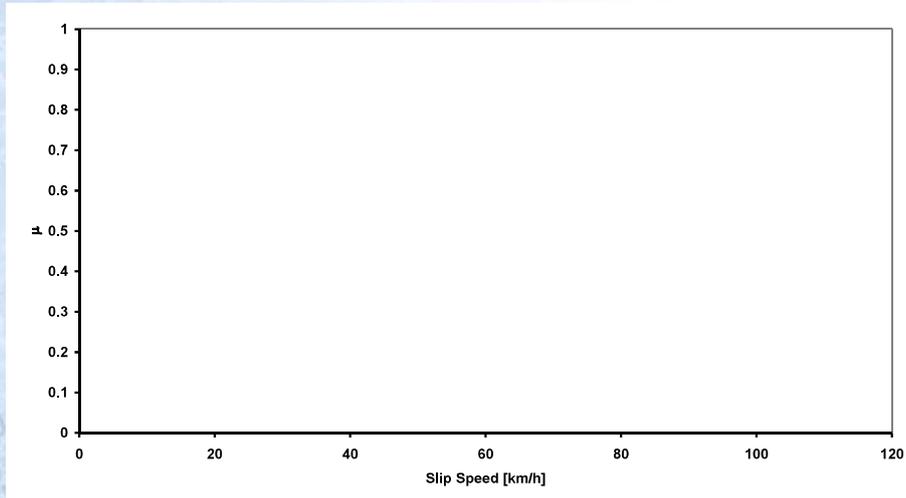
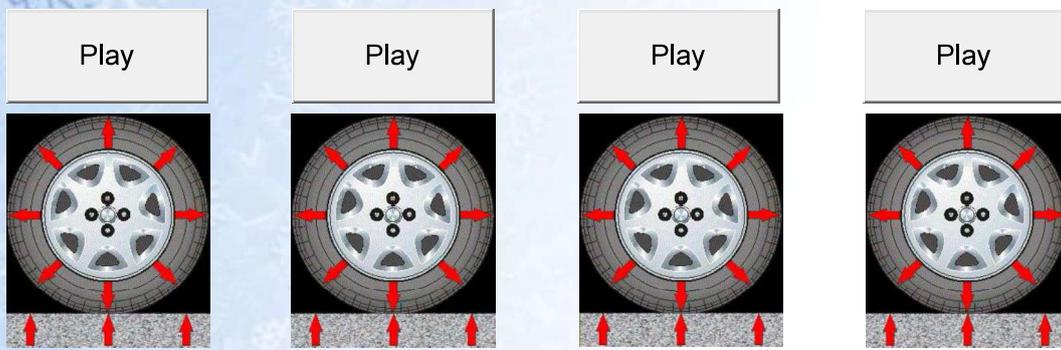
## Vehicle Braking and Friction

- Friction → Potential
  - Available friction determined by Tire-Surface-Environment
- Vehicle-Brake-Control
  - Utilizes AVAILABLE friction
- ABS
  - 1959
  - Does NOT necessarily improve safety



4

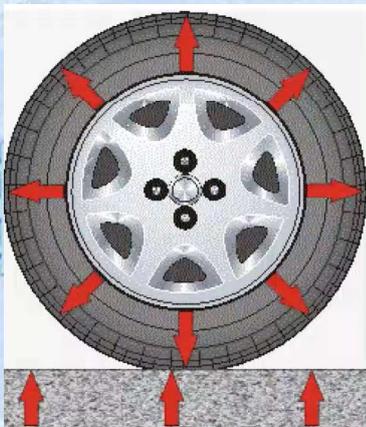
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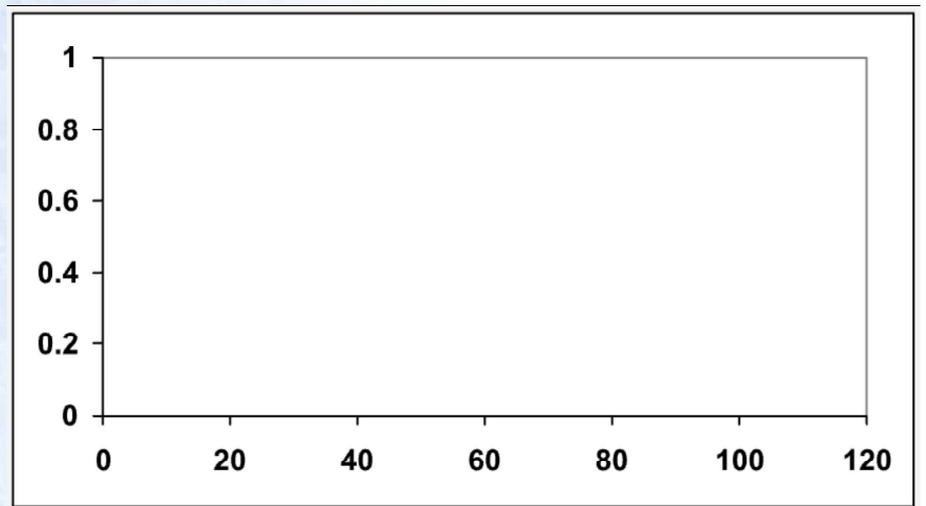
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## Conventional Braking



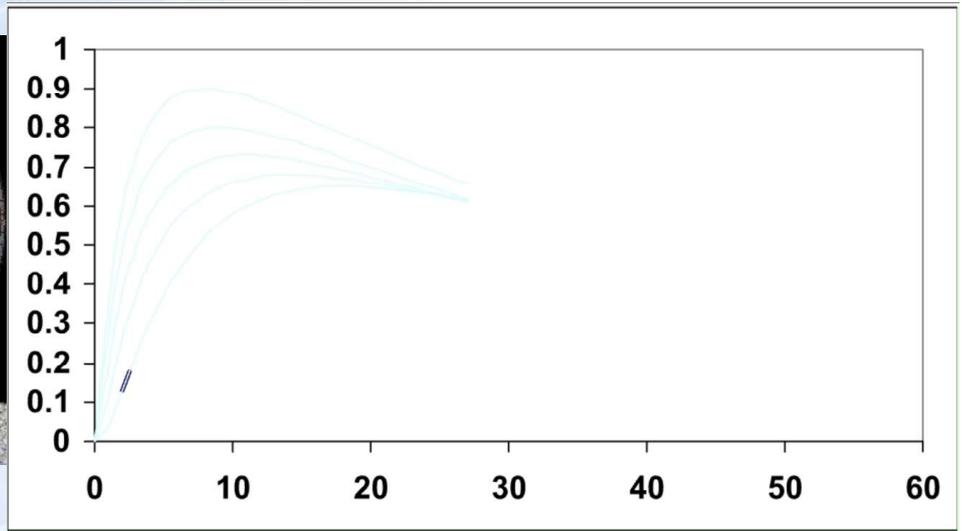
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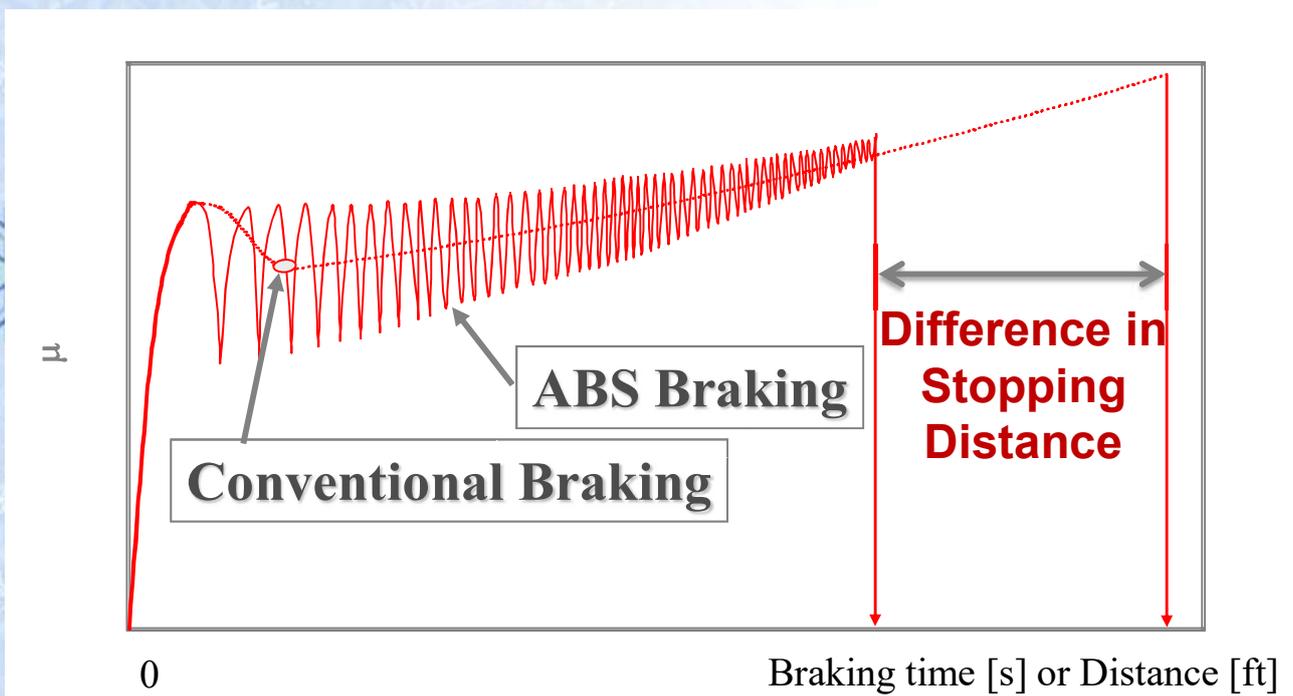
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# Braking with ABS

