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Experimental study and modelling of rubber wear mechanism under motorsport usage conditions

Development of a tribological laboratory test protocol

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Experimental study and modelling of rubber wear mechanism under motorsport usage conditions: Development of a tribological laboratory test protocol

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Abstract

Tires are a critical component of any vehicle, providing the only contact between the vehicle and the road. Their design and condition strongly influence safety, handling, noise emissions, fuel consumption, and comfort. Over time due to different operating conditions, tires experience wear: the progressive loss of tread and material that affects performance and lifetime. Understanding tire wear is therefore essential for improving durability, safety, and overall vehicle performance.

This MSc. thesis was performed in collaboration with Michelin in France, a leading company in composite material that develops tires for all applications: from automotive to bikes, motorcycles, and trucks. Michelin also develops tires for motorsport applications such as WEC tires or Moto GP tires. In motorsport, tire performance and wear are especially important. Racing places extreme demands on tires through high speeds, large lateral forces, rapid temperature changes, and varying track surfaces. Managing tire wear in this context is a key factor for lap times, racing strategy, and safety. Motorsport also provides a demanding environment that drives innovation; lessons learned on the track often translate into better products for everyday road use. Michelin has long been active in both road and motorsport tire development. The company combines advanced materials, testing, and simulation to optimize tire performance and longevity under a wide range of conditions.

This thesis develops a robust experimental test protocol to classify materials based on their wear behavior, specifically under motorsport conditions. It models tire wear in controlled laboratory settings and details the creation of a protocol for comparing different compounds based on their wear properties. The focus is on the wear of the tread rather than the entire tire, examining only the compound-ground contact.

To create the protocol, a thorough investigation was conducted that included a detailed analysis of the operating points using TameTire, a tire simulation software. This analysis ensured the design of a protocol that accurately reflects the track requirements and operating range. For the protocol to be robust, it is crucial to reproduce the real conditions experienced by tires on track. Various experiments were subsequently conducted to evaluate the repeatability and reproducibility of the results, thereby validating the reliability of the protocol.

Two tribometers were employed: the µPiste and the LAT100. The LAT100 protocol is not yet fixed or approved and is currently undergoing repeatability testing. The findings show that the protocol on µPiste is effective in ranking materials based on their wear properties. A key discovery is that tire wear is directly linked to compound rigidity: the more rigid the material, the lower the wear rate. Additionally, factors such as temperature (both of the specimen and the contact surface), sliding speed and glass transition temperature significantly affect wear. Finally, the thesis also highlights that despite similar mechanical properties, the method of increasing rigidity significantly impacts wear performance. For example, increasing the number of cross-links in the rubber compound is more effective for reducing wear than simply lowering the plasticizer volume fraction, underscoring the critical role of cross-link density in optimizing tire wear characteristics.

Keywords
Tribometer, Tires, Wear, Motorsport, Material design, Experimental protocol, Tire tread, Compounds, LAT100 machine, µPiste machine.

Sammanfattning

Däck är en kritisk komponent i alla fordon, då de utgör den enda kontakten mellan fordonet och vägen. Deras design och skick påverkar starkt säkerhet, köregenskaper, bulleremissioner, bränsleförbrukning och komfort. Med tiden och till följd av olika driftförhållanden utsätts däck för slitage: den gradvisa förlusten av mönsterdjup och material som påverkar prestanda och livslängd. Att förstå däckslitage är därför avgörande för att förbättra hållbarhet, säkerhet och övergripande fordonsprestanda.

Denna masteruppsats genomfördes i samarbete med Michelin i Frankrike, ett ledande företag inom kompositmaterial som utvecklar däck för alla tillämpningar: från personbilar till cyklar, motorcyklar och lastbilar. Michelin utvecklar också däck för motorsporttillämpningar som WEC-däck och MotoGP-däck. Inom motorsport är däcks prestanda och slitage särskilt viktigt. Tävling ställer extrema krav på däck genom höga hastigheter, stora sidokrafter, snabba temperaturförändringar och varierande banunderlag. Att hantera däckslitage i denna kontext är en nyckelfaktor för varvtider, körstrategi och säkerhet. Motorsportsmiljöer driver också innovation; lärdomar från banan översätts ofta till bättre produkter för vardagligt vägbruk. Michelin har länge varit aktivt inom både väg- och motorsportdäckutveckling. Företaget kombinerar avancerade material, tester och simulering för att optimera däckets prestanda och livslängd under en mängd olika förhållanden.

Denna uppsats utvecklar ett robust experimentellt testprotokoll för att klassificera material baserat på deras slitagebeteende, specifikt under motorsportförhållanden. Den modellerar däckslitage i kontrollerade laboratoriemiljöer och beskriver skapandet av ett protokoll för att jämföra olika komponenter baserat på deras slitageegenskaper. Fokuset ligger på slitage av slitbaneblandningar snarare än hela däcket, där endast kontakten mellan material och mark undersöks.

För att skapa protokollet genomfördes en grundlig undersökning som inkluderade en detaljerad analys av driftpunkterna med hjälp av TameTire, en däcksimuleringsprogramvara. Denna analys säkerställde att protokollet utformades så att det noggrant återspeglar banans krav och driftområde. För att protokollet ska vara robust är det avgörande att återskapa de verkliga förhållanden som däcken upplever på banan. Olika experiment genomfördes för att bedöma upprepbarheten och reproducerbarheten av resultaten för att validera protokollets tillförlitlighet. Två tribometrar användes: µPiste och LAT100. Protokollet för LAT100 är ännu inte fastställt eller godkänt och genomgår för närvarande repeterbarhetstestning. Resultaten visar att µPiste protokollet är effektivt för att rangordna material baserat på deras slitageegenskaper. En viktig upptäckt är att däckslitage är direkt kopplat till materialets styvhet: ju styvare materialet är, desto lägre är slitagegraden. Dessutom påverkar faktorer som temperatur (både för provet och kontaktytan), glidningshastighet och glasövergångstemperatur slitage påtagligt. Slutligen belyser examensarbetet också att trots liknande mekaniska egenskaper påverkar metoden för att öka styvheten slitaget avsevärt. Till exempel är det mer effektivt att öka antalet tvärbindningar i gummiblandningen för att minska slitage än att helt enkelt sänka andelen mjukgörare, vilket understryker den avgörande rollen hos tvärbindningstätheten för att optimera däckens slitbana.

Nyckelord
Tribometer, Däck, Slitage, Motorsport, Materialutformning, Experimentellt testprotokoll protokoll, Däckmönster, Gummiblandningar, LAT100 maskin, µPiste maskin.

Preface

This master's thesis was conducted in collaboration with Michelin, headquartered in Clermont-Ferrand, France. The company is a global leader in the tire manufacturing industry, dedicated to providing advanced tire solutions for automotive, motorcycle, and commercial vehicle applications, particularly in performance sectors. The thesis has been conducted in the Research & Development center of Michelin in Ladoux, as part of my final year internship.

This MSc. thesis serves as study validation for a double degree between *l'Ecole Nationale d'Arts et Métiers (France)* and *KTH Royal Institute of Technology (Sweden)*. This thesis is not just a reflection of my learning over the past years but also an exploration of innovative methodologies and applications that can contribute to the field.

Throughout this process, I have been fortunate to work alongside experienced professionals who have provided invaluable guidance and support. Their mentorship deepened my understanding of tire engineering and the factors affecting tire performance.

I hope that this thesis can serve as a valuable resource for future research and inspire others in their endeavors within the tire industry and beyond. I am excited about the potential implications of this work and look forward to contributing to advancements in this vital field.

Acknowledgments

I would like to express my sincere gratitude to all those who supported me throughout this thesis.

First, I thank my three main tutors for their guidance and support: Pierre Cormier, Romain Jeanneret, and Pierre Tregouet. Their advice, feedback, and encouragement were essential to the completion of this work. They trusted me and showed constant patience and understanding. They gave me freedom to make decisions while always offering clear guidance when I needed it. Most importantly, they taught me a great deal about tires and tire engineering.