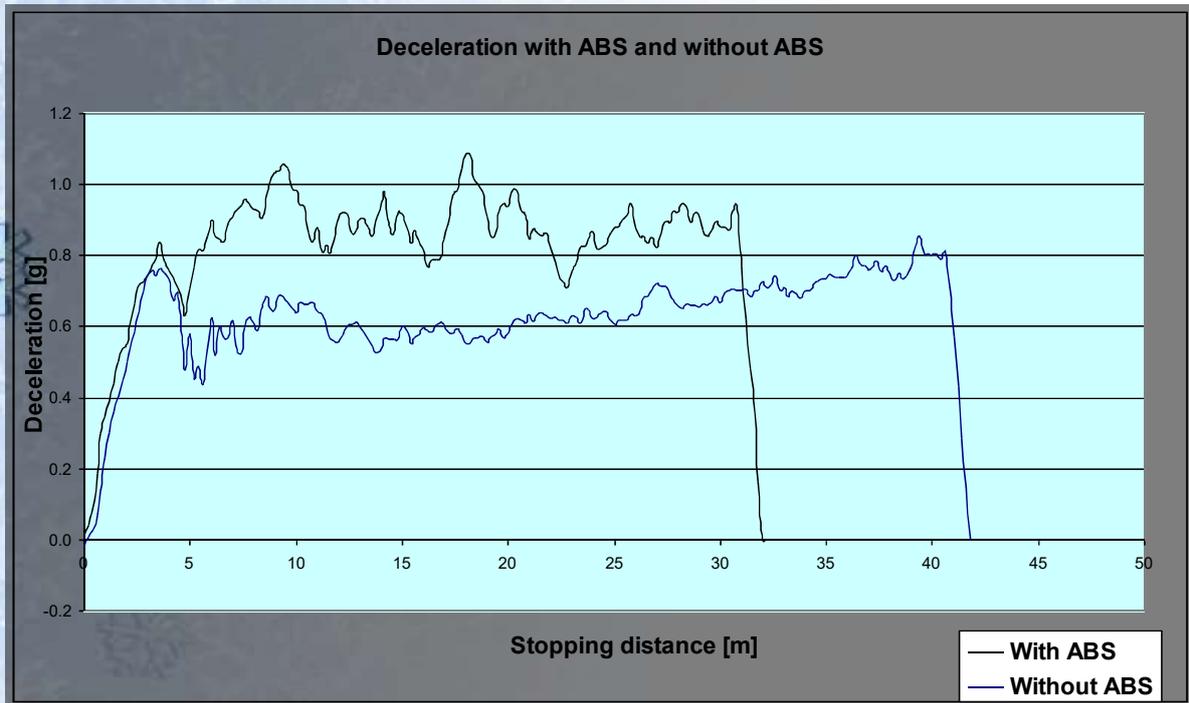


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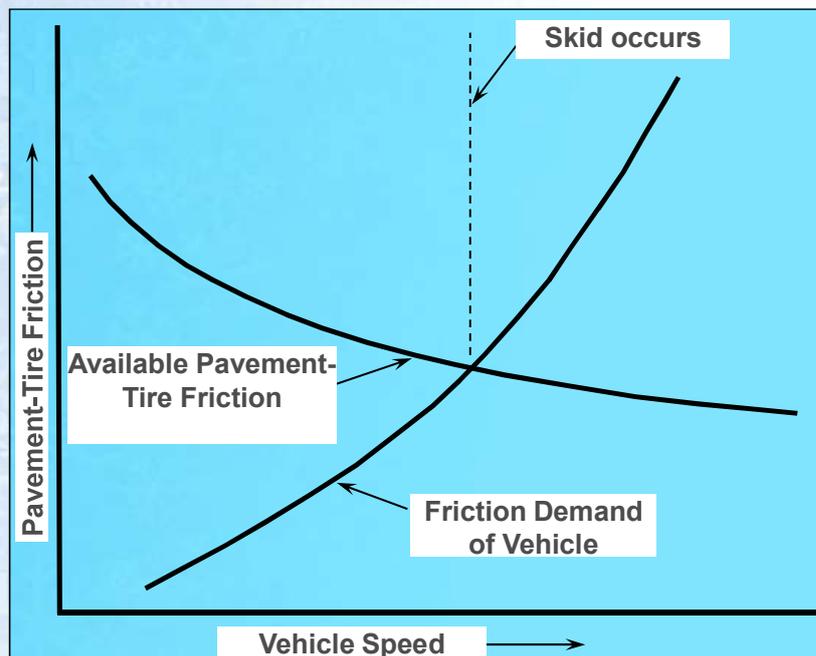
# Braking Processes



# Actual data measured



# Friction potential – demand balance



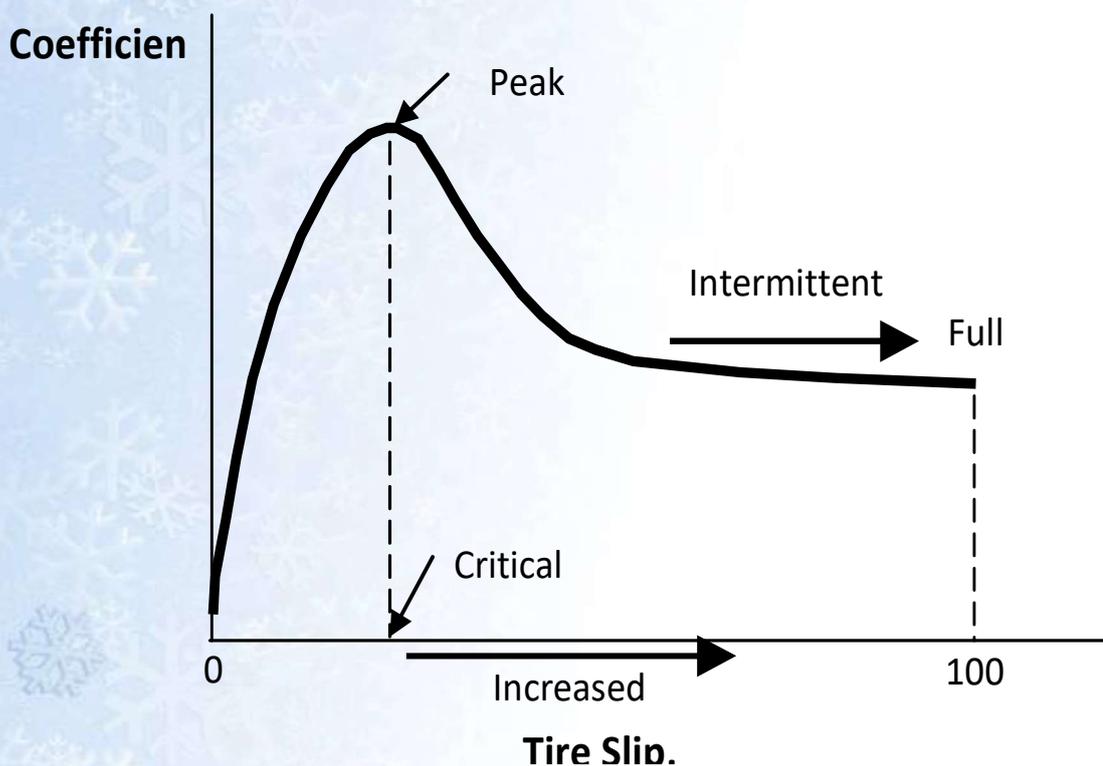
# Factors Affecting the Friction Supply-Demand Balance

- Type and Composition of the Surfacing Materials
- Micro-, macro-texture
- Geometry
- Road Site
- Road Conditions/Surface irregularities
- Traffic Density and Age
- Seasonal variation, temperature

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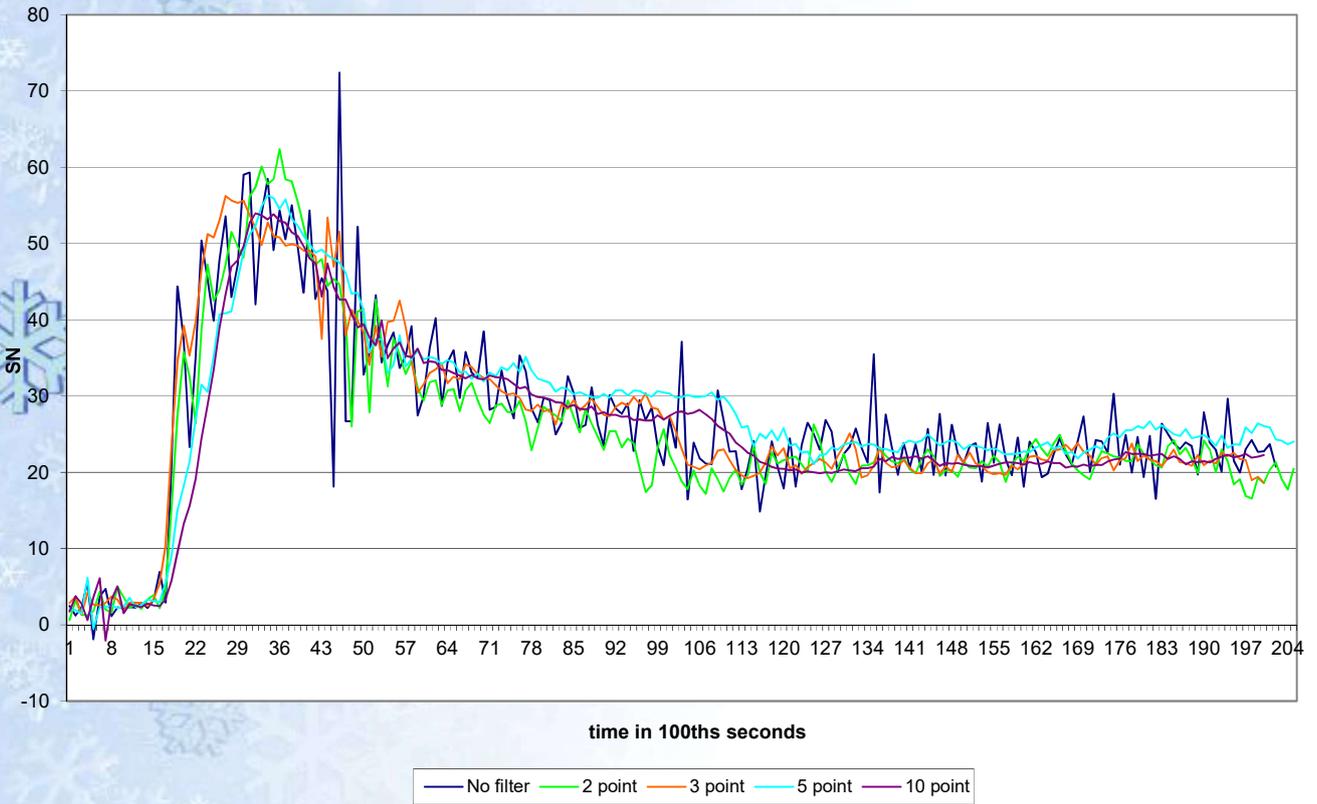
## Unit 2 - Pavement friction versus tire slip