I am grateful to the teams at Michelin with whom I had the chance to work: the physical materials measurements team, the motorsport team, and the materials design team. Thank you for welcoming me, sharing your expertise, and providing a collaborative and stimulating environment.

Special thanks to my tutor at KTH, Jenny Jerrelind, for academic supervision and helpful comments that improved the quality of this thesis.

I would also like to thank Michelin as a company for the opportunity to complete my internship and for the trust you placed in me. This experience was invaluable for my professional and personal development.

Finally, I thank my friends and family for their ongoing support and encouragement during this period.

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List of abbreviations

COF: **C**oefficient **O**f **F**riction

CP: **C**ontact **P**atch

CV: **C**oefficient of **V**ariation

DSL: **D**egraded **S**urface **L**ayer

FDSL: **F**luid **D**egraded **S**urface **L**ayer

IMSA: **I**nternational **M**otor **S**ports **A**ssociation

LMH: **Le** **M**ans **H**ypercar

MSP: **M**otor**sp**ort

PC: **P**assenger **C**ars

TR: **Tr**uck

WEC: **W**orld **E**ndurance **C**hampionship

Glossary

Symbol	Description	Unit
T_g	Glass transition temperature	(°C)
V_g	Sliding speed	(m/s)
T_S	Surface temperature	(°C)
P_c	Contact pressure	(bar)
l_g	Sliding length	(m)
V_u	Wear rate	(mg/m) or (mm/m)
$V_{u,loc}$	Local wear rate	(mg/m) or (mm/m)
F_S	Static friction force	(N)
δ_t	Limiting displacement	(m)
α or δ^*	Slip angle	(rad) or (°)
SR	Slip ratio	-
L_x	Length of the contact patch	(m)
pap	Percentage of the adhering part	(%)
μ_{dyn}	Dynamic friction coefficient	-
μ_{max}	Maximal friction coefficient	-
μ	Friction coefficient	-
R^2	Linear regression coefficient	-
F_f	Friction force	(N)
N	Normal force	(N)
δ	Hysteresis delay	(°C)
tan (δ)	Energy dissipation	-
G^*	Rigidity	(MPa)
M_i	Mass of the third body	(mg)
Q_S	Particle creation/detachment flux	(mg/s)
Q_w	Particle ejection flux	(mg/s)

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CONTENTS

1 Introduction

Tires are a critical component of any vehicle, providing the only contact between the vehicle and the road. Their design and condition strongly influence safety, handling, fuel consumption, and comfort. Over time and under different operating conditions, tires experience wear: the progressive loss of tread and material that affects performance and lifetime. Understanding tire wear is therefore essential for improving durability, safety, and overall vehicle performance.

In motorsport, tire performance and wear are especially important. Racing places extreme demands on tires through high speeds, high lateral forces, rapid temperature changes, and varying track surfaces. Managing tire wear in this context is a key factor for lap times, racing strategy, and safety. Motorsport also provides a demanding environment that drives innovation; lessons learned on the track often translate into better products for everyday road use.

Michelin has long been active in both road and motorsport tire development. The company combines advanced materials, testing, and simulation to optimize tire performance and longevity under a wide range of conditions. This thesis, carried out in collaboration with Michelin, focuses on developing a robust experimental test protocol to classify materials according to their wear behavior. The thesis is clearly described in the parts below.

1.1 Problem definition and purpose of the thesis

The main goal of this project is to understand better the tire wear for the motorsport application, and more specifically LHM Cars' tires. A tire of a Le Mans Hypercar (LMH) is a high-performance racing tire engineered for grip, durability, and optimal handling during endurance races. Indeed, the wear is a very complex topic and especially with motorsport tire material where the mechanisms are very different from passenger cars and truck tires.

Concretely, this thesis describes the development of a tribological laboratory test protocol to sort materials based on wear generated.

In order to achieve this, this thesis should tackle and answer the following questions:

- What are the right usage conditions to estimate the tire wear under motorsport conditions?
- What are the influential factors affecting tire wear, and how should they be managed?
- How to reproduce the right type of wear on the tread rubber using a laboratory tribometer?
- How to evaluate the tire wear on the tread using a laboratory tribometer?
- How to create a reliable, repeatable and reproducible protocol for measuring wear accurately?
- What methodology should be used to compare compounds and rank them according to their wear performance?
- What compounds properties influence wear rate and what is the effect of each ?

1.2 Limitations of the thesis

Some limitations have been made during the project, to restrict the study to a more specific subject.

- The study focuses only on the motorsport materials (specific mixtures different from tourism car and truck compounds). Testing methods use specific conditions that are representative of motorsport conditions.
- The study focuses on the wear of the tread compound only, which is relevant for slick tires, but less for tires with patterns. The tests were carried out with rubber/laboratory ground friction, which behaves significantly differently from tire/road contact. One difference is a material perspective, while the other is based on the tire's reference frame.
- Since the thesis is in collaboration with MFP Michelin, the study is valid for the rubber of the company specifically. For confidentiality reasons not all results of the thesis can be presented in the public thesis.

1.3 Presentation of the company

Michelin is a global leader in mobility, renowned for its innovation in tire technology and its long-standing commitment to safety, performance, and sustainability [1, 2]. Founded in 1889 by Édouard Michelin and André Michelin, the company initially focused on bicycle tire development and has since expanded its expertise to all segments of the automotive and transport industries. Since its origins in France in the late 19th century, the company has expanded from pioneering detachable and radial tires to a diversified portfolio that supports passenger vehicles, commercial fleets, motorsport, and emerging mobility solutions. Michelin is mainly based in France, in Clermont-Ferrand, where there are several sites, including a Research & Development center in Ladoux where this thesis work was performed (see Figure 1). Over more than a century, Michelin has aligned technological advancement with service excellence, brand stewardship (including the famous Michelin Guide), and a vision for reducing environmental impact across the mobility ecosystem.

Figure 1. Michelin Ladoux R&D site [2]

Building on this heritage, Michelin continues to invest in research and development, circularity, and digitalization to address evolving customer needs and regulatory expectations worldwide. In 2024, the company reported revenue of €27.2 billion, reflecting the scale of its global operations and the enduring demand for its products and services [2].

Competition has long been integral to Michelin's identity and progress. From supplying the winning tires in the "Paris-Brest-Paris" race in its early years, the company has gone on to participate in premier motorsport series, including the World Rally Championship (2011-2020) and Formula One (2001-2006). Since 2012, Michelin has been the exclusive tire supplier to the World Endurance Championship (WEC), using racing as a proving ground for innovation.

Through initiatives such as #WeRaceForChange, the Group aligns motorsport with today's sustainability imperatives, introducing tires that incorporate recycled materials while maintaining comparable performance: an approach that supports the analysis developed in this MSc thesis.

1.4 Sustainability goals

In our actual society, it is very important to think about a sustainable point of view, in every company and especially in the transport field where the thesis was made. Indeed, sustainable transportation is crucial for achieving global environmental goals, enhancing economic accessibility, and fostering urban resilience by reducing emissions and improving infrastructure. Recognized internationally as a core element of sustainable development, it connects economic growth with environmental stewardship [3]. Society needs to deal with transport sector because it "plays a crucial role in connecting people to goods, services, social and economic advancement opportunities, and in fostering development" [4]. Moreover, there are today more than "1.4 billion ground vehicles today including passengers vehicles, trucks, buses, and motorcycles" [5], and the majority of these vehicles are equipped with pneumatic tires that wear over time as they roll across different surfaces and under varying operating conditions. And in 2020, estimates indicate up to 5,917,518 tons per year of tire-wear emissions worldwide, and up to 2.6 kg per person per year in Europe [5]. So "tire wear particles are a significant source of microplastic emissions" [5] and it is important to focus on this subject.