12

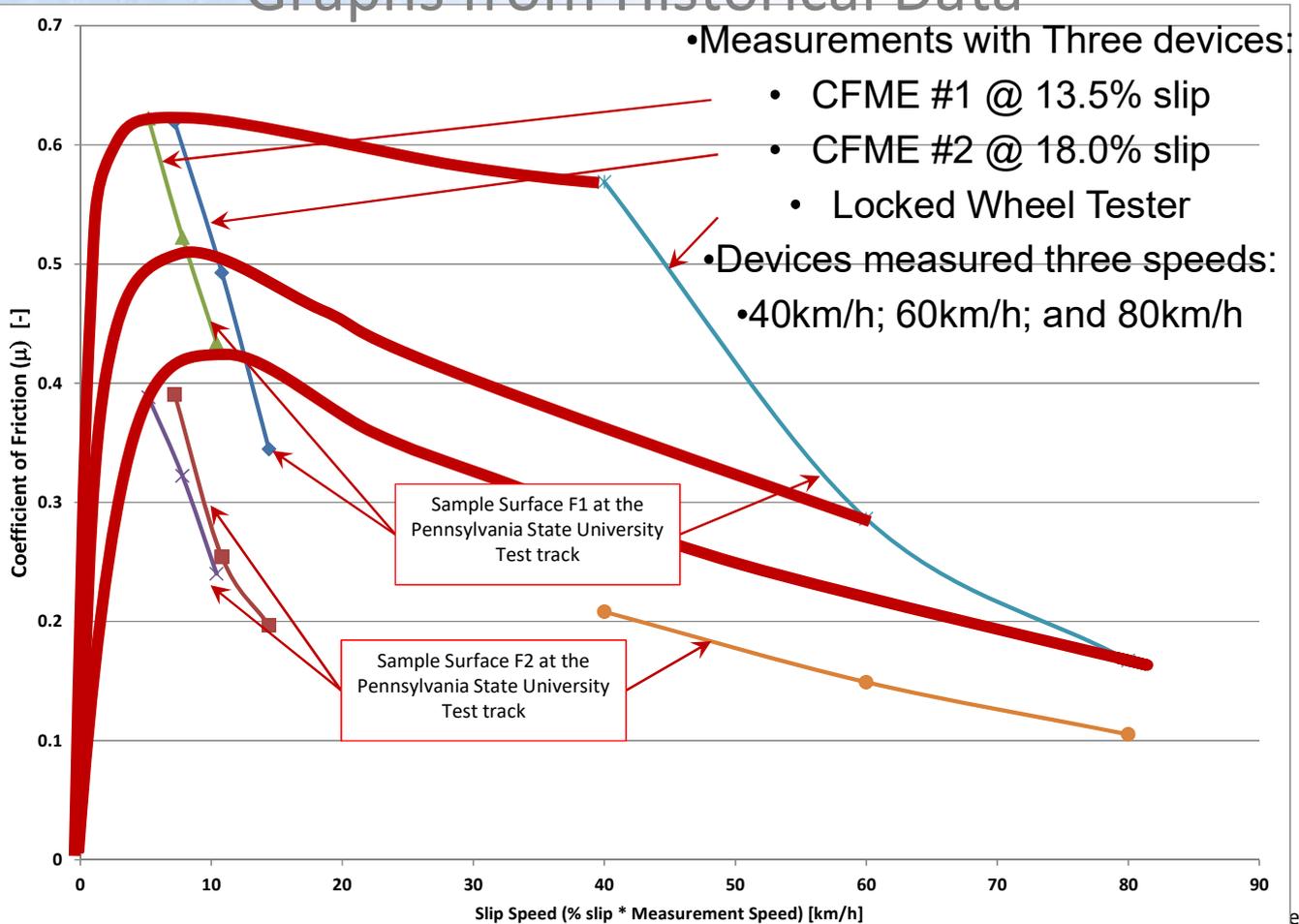
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### Data Filter Comparison



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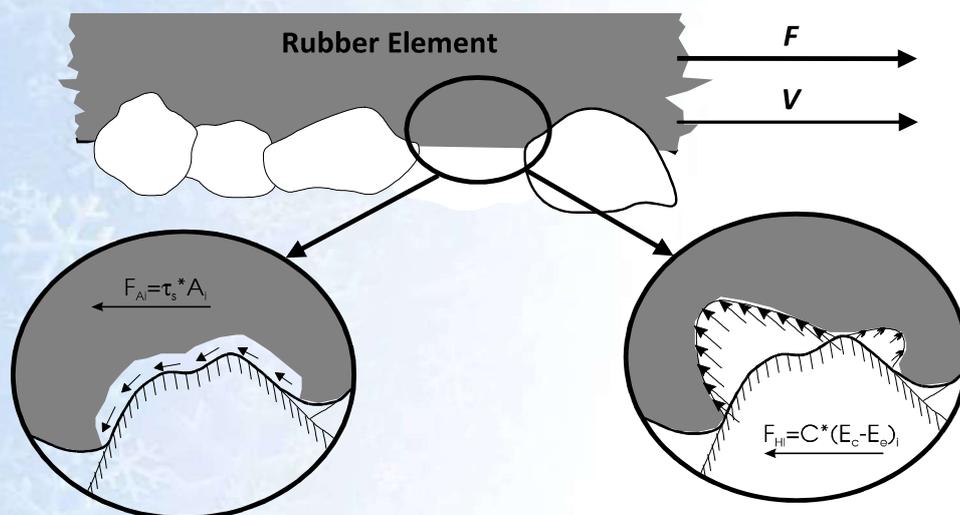
### Graphs from Historical Data



# -Micro-texture

# -Macro-texture

## Unit 2 - Mechanisms (of Pavement Friction)



**Adhesion**

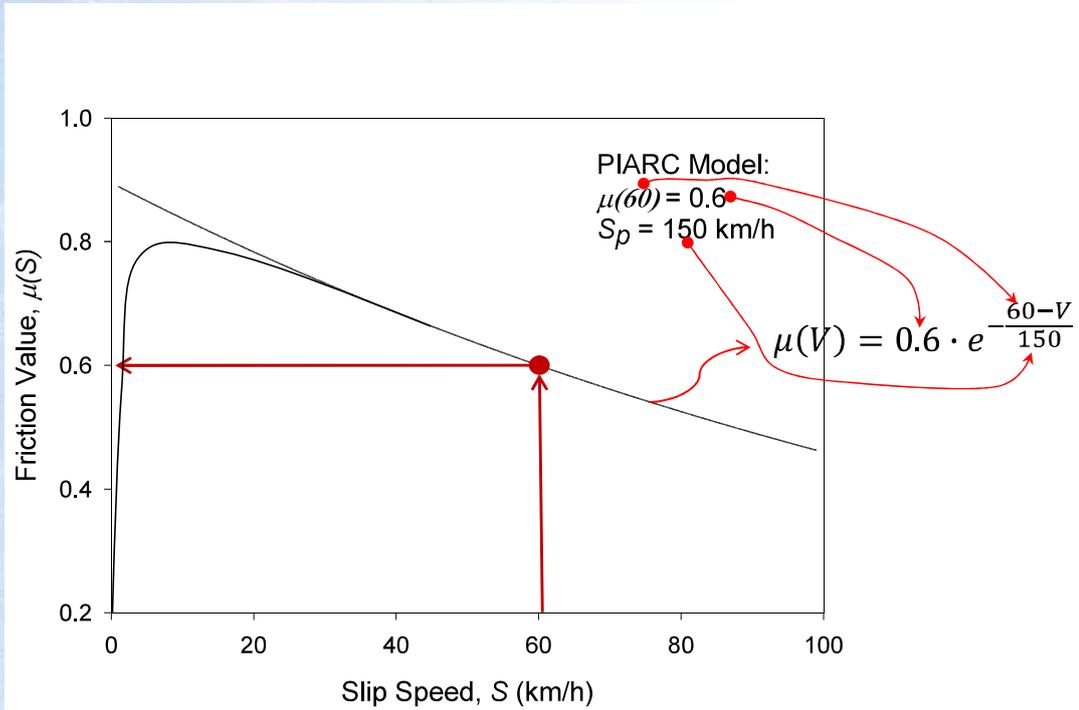
Depends mostly on micro-level

**Hysteresis**

Depends mostly on macro-

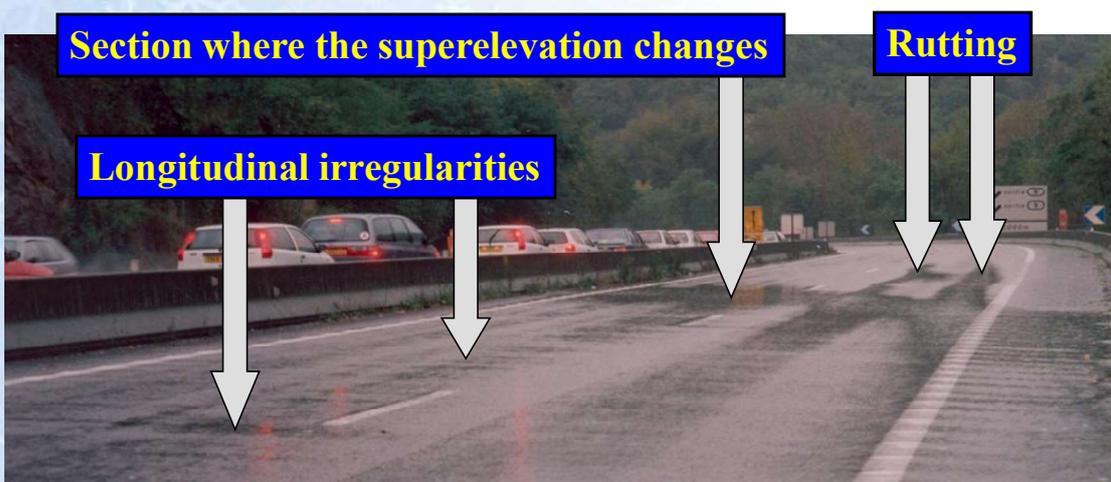
# Sample PIARC Friction Curve

## Friction of $\mu=0.6$ measured at 60 km/h



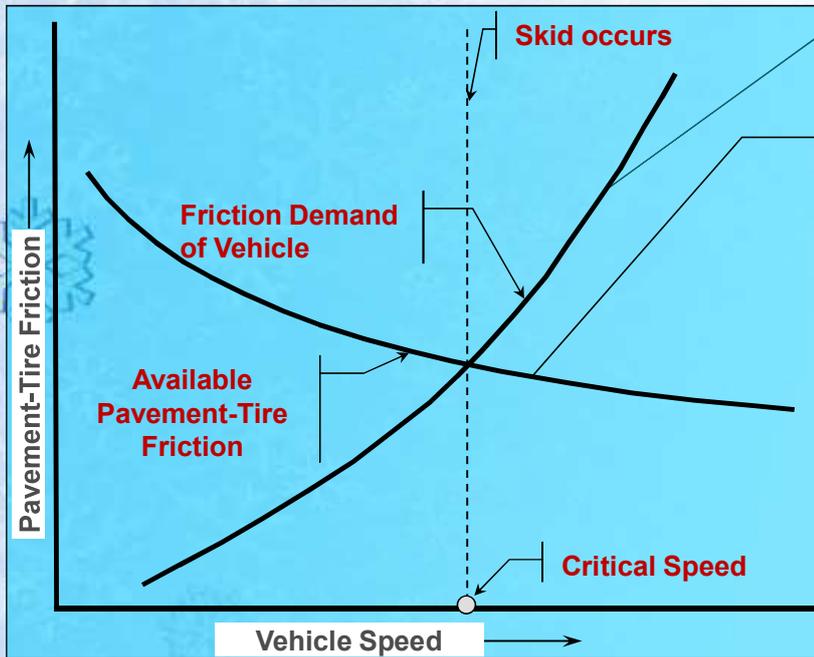
From: "Surface Friction: roads and runways : 1-4 May 2005 Christchurch, New Zealand" By: Michel Gothié

## Effect of road surface irregularities



**Surface irregularities : Water depth up to an inch or more**  
**Without surface irregularities:**  
**the most probable situations**  
**Water depth from 0.5 to 1 mm**

# Conclusions Continued



- Road Geometry
- Vehicle maneuver
- Speed

- Road Geometry
- Surface characteristics
- Irregularities
- Contaminants
- Tire

- Demand
  - Predictable
  - Controllable
- Potential
  - Deliverable
  - Controllable

# Equations to Remember

- $V \rightarrow$  Speed
- $S \rightarrow$  Speed at which friction was measured
- $S_p \rightarrow$  Speed number
- $MPD \rightarrow$  Mean Texture Depth

$$\mu(V) = \mu_s \cdot e^{-\frac{s-V}{S_p}}$$

$$S_p = 14.2 + 89.7 \cdot MPD$$

# Equations to Remember

## Simplified Stopping Distance

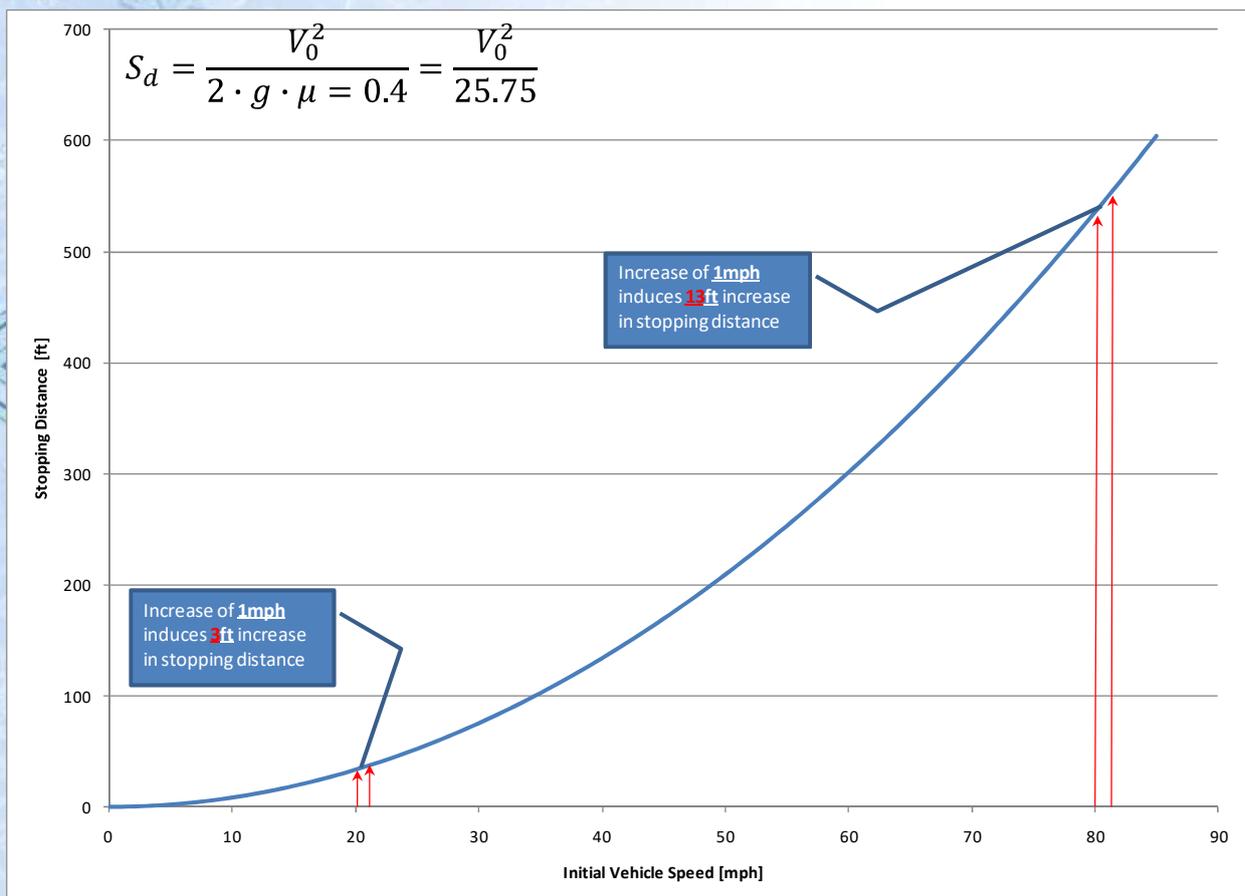
$$S_d = \frac{V_0^2}{2 \cdot g \cdot \mu}$$

- $S_d \rightarrow$  Stopping Distance
- $V_0 \rightarrow$  Initial Speed of vehicle
- $g \rightarrow$  Gravitational constant
- $\mu \rightarrow$  Coefficient of Friction

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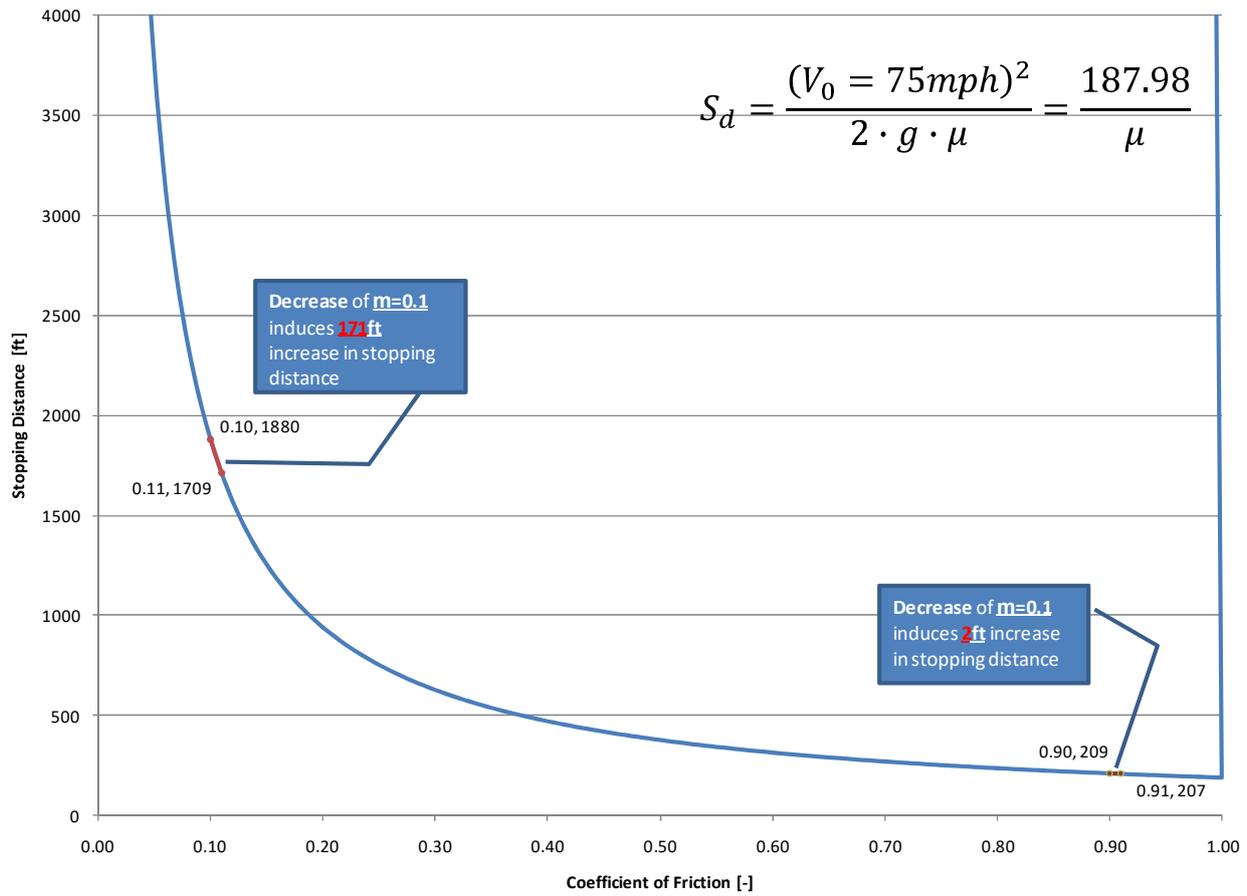
## Simplified Stopping Distance