One of the goals of sustainable transportation is to reduce the particles emissions emitted by the existing vehicles, because "Tire Road and wear particles [called TRWPs] are a major source of microplastic emissions" [5]. To reduce this pollution, a new regulation called '*Euro 7*' has been adopted in April 2024 and it marks a major advance by introducing for the first time the principle of setting emission thresholds for tire wear particles — a measure fully supported by Michelin [3, 4]. This regulation targets a significant reduction in tire wear particle emissions, limiting sales to compliant products. Michelin's proactive engagement highlights its dedication to innovation and environmental sustainability, addressing the annual generation of 500,000 tons of tire particles through strategic design choices [3, 4]. This thesis is partly aligned with this standard even though it focuses on motorsport mixtures, the objective is the same for motorsport: reduce wear particles in all the competitions where Michelin is involved.

Moreover, Michelin is truly engaged in achieving sustainable development goals, for example it develops new range of slick tires for WEC and IMSA with 50% of recycling material for 2026. The long-term goal is to achieve 100% by 2050. This is a strong and impactful measure because the impact on the planet will be significant [2]. Figure 2 expose the new 2026 WEC tire.

Figure 2. 2026 Michelin tire for WEC

This thesis focuses on understanding better the tire wear in motorsport usage conditions in order to achieve these goals: tires using recycled material and that emit less wear particles during tire's lifecycle. This thesis focuses on rubber tread wear, but this project is part of a larger project about tire wear within Michelin.

1.5 Outline of the thesis

In order to achieve the goal described in the Section 1.1, the thesis focuses on different aspects of the wear subject in motorsport. Below is a presentation of how the thesis is structured.

Chapter 2 provides the background needed to understand the main conditions and principles of wear mechanisms, including how a tire is designed and the specific conditions in motorsport.

Chapter 3 presents the key tools used during the thesis and describes the method applied to achieve the goals. Specifically, it explains how the protocol was developed and validated, using two different methods based on two tribometers.

Chapter 4 reports the findings and results of the thesis related to the protocol with the tested compounds. This chapter also analyzes the outcomes from the different parts of the work.

Chapter 5 summarizes the work carried out during the thesis and highlights the main trend and outcomes of the research. It restates the main results from the protocol and the tested compounds, and it concludes with the compounds ranking and comparison.

Finally, in Chapter 6, reflections on the final work are made and potential directions for future work is discussed, including ways to further explore the topic and aspects that can be improved or enhanced.

2 Background – State of the art

Before going into the work itself, it is crucial to have a solid understanding of the tire structure, composition and of the wear mechanisms. This chapter begins with an introduction to tribology and friction (Section 2.1), providing foundational concepts relevant to tire performance. It then presents the tire (Section 2.2), detailing its global architecture, tread composition, and elastomer materials that influence its characteristics. In Section 2.3, the focus shifts to the rubber and its grip, exploring its viscoelastic properties, and the mechanisms involved in rubber/ground friction. The phenomenon of tire wear is addressed in Section 2.4, which discusses generalities, different wear mechanisms and influential factors. Finally, Section 2.5 explores the specificity of tire wear for motorsport applications, examining wear management strategies during races and the unique wear phenomena encountered in this context.

2.1 General introduction

2.1.1 Tribology

Tribology is the study of friction, wear and lubrication; it is the science of interacting surfaces in relative motion [6]. Another translation can be the study of rubbing or sliding. Tribology corresponds to the "OLOGY" of the science "TRIBEIN" [7]. The definition of tribology of elastomers as a part of tribology can be "the science and technology for investigating the regularities of the emergence, change and developing of various tribological phenomena in rubber and rubber-like materials and their tribological applications" [7].

2.1.2 Friction

Friction can be simply defined as "the force that makes it difficult for one object to slide along the surface of another or to move through a liquid or gas" [8]. As illustrates in Figure 3, friction is divided into two regimes.

In the static friction regime, the friction force increases with preliminary displacement until it reaches the maximum static friction force (F_S), indicating the object remains stationary. Upon reaching the limiting displacement (δ_l) and initiating movement, the graph transitions to the dynamic friction regime, where the friction force stabilizes at a lower, constant value, representing kinetic friction (this is where μ_{dyn} is calculated).

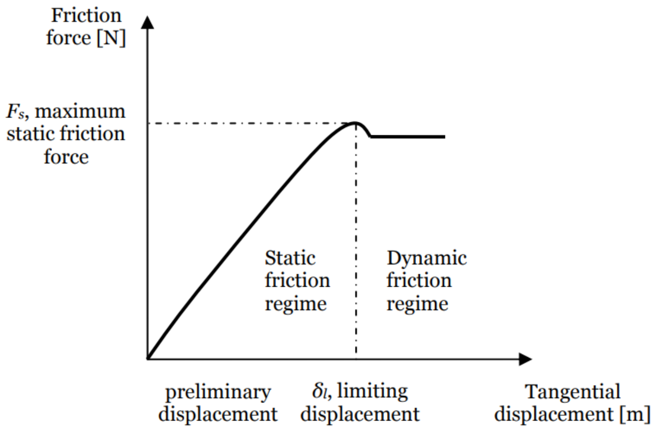


Figure 3. Friction force vs. tangential displacement [35]

A mathematical representation of the friction law was presented by Charles Augustin Coulomb, who performed detailed experiments to investigate the magnitude of the coefficient of friction (COF) during sliding, as follows:

$$F_f = \mu \cdot N \tag{1}$$

where F_f is the friction force (N), μ the COF, and N the normal force (N).

The classic laws of friction state that the static coefficient is greater than or equal to the kinetic coefficient, that friction force is proportional to the load, and that the COF is independent of contact area and sliding speed. While these principles provide insight into dry friction, they do not fully account for the characteristics of elastomers and rubber-like materials, where viscoelasticity leads to different friction behavior influenced by additional parameters.

2.2 The tire

2.2.1 Global architecture

To introduce the subject, it is essential to understand the overall architecture of a tire as well as its various components.

The touring tire (PC tire) and most competition tires (MSP) can be divided into nine main elements as illustrated in Figure 4, which will be described in the following paragraphs.

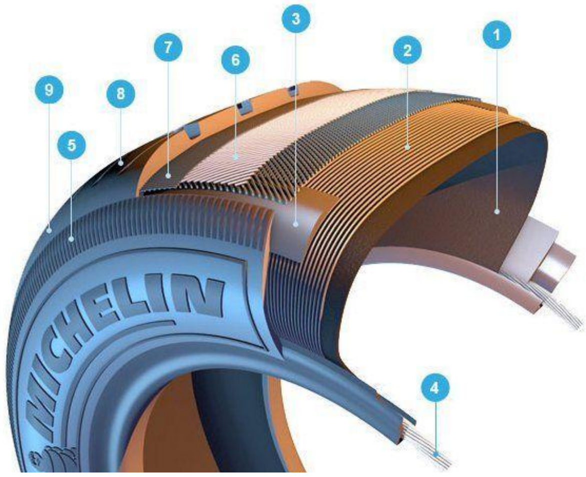


Figure 4. Architecture of a touring tire. Nomenclature: 1: Inner lining; 2: Sidewall fold; 3: Bead base; 4:Ring/Bead; 5: Side; 6: Ply casing; 7: Cushion or belt; 8: Apex plies; 9: Tread band [9]

The **inner lining** serves to seal the tire against air, similar to an inner tube [9]. The **sidewall fold** is made up of fine textile cords that provide strength and pressure resistance. Next, the **bead base** allows the tire to adapt to the metal rim, transmitting the engine's power to the contact surface with the road. The **beads** keep the tire securely on the rims, with each unit supporting a load of up to 1,800 kg in some specific cases, ensuring airtightness even under significant forces. The **sidewall** protects the tire's side against impacts, incorporating details on sizing and speed rating. The **ply casing** contributes to durability by consisting of strong steel cables embedded in rubber, ensuring flexibility and resistance. The **cushion** (or belt) helps dissipate friction heat and maintains the tire's shape with reinforced nylon cables. The **apex plies** provide a rigid base for the tread and impart good dynamics to the tire (cornering stiffness, lateral stiffness...). Finally, the **tread** guarantees traction and cornering grip, and is designed to resist wear, abrasion, and heat. These components interact to enable the tire to meet the specifications imposed on it.