reserved

# Simplified Stopping Distance

$$S_d = \frac{(V_0 = 75\text{mph})^2}{2 \cdot g \cdot \mu} = \frac{187.98}{\mu}$$



reserved

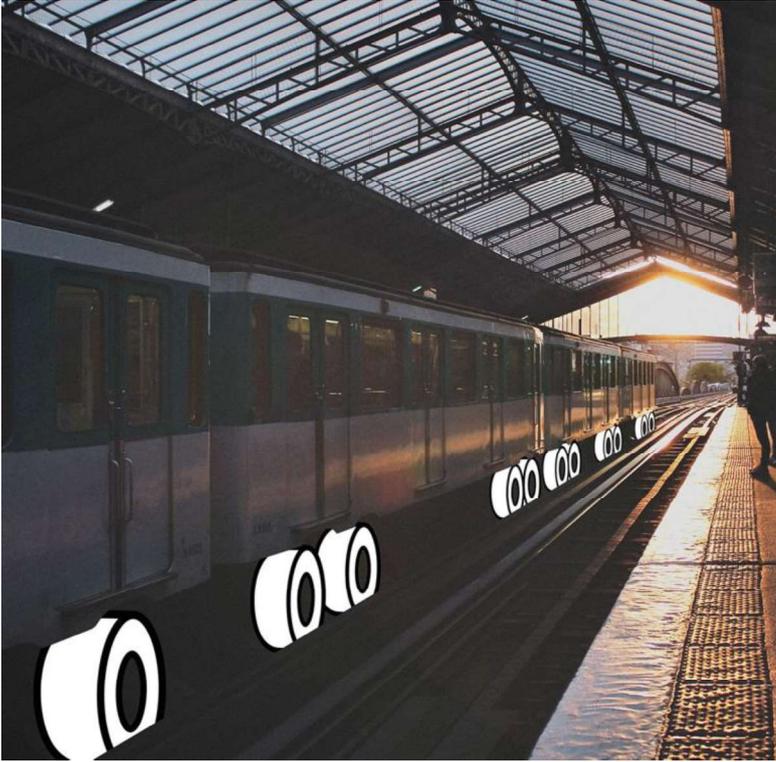
## 9.2 Presentation by Michelin, by Eric Berger

### Summary:

This technical presentation outlines the science of tire-road friction with a focus on tire grip mechanisms, tire wear mechanisms and surface texture.

Key insights include:

- Friction potential is dictated by **tire-surface interaction**;
- Emphasis on the importance of **macrotexture** and **microtexture** for achieving required grip, especially on wet conditions;
- Tire wear rate is highly impacted by microtexture: Friction can adversely influence pavement–tire factors such as tire wear.



## ***TIRE GRIP PERFORMANCE***

- ⊙ *Why do we need grip ?*
- ⊙ *Tire grip mechanisms*
- ⊙ *Roughness definition*
- ⊙ *Roughness and Grip measurements*
- ⊙ *Impact on wear performance*
- ⊙ *Conclusions*

Author : S. Oraison 2022 / E. Berger 2025 Confidential D4



### ***Why do we need grip ?***

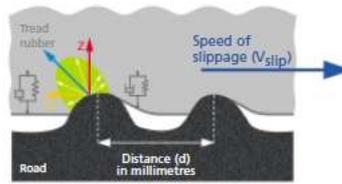
- Tires are the link between the vehicle and the track
- Grip is necessary to keep a vehicle on its course
  - Even at constant speed, to fight against natural forces (wind, surface irregularities, surface with slope, rolling resistance)
  - When we want to increase or decrease the speed
  - When we modify the direction (cornering)



## Rubber and grip

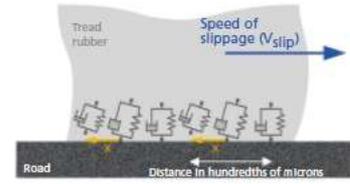
- Tire grip results from the frequency excitation of rubber under the effect of slippage over the road.
- Two main friction mechanisms come into play.
  - Indentation
  - Adhesion

### ROAD ROUGHNESS EFFECTS (INDENTATION)



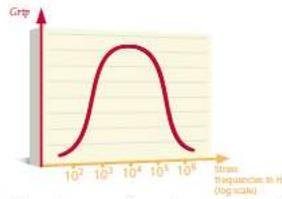
The tread block strikes against the rough spot and deforms, but, by a hysteresis effect, it does not immediately revert to its initial shape on the other side of the rough spot. This asymmetrical deformation generates a force field, the tangential resultant force of which (X) opposes skidding.

### MOLECULAR ADHESION



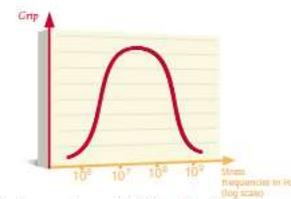
The molecular chain is stretched: its viscous properties, represented by the piston, resist deformation, generating a friction force X which opposes skidding.

### FREQUENCY RANGE OF ROAD ROUGHNESS EFFECTS



Road roughness continues to generate grip even when the road surface is wet.

### MOLECULAR ADHESION FREQUENCY RANGE



Surface wetness inhibits adhesion.

Author : S. Oraison 2022 / E. Berger 2025 Confidential D4

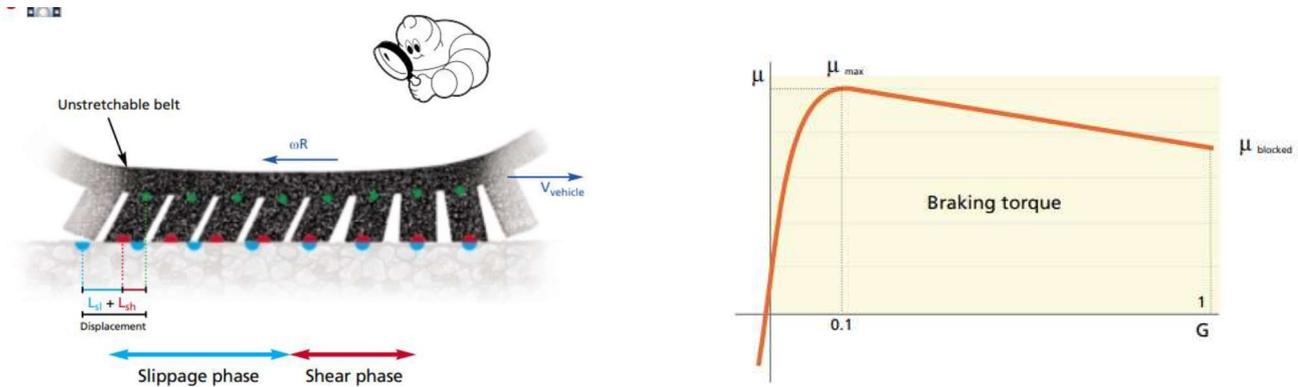


## Friction coefficient definition

- This friction force, X, depends on the load, Z, of the vehicle on the road surface, and on the type of road surface and tread compound. The force is defined by :  $X = \mu \cdot Z$
- The friction coefficient,  $\mu$ , illustrates the grip potential offered by a rubber-road interface
- The coefficient of longitudinal friction is equal to the acceleration or deceleration (in g)
  - Ex : Max deceleration needed =  $1.8 \text{ m/s}^2 \Rightarrow \mu \text{ min} = 0.18$
  - Layout impact if slope
    - $\mu \text{ min} = \mu \text{ +/- } \mu_{\text{slope}}$
    - Ex : Max deceleration needed =  $1.8 \text{ m/s}^2$  on 2% of slope  $\Rightarrow \mu \text{ min} = 0.18 + 0.02 = 0.20$



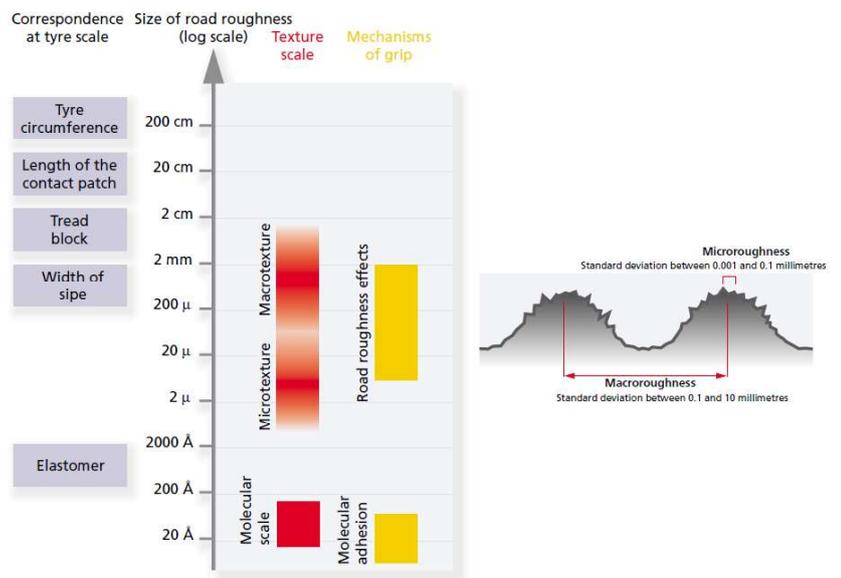
# GENERATION OF BRAKING FORCES IN THE CONTACT PATCH



- Each block entering the contact patch is first sheared, and then slips over the road surface
- The higher the slip ratio is, the higher is the length of slippage and the lower is the length of shear

## How road roughness affects grip

- Grip comes from road roughness effects and molecular adhesion.
  - Road roughness effects, require road surface "indenters", i.e. small bumps which will dig into the surface of the rubber.
  - Molecular adhesion necessitates direct contact between the rubber and the road surface, i.e. the road must be dry. For water dispersal, the road surface offers two solutions :
    - drainage of the water towards the sides of the road (camber, banking) or downwards (porosity);
    - storage of the water in the pits of the surface so that the peaks of the bumps stand clear of it.



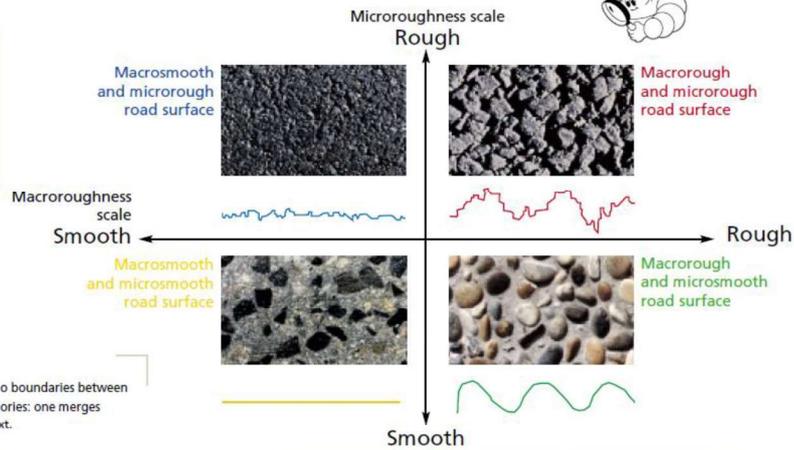
# Influence of road surfaces on the friction coefficient

As an initial approximation, road surfaces can be classified into four categories.

It has been observed that the value of the coefficient of friction - or coefficient of grip -  $\mu$  on a dry road surface is always between 1 and 1.3\*. However, on a wet surface, the coefficient of grip is always worse and varies enormously with the nature of the surface.

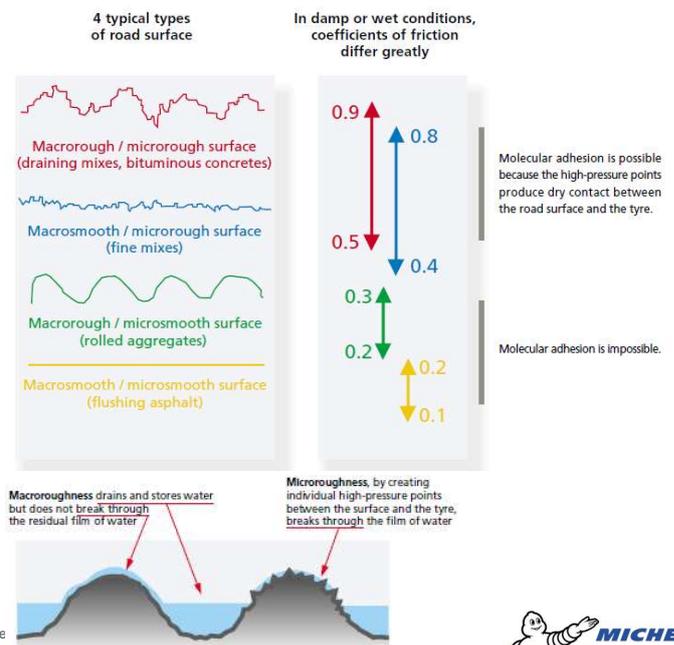


\* Values for  $\mu_{max}$



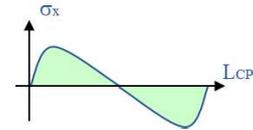
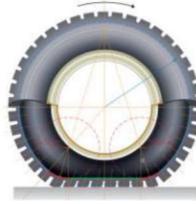
# Variation in friction coefficient on wet road surfaces

- In order to grip, the tire must be in contact with the road surface, which activates the grip mechanisms, i.e. indentation and molecular adhesion.
- The friction coefficient of a surface can be characterized for a given rubber.
- In DRY WEATHER, this friction coefficient depends very little on the type of surface. It is always close to 1.
- In WET WEATHER, the coefficient depends very much on the type of surface.
- On a damp surface, microrough road surfaces give the best grip, macroroughness playing a secondary role.

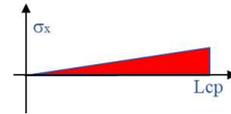


## Longitudinal stresses in the contact patch

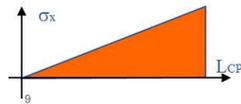
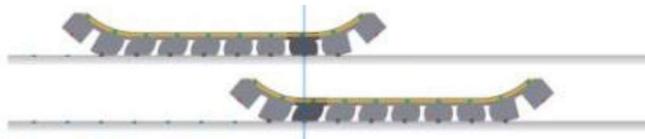
### Flattening



### Radius differences



### Torque (G%)



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## Wear and Longitudinal stresses in the contact patch

- Wear rate is a function of the frictional energy dissipation rate
- Frictional energy dissipation is caused by the sliding at the trailing edge of the contact patch
- Even in free rolling condition, sliding occurs at the trailing edge of the contact patch
- Friction energy increases when friction coefficient increases

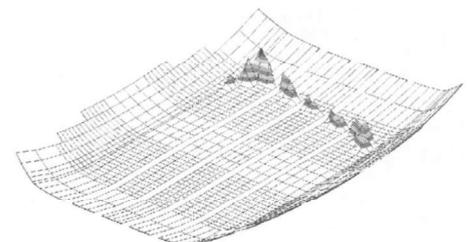
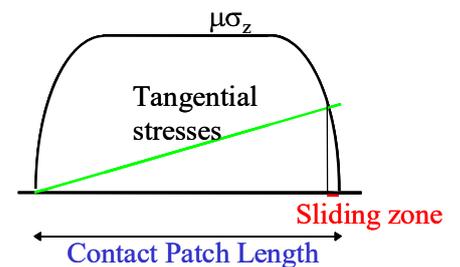


FIG. 7 — Frictional energy dissipation in the footprint.

Zheng, D., "Prediction of Tire Tread Wear with FEM Steady State Rolling Contact Simulation," Tire Science and Technology, 2002

24/01/2025

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10



# Tire Wear

- Tire wear is the combination of the probability density function of external forces and wear energy
- Wear energy is a power law of external forces
- Even with no external forces, wear energy is not equal to zero

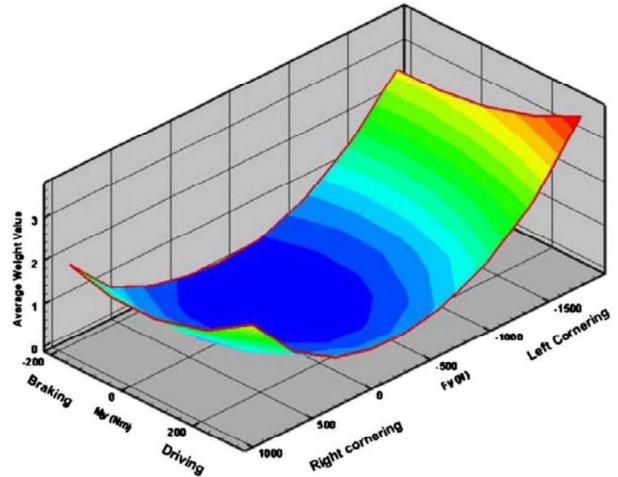


FIG. 8 — Weight function surface.

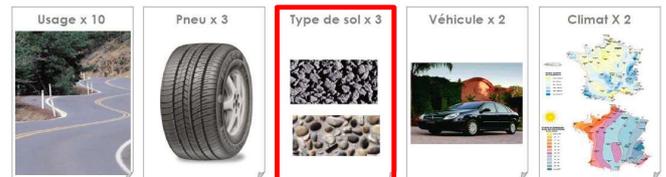
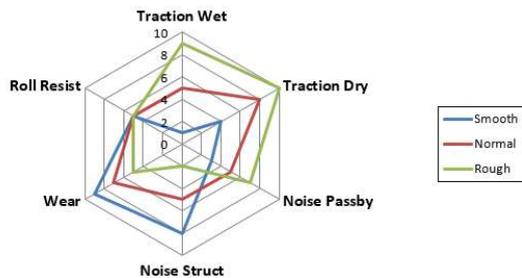
Cho, J. C. and Jung, B. C., "Prediction of Tread Pattern Wear by an Explicit Finite Element Model." Tire Science and Technology, 2007



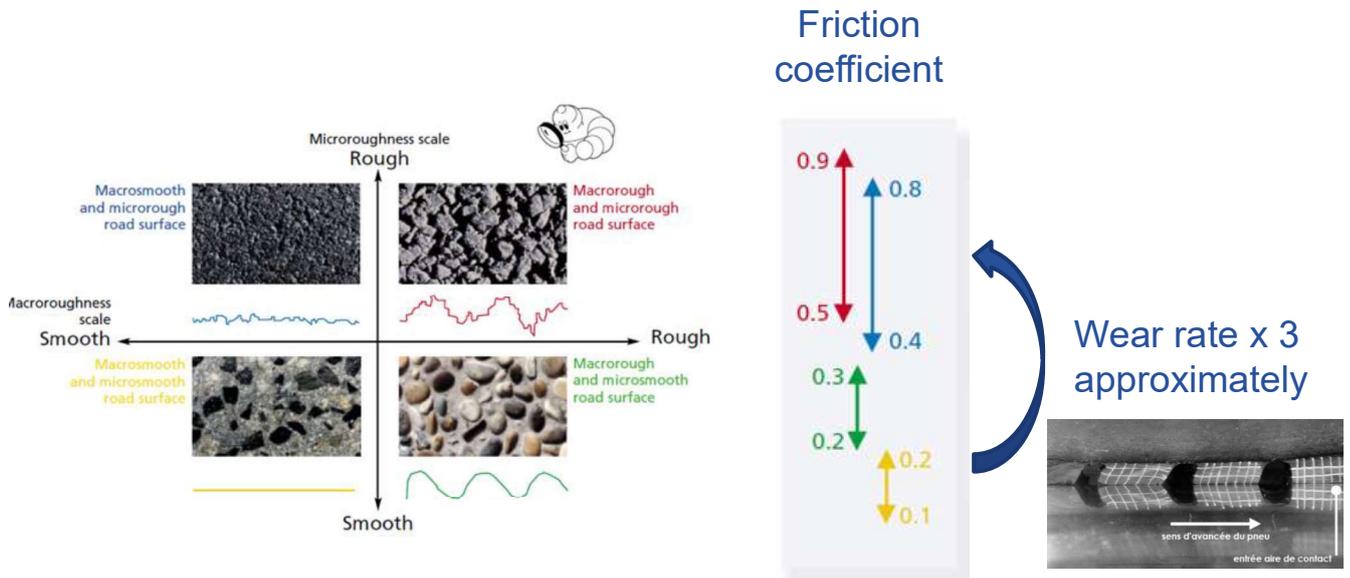
# Tire performance compromise

- The tire is a performance compromise
  - Traction, wear, noise, rolling resistance, etc...
  - Affected by ground characteristics