2.2.2 The tread and its composition

The **tread** is the rubber compound on the surface of the tire that ensures uniform contact with the ground. This compound plays a key role in grip and wear. In most cases (passenger car and truck tires), the tread is grooved to allow water evacuation on wet surfaces. For racing tires, however, there are two categories: 'WET' tires, used in rainy conditions and which are grooved, and 'SLICK' tires, with a smooth tread that provides a larger contact patch with the track [10].

An example of the composition of a rubber mix is shown in Figure 5. Elastomers are the main components of the compound. Fillers are the reinforcing agents in the compound: they improve tensile and fatigue resistance and reduce wear. Plasticizers enhance raw mix processability and allow adjustment of properties after curing. Vulcanizing agents provide dimensional stability to the compound [10].

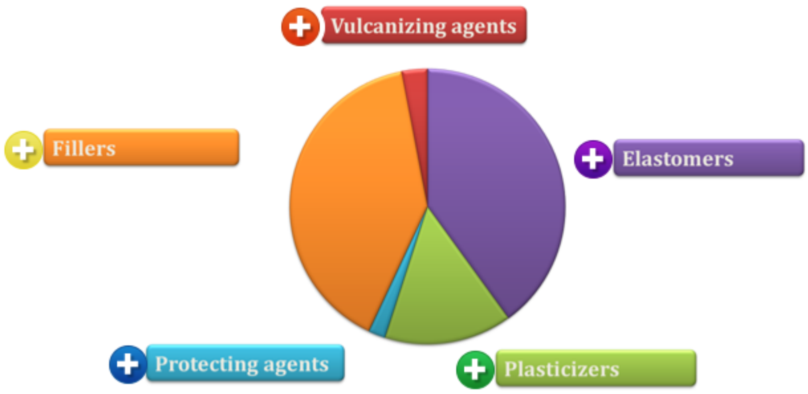


Figure 5. General composition of a rubber mix [10]

The objective of a materials designer is therefore to create a formulation that imparts specific properties to the mix in order to meet the specifications and establish the best trade-off among conflicting performance criteria [10]. Indeed, in tires everything is a matter of compromise among grip, comfort, durability, wear, handling, rolling resistance, etc.

2.2.3 The elastomers

Unlike metallic materials, elastomers are described as *viscoelastic*, meaning their deformation depends on time in addition to the applied stress. Their purpose is to improve tire grip, and they also provide better mechanical strength. There are two major families of elastomers: natural rubber and synthetic elastomers.

The glass transition temperature (T_g) is a crucial characteristic for elastomers, marking the transition of the material from a rigid state to a more compliant (viscoelastic) state, as illustrated in Figure 6. Below T_g, molecular chains are immobile, making the elastomer hard and brittle, whereas above this temperature they become mobile, allowing the material to be flexible and to absorb energy effectively. For a tire, this transition means that its performance (particularly in terms of grip and wear resistance) varies significantly with temperature, thereby influencing its optimal use under different climatic conditions [10].

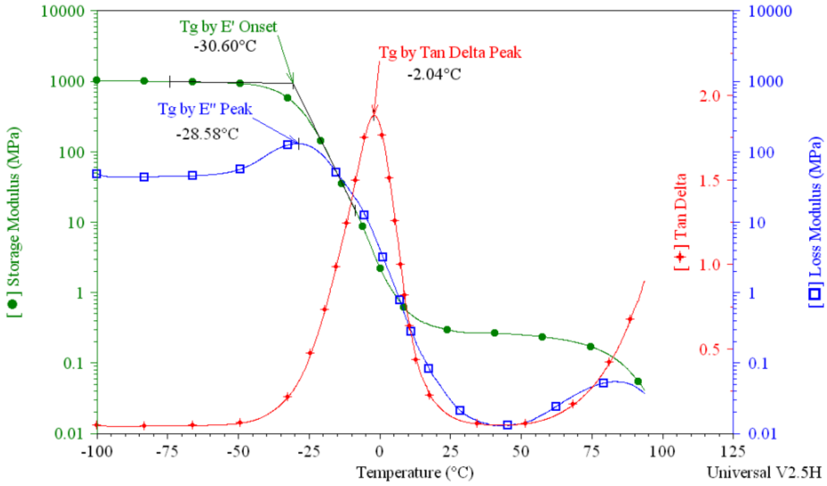


Figure 6. Module (stiffness) and loss factor (tan(δ)) as a function of temperature for an elastomer, illustrating the glass transition temperature (T_g) [32]

2.3 The rubber and the grip

2.3.1 A viscoelastic material

In a simple way, a viscoelastic material can be represented by a spring-damper model. There is energy dissipation, known as loss (*tan(δ)*). Relative to the applied stress, compression and the return to equilibrium occur with a delay: this is the hysteresis phenomenon (denoted δ) [11].

This viscoelasticity arises from vulcanized elastomers whose polymer chains are intertwined and connected by 'sulfur bridges', giving them the ability to behave like springs while exhibiting resistance to motion due to friction between the chains [11].

2.3.2 Influence of stress frequency and temperature

This section examines how stress frequency and temperature affect the mechanical properties of rubber in tire dynamics. At low frequencies, rubber behaves elastically, while higher frequencies introduce viscoelastic characteristics that influence grip. Additionally, temperature changes significantly modify the rubber's modulus, impacting its stiffness and elasticity.

a) Influence of stress frequency

As shown in Figure 7. The left graph shows the energy loss of rubber materials at various frequencies, peaking in the "zone of maximum hysteresis," while the right graph illustrates that the modulus increases with frequency, indicating a transition from a rubbery to a glassy state. *Modulus* in the context of rubber materials refers to the stiffness or resistance to deformation of a rubber material when subjected to stress.

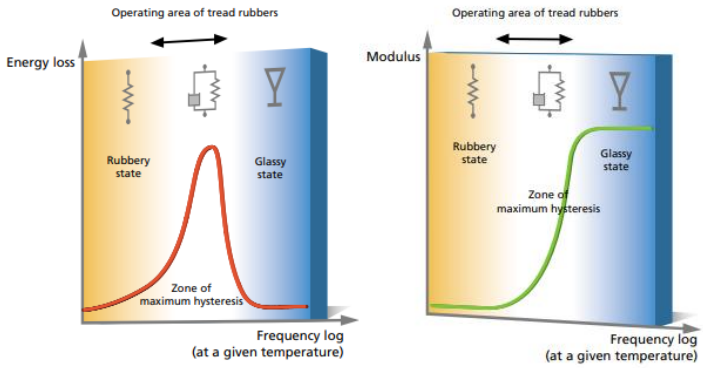


Figure 7. Influence of the stress frequency on rubber behavior [11]

At low frequency, the material deforms slowly and only a small force is needed to move the damper. The spring-like behavior dominates, so the material is mostly elastic with low hysteresis: typical rubber behavior. As frequency increases, both the force needed and the damper's resistance rise. Viscoelastic behavior becomes prominent, with a frequency range where grip is optimal and hysteresis reaches a maximum. At very high frequencies, the material becomes almost undeformable, which significantly changes its mechanical properties [11].

b) Influence of temperature

In contrast to the stress frequencies dependency, the rubber's modulus is high at low temperatures, making the material stiff and brittle, while at high temperature the modulus is low, resulting in a soft and elastic material. Figure 8 show this. Around the glass transition temperature (T_g), the material is most viscous: polymer chains move while rubbing against their surroundings, generating hysteresis and giving the material a viscoelastic behavior [11].

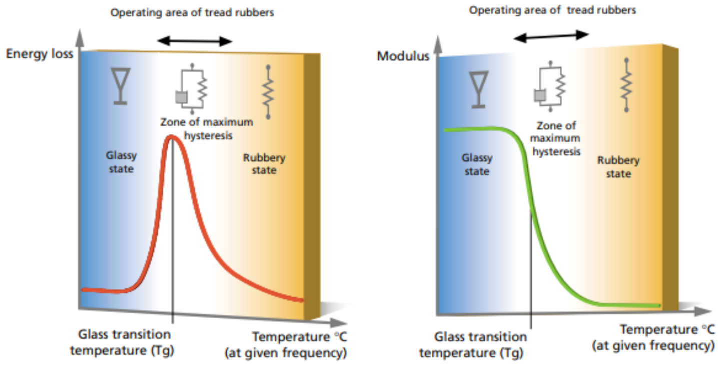


Figure 8. Influence of temperature on rubber behavior [11]

c) Frequency-temperature equivalence

Based on the rubber characteristic presented in point a) and b) there is therefore a relationship between load frequency, temperature and modulus. And this is well summarized by this sentence: "Whenever the stress frequency is increased at a given temperature, the material becomes rigid. Whenever the material heats up at a given stress frequency, it becomes softer." [11].