- Main influencing parameters for wear performance :



# Grip and Wear performance compromise



## Conclusion

- To generate longitudinal force in the contact patch
  - The tread is sheared, the block, in order to relax, will scrub on a slippage length, which activates the mechanisms of molecular adhesion and indentation
  - The friction coefficient,  $\mu$ , illustrates the grip potential offered by a **rubber road-interface**
  - This friction coefficient has an impact on wear performance
  
- It's important to define the grip potential needed
  - Taking into account driving/braking performances + track layout
  - On dry surface, friction coefficient is close to 1
    - No grip issue
  - On wet surface, friction coefficient varies a lot with the nature of the surface
    - **Macro + micro roughness** allow to achieve high friction coefficients levels, implementing the both tire grip mechanisms (indentation + adhesion)
  - Microroughness can increase wear rate by up to 3 times

## Conclusion

- Friction coefficient can evolve with time caused by the traffic and the aging of the track
  - In case of loss of aggregates
  - With the polishing of the track
  - With the fouling of the track
  
- It is necessary to regularly check the surface condition of the tracks then to clean and restore them if necessary (shot blasting, etc...)
  
- For public roads
  - Mean texture depth (macroroughness) encountered is generally in the range [0.6 ; 1.4]mm.
  - A good level of microroughness is adopted, with the requirements imposed on the aggregates and the coating formula.

### 9.3 Innova-Collection of Top Surface Finishing R1, by Lucas Bernardi Moreira

#### **Summary:**

This PowerPoint presentation documents surface finishing practices across leading monorail systems worldwide, comparing textures and finish specifications from major OEMs: Alstom, CRRC, Hitachi, and Scomi.

Featured systems include:

- Las Vegas, São Paulo, Bangkok, Cairo, Santiago de los Caballeros (Alstom)
- Monterrey, Wuhu (CRRC)
- Osaka and Chongqing (Hitachi)
- Mumbai and São Paulo Line 17 (Scomi)

Each system's top surface finishing approach is presented visually, showing grooving patterns, texture depth, or brushing techniques.

#### **Relevance:**

Provides comparative benchmarks for guideway surface finishing across regions. Valuable for proposing or validating surface finishing specifications on new monorail projects, especially in aligning with global OEM practices.

# Monorail Top Surface Finishing

- Bombardier/Alstom/CRRC
- Hitachi
- Scomi



1

## Requirements

### Alstom/Bombardier/CRRC

#### Skid Number

$0.35 \geq SN65 \leq 0.40$

+ DFT20 (Dynamic Friction Test Number): 0.45-0.55

+ MPD (Mean Profile Depth): 0.6-0.8

### Hitachi (Panamá Line 3)

#### Coefficient of friction and Rugosity

$0.3 \leq CF$  and  $250 \mu m$

### Scomi

#### Coefficient of friction

$0.70 \geq CF \leq 1.20$

2

# Comparison

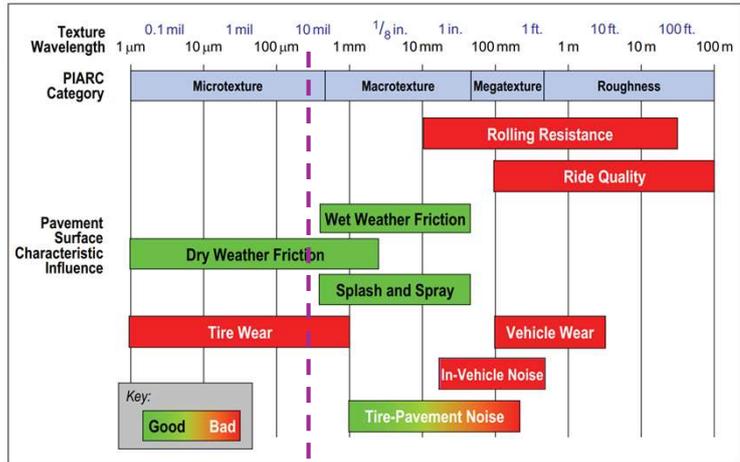


Figure 1. World Road Association (PIARC) texture definitions and their influence on pavement surface characteristics

3

# Surface Finish

- Alstom
- Las Vegas Monorail



4

## Surface Finish

---

- Alstom
- São Paulo, Line 15



5

## Surface Finish

---

- Alstom
- Bangkok, Yellow and Pink Lines



6

## Surface Finish

---

- Alstom
- Cairo, East of Nile and West of Nile Lines

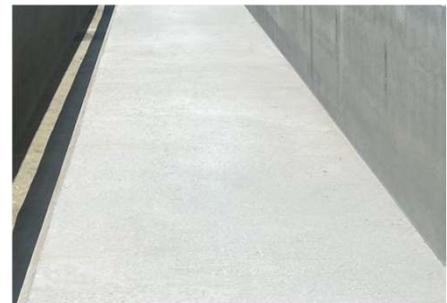
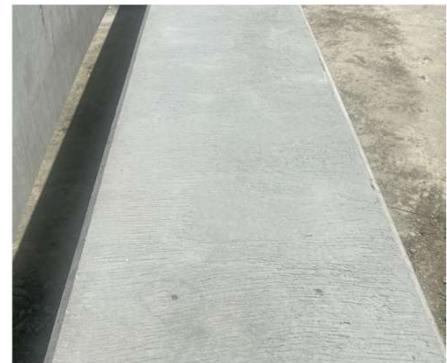


7

## Surface Finish

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- Alstom
- Santiago de los Caballeros, RD

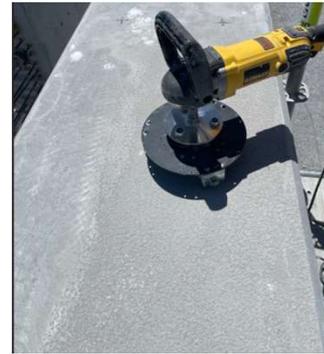


8

## Surface Finish

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- CRRC
- Monterrey, Lines 4 and 6



9

## Surface Finish

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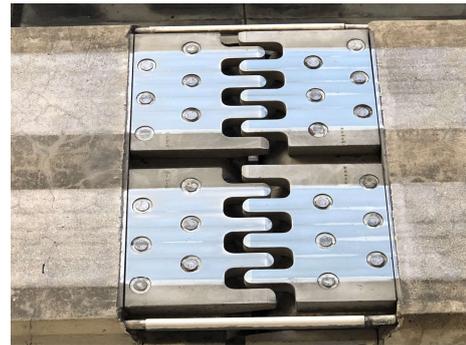
- CRRC-Puzhen Alstom Transportation Systems (PATS)
- Wuhu, Lines 1 and 2



10

## Surface Finish

- Hitachi
- Osaka Monorail Lines



11

## Surface Finish

- Hitachi
- Chongqing Lines 2 & 3



12

## Surface Finish

---

- Scomi
- São Paulo, Line 17



13

## Surface Finish

---

- Scomi
- Mumbai Monorail



14

## 9.4 Metrô SP- Japan Monorails Guideway Surfaces, by Rodolfo Szmidke

### Summary:

This PDF contains a presentation on **Japan's monorail guideway surface practices**, particularly highlighting **durability and performance under operational and environmental stress**.

While text detail is limited, it likely includes:

- Surface wear behavior under continuous rolling loads.
- Finish patterns or groove strategies used in Japan.
- Lessons from long-running systems (e.g., Tokyo Monorail or Osaka).

### Relevance:

Japan's monorail systems are considered among the most mature globally. This document contributes **practical longevity and performance insights** to guide surface selection and long-term maintenance planning.