2.3.3 Mechanisms involved in rubber/ground friction

The grip of tires is mainly explained by two mechanisms of stress that occur due to relative slipping between the rubber and the ground.

a) The road roughness effect

Figure 9 models tire tread indentation on a road surface using a spring-damper system, showing how slippage creates hysteresis. It also features a graph illustrating the relationship between road roughness frequencies and grip, with optimal grip at certain frequencies.

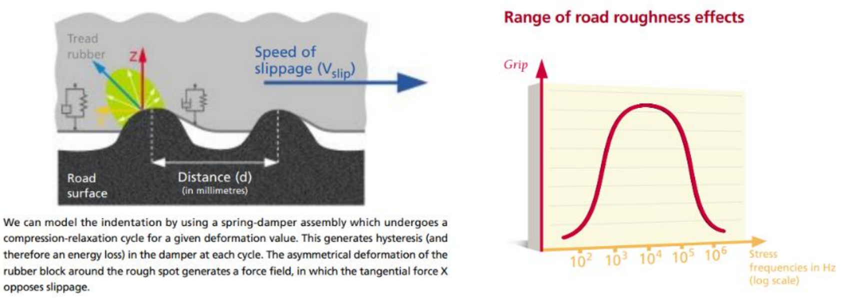


Figure 9. Road roughness effect diagram [11]

It is characterized by deformation of the rubber as it conforms to surface roughness, producing a flow with delayed recovery due to rubber hysteresis.

This asymmetric interaction around the asperities generates reaction forces that oppose sliding and depends strongly on the loading frequency, which must lie within an optimal range to maximize grip [11].

b) Molecular adhesion

This phenomenon is due to Van der Waals molecular interactions between the rubber and the ground, where bonds continuously form and break during a cycle, creating viscoelastic work that generates forces opposing sliding (See Figure 10). The optimal loading frequency varies with temperature and sliding speed, with a range of 10^6 to 10^9 *Hz* that maximizes adhesion forces by preventing significant slip [11].

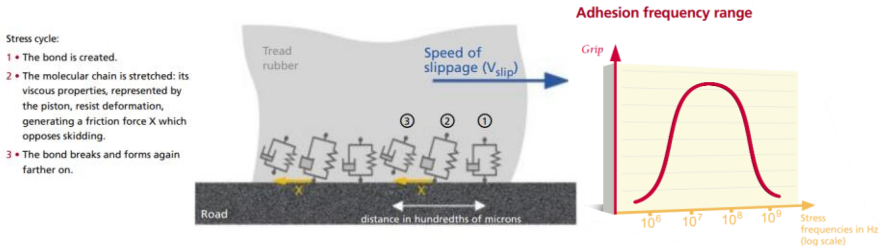


Figure 10. Molecular adhesion diagram [11]

2.4 The phenomenon of tire wear

2.4.1 Generalities

a) Definition and description of tire wear

The definition of tire wear can change depending on needs and descriptors, hence the importance of defining it clearly in the context of this thesis. In general, tire wear manifests as a loss of material on the tread.

According to "Wear in 60 pages [L'usure en 60 pages]" [12], a speed mismatch occurs during acceleration or braking, which induces a progressive shear within the rubber layer as it passes through the contact patch (CP). During its passage in the CP, the tread block continually attempts to recover its original undeformed shape. It is at the exit of the CP, when the normal pressure begins to decrease, that relative slip between the tread and the road appears, causing the block to rub against the surface and thereby generating wear [12]. This explanation (where wear occurs only at the CP exit) holds only for small slip angles, and thus for passenger car or truck applications, but not in motorsport.

In motorsport, the demand can be such that the entire CP may be sliding. The wear mechanisms will be discussed in Section 2.4.2.

It is important not to confuse wear with endurance and degradation. Endurance and degradation relate more to the tire's ability to remain performant after having undergone a certain amount of wear. While wear is the loss of material on the rubber tread. Moreover, to limit the scope of this study, wear of any component other than the tread will not be considered.

b) Quantification of wear

It is possible to quantify wear by measuring a loss of mass and/or a loss of height on the tread. In a more qualitative manner, the facies (the appearance of the worn surface of a tire or sample) can also be examined following a wear test [13].

There are two possible ways to characterize wear:

- The 'wear profile', corresponding to the distribution of wear across the tread surface on a tire. This depends not only on the material but also on usage and vehicle characteristics (camber, toe, slip angle, etc.).
- The local wear rate ($V_{u,loc}$), see paragraph below. Related directly to the compound itself.

c) Local wear rate

This wear rate can be expressed with two units: mg/mm_{slip} (loss of mass) or mm_{loss}/mm_{slip} (loss of height). In the first case, the measurement refers to the weight of the material lost, while in the second, it indicates the reduction in tread height. Both cases are linked by the material's density, taking into account the contact surface. Thus, wear rate may be defined over a specified distance, e.g., per meter or per 100 km [14].

2.4.2 The different wear mechanisms

Several physical wear mechanisms are involved when discussing tread wear. The phenomena described below are well established for passenger car (PC) and truck (TR) compounds, but their effects are not yet fully certain for motorsport (MSP) compounds. In general, there are three main wear mechanisms: fatigue wear, smearing, and tear-out wear [13].

a) Description of the '3rd body'

Before describing these mechanisms, it is essential to introduce the concept of the "third body". In the 1970s, Godet introduced the notion of a "third body" present at the interface between two solids in contact and sliding [15]. This third body eliminates direct contact between the two solids and thus influences sliding speed and wear [14, 15].

The baseline models from the two earlier studies ([15, 16]) were integrated to propose a comprehensive wear model incorporating the third-body concept [16]. In this view, particles released from the rubbing bodies act as a third body (providing protection, solid lubrication, etc.) before being expelled from the contact.

The mass of the third body (M_i) within the contact is determined at each instant by the competition between the particle creation/detachment flux (Q_S) and the ejection flux (Q_W). Fillot and al. demonstrate that the fluxes converge to a steady regime with stabilize third body mass [14, 16], this is show in Figure 11.

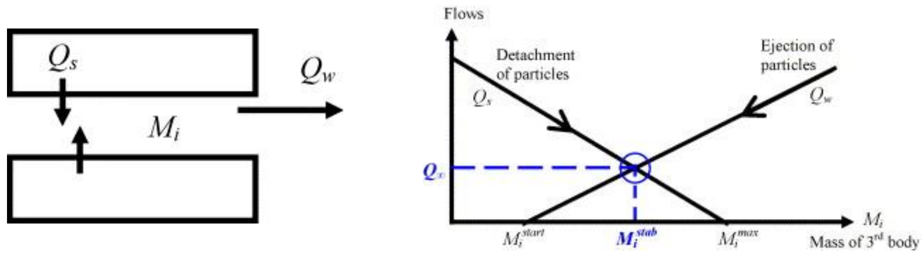


Figure 11. a) Simplified representation of a tribological contact. b) Diagram of the competition between creation and ejection fluxes as a function of third-body mass [16].

b) Fatigue wear

This type of wear is characterized by the formation of a degraded surface layer (DSL) and an increasing mass loss originating from this layer. This mechanism produces a smooth, homogeneous surface appearance [13].

O. Ronsin provides an excellent description of this mechanism for passenger car (PC) and truck (TR) mixes [17]. When “the rubber rubs on the ground and encounters successive indenters” [17], the rubber is highly stressed, and each indenter generates a mechanical stress field. Under this stress field, the material is damaged at the surface, notably through the breaking of links between elastomers. The material degrades until it becomes sufficiently viscous at the surface, allowing mineral inclusions from the ground to penetrate; this is how the DSL forms [17]. Subsequently, as the DSL becomes enriched with mineral inclusions, it dries out and forms clumps and particles that agglomerate into larger particles. Eventually, these pellets detach from the tire and become wear debris.

With motorsport tires, a fluid degraded surface layer (FDSL) can also be observed. This consists of the formation of a thick, mobile layer on racing tires, composed of worn rubber and gravel that adhere easily due to the sticky nature of the mix. This layer is known to move laterally on the tire, which can lead to a loss of grip, and it often must be removed manually upon return to the pit (service stop during racing) to optimize performance or enable wear analysis of the tire [13].

c) Smearing (“Poissage” in French)

Smearing can be understood as what blackens the ground, due to the sticky nature of the rubber compound. It is therefore a crucial wear effect in MSP, where mixes are quite soft and sticky.

Smearing mechanism is characterized by the deposition of a sticky layer of material from the mix within the contact trace over successive friction cycles. This mechanism alters contact conditions by masking asperities and changing the coefficient of friction, which is generally considered undesirable. Key features of smearing include the glossy appearance of the worn surface and its sticky texture [14], as shown in Figure 12.

Figure 12. Sample with smearing on the surface

It is possible that smearing represents the predominant wear mechanism of tires in motorsport. Due to repeated passage of many vehicles on the same track, the contact becomes very clean, with very little dust/minerals [18]. However, this still needs to be verified.

d) Tear-out wear

Tear-out wear is described by G. Lufau in his report [14] as “a propagation of cracks which, as they open, raise small ripples [translated from French]” [14]. This wear thus appears as ‘wrinkles’ on the tread surface, described as oscillatory wear with more or less regular intervals as shown in Figure 13. It should therefore be understood that this mechanism is primarily governed by crack initiation and propagation.

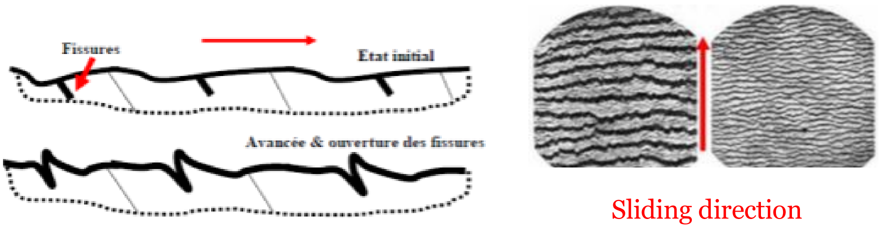


Figure 13. Formation mechanism of characteristic wear cracks due to tear-out wear [33]

This mechanism appears when the demands are more extreme than for the other mechanisms [13]. And according to B. Paixão, this phenomenon can be related to what is called 'graining' in MSP (see Figure 14). Indeed, he noticed that the appearance was very similar even though the connection between the two has not yet been established [13].

Figure 14. Photo of a tire tread showing graining [26]

2.4.3 Influential factors for tire wear

a) Use-wear sequence

The use-wear chain is very useful for linking driving and track layout (use) to local solicitations at a microscopic scale (wear) [12]. It is a highly influential factor, as use and the loads applied to the vehicle as a whole, have a major impact on tire wear. This chain is illustrated in Figure 15. This is especially true in motorsport, where use is extremely demanding on the tire: braking, acceleration, high-speed cornering, aerodynamic downforce, etc.

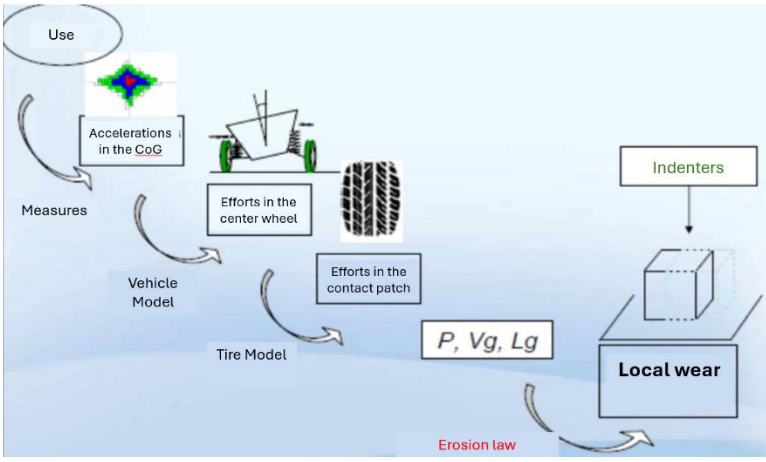


Figure 15. Use-wear sequence [translated from French] [33]

b) Contact pressure

The normal pressure between the material and the ground during friction is a key parameter for the wear rate. For the remainder of the work, it is assumed that the pressure "felt" by the tread is almost equal to the tire's internal pressure. Load transfers are therefore not considered here. M. Vantal agrees that [12]:

$$V_u \propto P_c^{\delta} ; with\ \delta \in \mathbb{R} \quad (2)$$

c) Temperature

Temperature also has a very significant effect on $V_{u,loc}$, although P.-A. Toulemonde et al. concludes that accounting for temperature does not significantly improve the correlation between the scuffing protocol and tire tests [19]. Ronsin et al. concludes that "tire wear rate varies greatly with temperature" and that four physical mechanisms affect the wear-temperature dependence [20]:

- The glass transition temperature T_g
- The frequency-temperature equivalence
- The modulus level at the operating point
- The shape of the mechanical property spectrum

In MSP, rubber and ground temperatures are very high. The tire has a limited operating temperature range, and it is important to be in the right place.

d) Sliding length

It is important to distinguish between total slipped length and slipped distance per event. According to G. Lufau, "the slipped length per cycle can lead to a reversal of the ranking" [14]. The total length has a limited impact, whereas the slipped length per cycle has a significant impact.

e) Sliding speed

According to J. Parent, sliding speed has a linear effect on $V_{u,loc}$, with a greater influence on local wear performance, improving correlation with measurements taken on the tire [21]. Its influence appears to be smaller compared to other factors. B. Paixão wrote in his report [13] that:

$$V_u \propto V_g^{\alpha} \, ; with \; \alpha \in \mathbb{R} \tag{3}$$

Sliding speed is a very important factor in this case, because it affects the frequencies at which the material is under stress. At low sliding speed, the solicitation frequencies will be lower than at high sliding speed.

f) Grounds

The ground can be measured at two scales: its macroroughness and its microroughness as shown in Figure 16. Macroroughness is related to the size of the aggregates that compose it, while microroughness is related to the surface asperities of these aggregates [11].

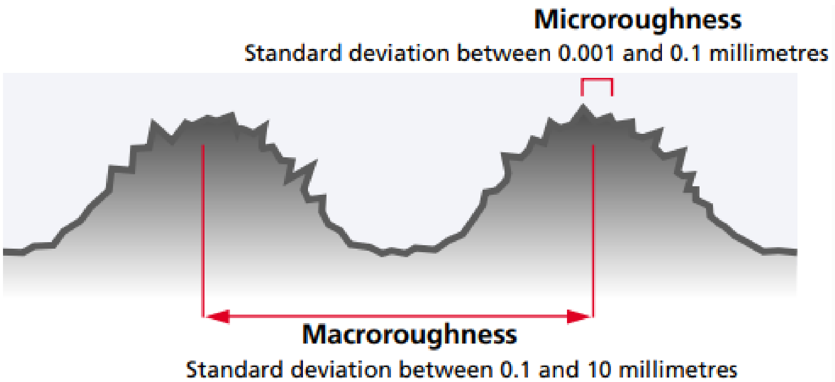


Figure 16. Diagram of ground roughness [11]

As explained in Figure 17, it is possible to sort the grounds into four categories. These grounds have very different impact on wear rate and wear performance [11].

The conclusion of the report by J. Parent et al. highlights the importance of cleaning the surface to improve wear performance repeatability in the experiments [22]. They observed less dispersion when the surface was cleaned (brushed) before each measurement. On average, cleaning the surface increases the wear rate because the surface becomes more aggressive [22]. An important finding from their research is that the nature of the surface affects the wear rate and the relative dynamics between mixes without reversing the rankings.