# JAPAN MONORAILS GUIDEWAY SURFACE



*Rodolfo Szmidke*

*Civil Engineering*

*Sao Paulo Metro*



<https://upload.wikimedia.org/wikipedia/commons/2/27/Tama-monorail-1004.jpg>



## INTRODUCTION

*Guideway surface*

# OKINAWA MONORAIL



**START OPERATION  
2003**

**EXTENSION  
17 km**

**STATIONS  
19**

**TRAIN WITH 2 OR 3 CARS**

# OKINAWA MONORAIL



**Cross grooves on the concrete  
beams**



# OKINAWA MONORAIL



Sometimes hard to see



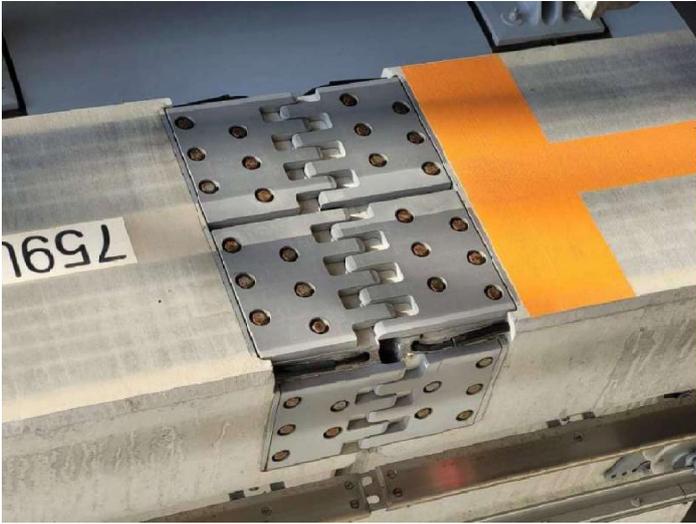
# OKINAWA MONORAIL



Concrete beam from new stretch



# OKINAWA MONORAIL



Area with signal coating



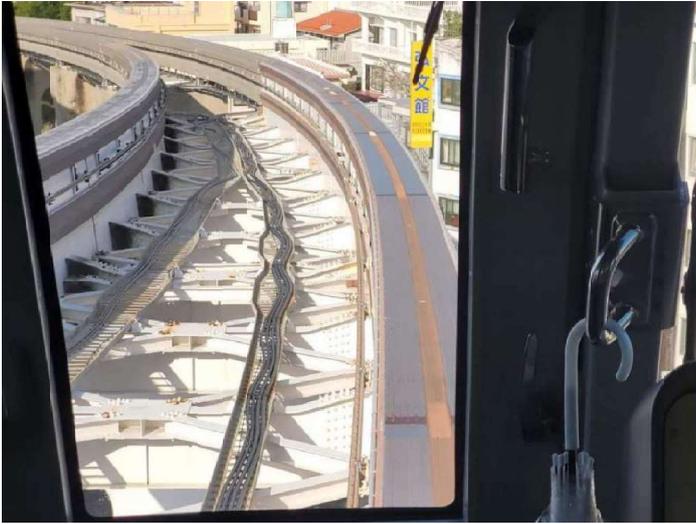
# OKINAWA MONORAIL



Some stretch with steel beams



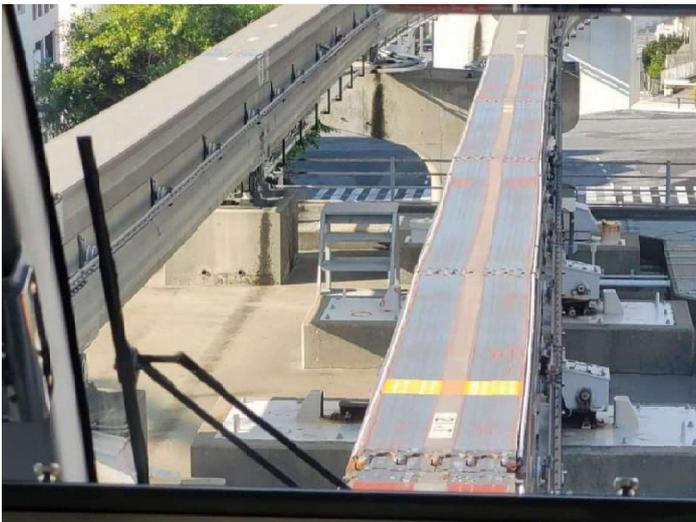
# OKINAWA MONORAIL



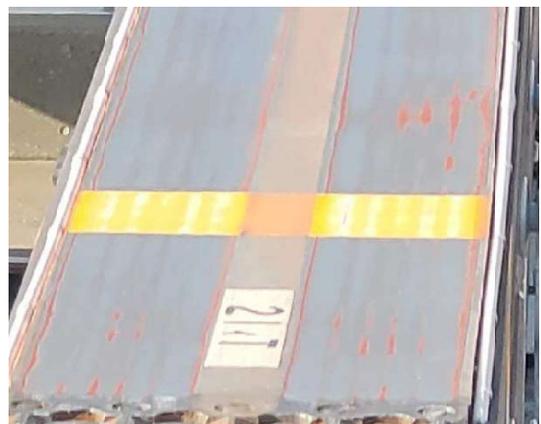
Steel beams with grooves



# OKINAWA MONORAIL



Deck switch steel beams  
without grooves



## TOKYO DISNEY MONORAIL



**START OPERATION  
2001**

**EXTENSION  
5 km**

**STATIONS  
4**

**TRAIN WITH 6 CARS**

## TOKYO DISNEY MONORAIL



**Cross grooves on the concrete  
beams**



## TOKYO DISNEY MONORAIL



Sometimes it's disappeared  
from the surface



## TOKYO DISNEY MONORAIL



Steel beams without surface



# TAMA MONORAIL



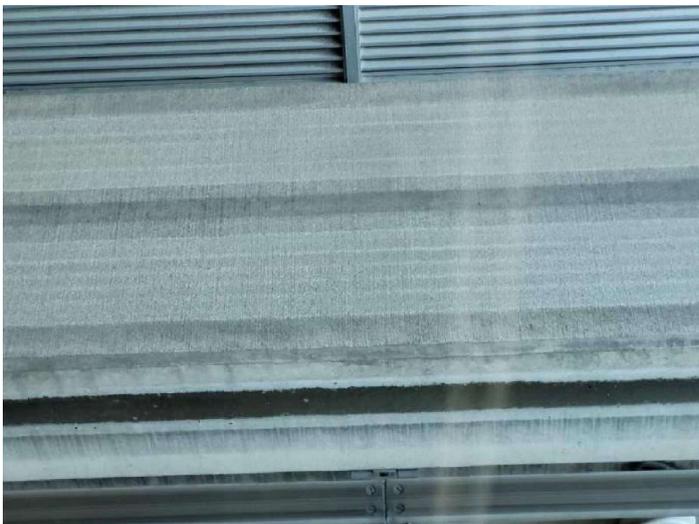
**START OPERATION**  
**1998**

**EXTENSION**  
**16 km**

**STATIONS**  
**19**

**TRAIN WITH 4 CARS**

# TAMA MONORAIL



**Concrete beams with groove**



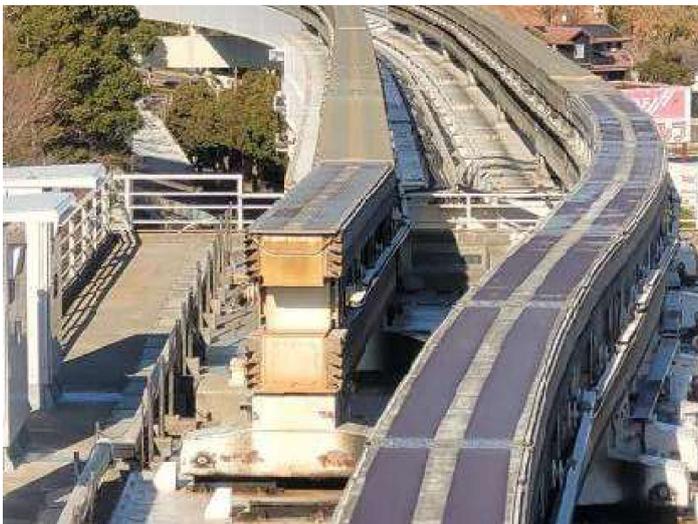
## TAMA MONORAIL



Steel beams without groove



## TAMA MONORAIL



Deck switch steel beams  
without groove



# OSAKA MONORAIL



**START OPERATION**  
**1990**

**EXTENSION**  
**28 km**

**STATIONS**  
**18**

**TRAIN WITH 4 CARS**

# OSAKA MONORAIL



**It appears to have a groove  
on concrete beam**



## OSAKA MONORAIL



It appears to have a groove  
on concrete beam



## OSAKA MONORAIL



Or not



# OSAKA MONORAIL



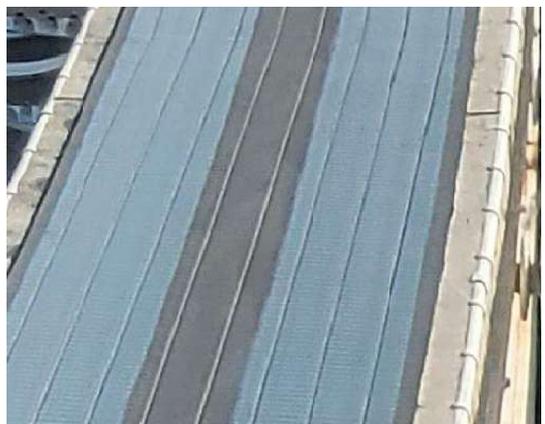
Some steel beams without groove



# OSAKA MONORAIL



And others with



## KITAKYUSHU MONORAIL



**START OPERATION**  
**1985**

**EXTENSION**  
**8.8 km**

**STATIONS**  
**13**

**TRAIN WITH 4 CARS**

## KITAKYUSHU MONORAIL



**The surface doesn't have a  
groove**



## KITAKYUSHU MONORAIL



But have some repairs



## KITAKYUSHU MONORAIL



Polymeric coating with sand?



# KITAKYUSHU MONORAIL



But....



# KITAKYUSHU MONORAIL



Steel beams with some grooves



## TOKYO HANEDA MONORAIL



**START OPERATION**  
**1964**

**EXTENSION**  
**17.8 km**

**STATIONS**  
**11**

**TRAIN WITH 6 CARS**

## TOKYO HANEDA MONORAIL



**Concrete beams with groove**



# TOKYO HANEDA MONORAIL



The future!



# TOKYO HANEDA MONORAIL



Surface treatment



# TOKYO HANEDA MONORAIL



Problems of adhesion



# TOKYO HANEDA MONORAIL



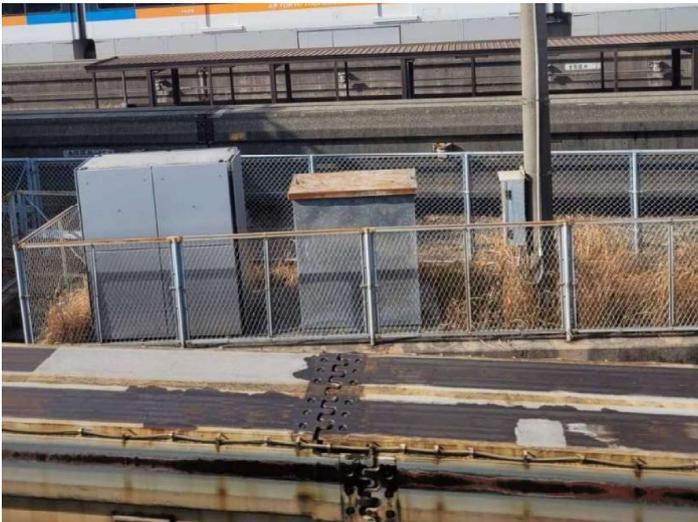
Switch beams



# TOKYO HANEDA MONORAIL



# TOKYO HANEDA MONORAIL



Steel beams



## CONCLUSION



- *Some Japanese monorails have groove on concrete beams*
- *Steel beams can have groove or not, depending at the local*
- *Finger plates could have grooves*
- *Repairs tend to go out with the time*
- *Understand and research what to do to prologue the cycle life*



**THANK YOU!**

[rszmidke@metrosp.com.br](mailto:rszmidke@metrosp.com.br)



INTERNATIONAL **M**ONORAIL **A**SSOCIATION



# Technical Framework for Straddle Beam Type Monorail Tire-Guideway Interaction

First Edition, 2025



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