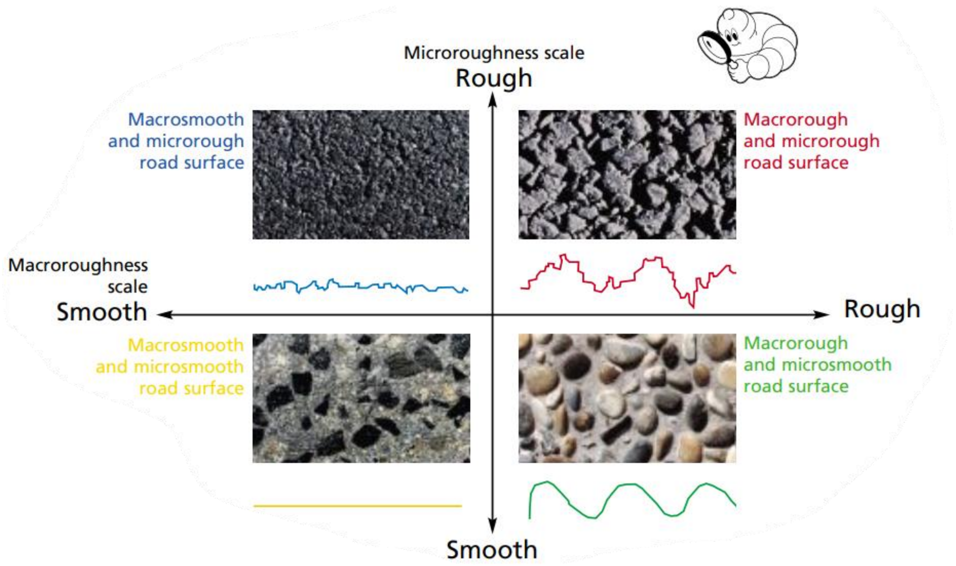


Figure 17. Ground classification based on their roughness [11]

g) Mineral inclusions (3rd body)

Several studies on wear describe that the wear rate is highly dependent on the amount of added inclusions (such as talc) [14, 17]. According to O. Ronsin, not adding them improves measurement's repeatability, but this is not realistic in the context of PC and TR applications. Mineral inclusions strongly influence the wear rate because they govern the fatigue wear mechanism: without a third body, wear is slower.

Today, the use of a third body for so-called "conventional" applications (notably PC and TR) is validated, but this is not the case for MSP. Indeed, it is still unclear whether using a third body is truly necessary to represent tire wear under motorsport conditions ("cleaned" track, vehicle passages). B. Paixão concludes that removing the third body helps improve wear-performance rankings [13]. He observed that results without a third body are closer to the reference performance values.

h) Other influencing factors

Other influential parameters exist and are cited in the report "Tribology for Wear [Translated from French]" [23]. These may be due to specimen preconditioning (manufacturing, rubber aging), environmental factors (humidity, atmospheric pressure, etc.), or the method used to measure the mass difference [23].

2.4.4 Operating point

In a materials wear context, the operating point consists of a triplet: contact pressure, temperature, and sliding speed. During rolling, each element of the contact patch operates at a unique operating point, and thus, at any given instant, the tread experiences an infinite number of operating points [14].

These three parameters are the main drivers of wear rate, and there is no single triplet that corresponds to a given case. This is why J. Parent and al. explain that a test protocol cannot be built around a single defined operating point, as it would not be representative of the diversity experienced by the tread compound [22]. "Moreover, the operating point (P_c, V_g, T_s) could vary from one compound to another [Translated from French]" [22].

2.5 Specificity of the tire wear for motorsport applications

In motorsport, tire wear differs clearly from conventional PC and TR contexts due to extreme operating conditions: high sliding speeds, elevated temperatures, high normal loads (including aerodynamic downforce), and sustained transient maneuvers such as hard braking, rapid acceleration, and high-speed cornering. These conditions "shift" the operating point across a wide and rapidly varying range, activating distinct wear mechanisms and interactions with the track surface. As a result, phenomena such as full-contact-patch slip, heightened hysteresis near the compound's glass transition, and tear-out or tack-driven wear can dominate. This section outlines these specific drivers, the resulting wear signatures, and their implications for performance, and test representativeness in motorsport.

2.5.1 Management of wear during the race

During a race, wear is often linked to degradation. In competition, tire wear leads to a degradation of tire performance. Indeed, "a tire's ability to generate grip decreases over time. This degradation in tire performance means they do not last as long [Translated from French]" [24]. Wear is seen as one of the causes of tire degradation: as the rubber rubs against the track, it wears, leaving less rubber to generate heat. As a result, tire temperature drops and the rubber becomes stiffer, which reduces grip and thus increases wear, and so on [24]. It is therefore essential to reduce wear to preserve the rubber and maintain grip for longer during a race.

2.5.2 The wear phenomena specific to motorsport

In addition to typical wear, motorsport applications experience three specific wear phenomena which are graining, blistering and excessive pick-up.

a) Graining

Graining is more of a mechanical process. It may appear during the first laps of the race. This can be caused by the track that is too cold for the rubber compound or by using a compound that is too soft for the track [25]. The appearance of graining is characterized by the presence of small pull-out ridges in the rubber, as shown in Figure 18. The impact on grip is very significant [26]. Graining occurs when the operating temperature of the tire is lower than its glass transition temperature (T_g) [27].Motorsport tire designers will do their best to avoid creating tires that easily develop this type of wear, as it is not desirable for overall tire performance.

Figure 18. Example of graining on the surface of a tire

b) Blistering

Blistering is a severe tire degradation mainly caused by overheating. When the tire overheats, it releases gas internally, which creates pockets that can burst and form blisters on the tire surface. This can occur if the rubber compound is too soft for the track or if the track is too hot for the tire [26]. Other causes of tire overheating can include oversteering and understeering, as well as excessive tire pressure. Blistering occurs when the operating temperature of the tire is higher than its glass transition temperature (T_g) [27]. Examples of blistering are presented in Figure 19.

Figure 19. Example of blistering on the surface of a tire

c) Excessive pick-up

Pick-up corresponds to the process of rubber pieces on the track sticking to the tire. The pieces present on the track can adhere to the tire when it is hot and the pieces are cooler [26]. This typically occurs when the vehicle is off the racing line and collects the rubber crumbs. Figure 20 illustrated this. This type of wear will not be focused on in the current master's thesis.

Figure 20. Tire with excessive pick-up [26]

3 Tools and methods

This section outlines the specific tools and machines employed in this thesis, detailing their roles in conducting experiments and analyzing tire performance. It starts with an overview of the software tool "TameTire" developed by Michelin and two tribometer machines: the µPiste tribometer and the LAT100 tribometer. Next, it explains how to analyze the specific test conditions to create protocols suited for different track conditions. The method for measuring abrasion is also covered, detailing how the LAT100 and µPiste machines are used; this subpart discusses how the protocols were designed and created. Finally, it provides a brief description of the compounds tested in this research.

3.1 Simulation software and experimental setups

3.1.1 Software simulation TameTire

TameTire is an advanced tire simulation model developed and own by Michelin [28]. Unlike empirical models, TameTire is based on physical principles and includes parameters like contact patch dimensions, tread and sidewall stiffness, and rubber compound properties. This allows it to predict tire performance more accurately by factoring in the thermal effects of rubber. It provides a detailed physical representation of tire behavior under various dynamic conditions, enabling car manufacturers and racing teams to enhance vehicle performance and handling. The first version is a *Single-Rib* simulation that considers the tire as a whole. In its *Multi-Rib* version, TameTire discretizes the tire into five ribs across the width of the tire and into 10 points per rib in the area of the contact patch where slipping occurs, as well as in the longitudinal direction (see Figure 21). At each time step, the model calculates several parameters in the slipping part of the contact patch.

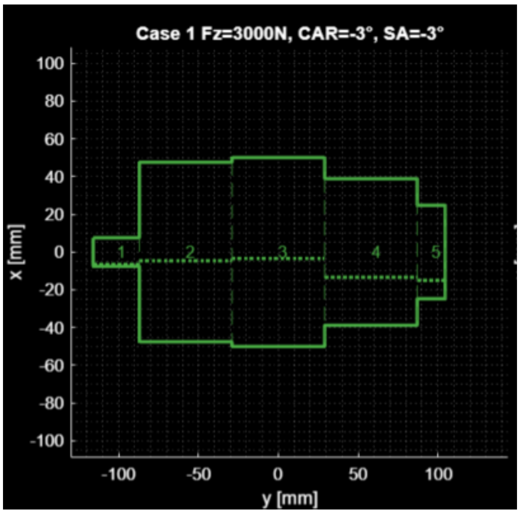


Figure 21. CP illustration in TameTire (extracted from TameTire)

Among the parameters calculated at each point are contact pressure, slip speed, tangential force and temperature. Additionally, other parameters are calculated per rib: the length of the contact patch, the percentage of the adhering part, the slip angle, and so on.

Furthermore, it is possible to calculate the local slip length using the length of the CP (L_x), the percentage of adhering part (pap), the slip angle (δ^*), and the slip rate (SR) by using the formula (extracted from [29]):

$$L_g^{CP} = \sqrt{\delta^{*2} + SR^2} \times L_x \times (1 - pap) \quad (4)$$

TameTire is a model that works very well in certain cases, but describing its complete functioning is beyond the scope of this thesis. It is important to note that the model needs to be 'fed' to operate optimally, which is why there is a need for a precise formulation of the cohesion factor derived from laboratory tests. The cohesion factor is a scaling factor translating the force which unites the molecules. The idea behind that is to 'feed' TameTire with experimental analytical data.

3.1.2 µPiste tribometer

µPiste is a tribometer that rub with a circle sample. Figure 22 illustrates the 3D image of the real machine.

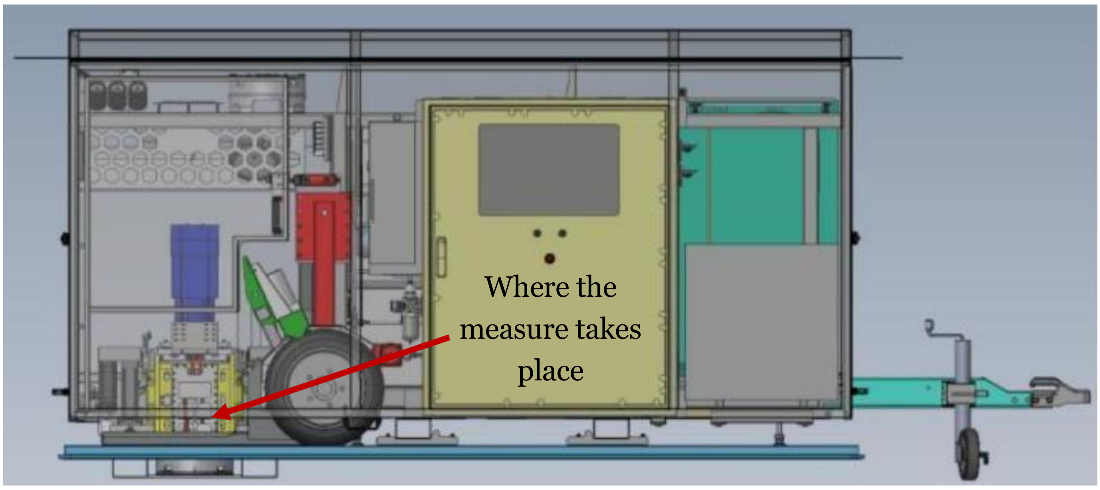


Figure 22. 3D modelisation of the µPiste machine

The µPiste machine applies a force to the rubber on the ground through vertical displacement of the sample, a torque, and a rotational speed via the rotation of the rubber sample; it also provides temperature control and regulation by heating from within the sample. The ground is fixed as shown in Figure 23.

This machine allows to test tread compounds efficiently with specific conditions. The following inputs can be controlled:

- the contact pressure (pressure apply to the sample on the ground): up to 3 bars.
- the sliding speed (using the rotational speed of the sample): from 0.1 m/s to 4 m/s.
- the surface temperature: up to 120°C.

The laboratory ground can be modified to create different roughness parameters on the machine. Additionally, the machine can be repositioned to conduct tests on actual surfaces (track's asphalt, for example).

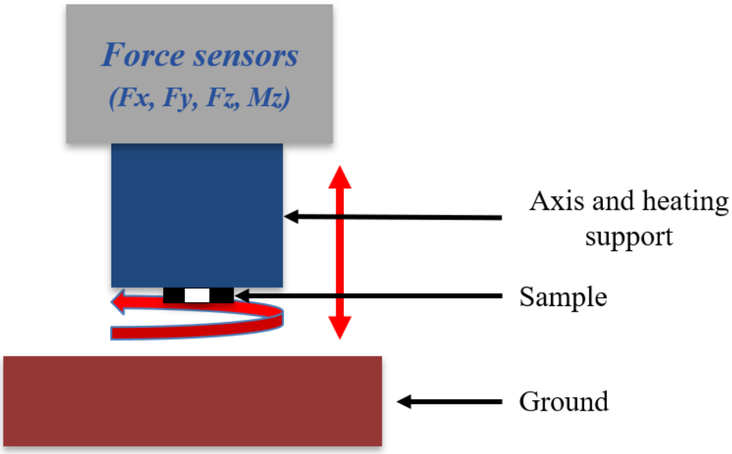


Figure 23. Schematic view μPiste tribometer with displacement

3.1.3 LAT100 tribometer

The LAT100 tribometer (shown in Figure 24) can be considered as a rolling tribometer [30]. It is designed for laboratory testing of rubber compounds, specifically focusing on their abrasion resistance and friction properties. This instrument simulates real road conditions to enable accurate and reliable analysis of tire tread performance, thereby facilitating research and development in tire technology.

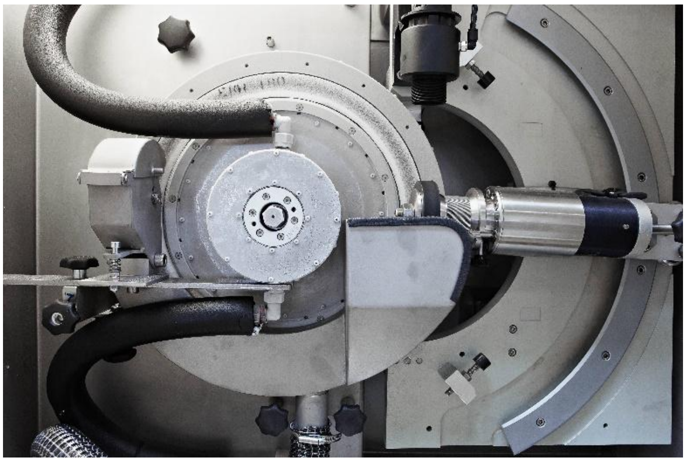


Figure 24. LAT100 machine [30]

Establishing a dry grip testing procedure with the LAT100 requires consideration of various factors. Additionally, understanding how these factors affect friction is essential. Table 1 lists all the key factors, including the LAT100's inputs and outputs, their measurement ranges, and the details of the testing procedure.

Table 1. Parameters for the LAT100 [7]

LAT100 input parameters	*Test procedure factors*	*LAT100 output parameters*
Slip angle (-45°-45°)	Disc roughness	Friction force (2 to 100 N)
Speed (0.002 to 100 km/h)	Wheel diameter	Side force (2 to 120 N)
Distance (1 m to 20 m)	Temperature	Surface temperature of sample
Normal force (2 to 140 N)	Pressure distribution	
Powder (0 to 100% dosage)	Friction components	
Disc roughness		
Disc temperature (-20°C to 80°C)		
Air temperature (-20°C to 80°C)		

Figure 25 shows a schematic view of the LAT100 machine to understand the kinematic of the machine. Especially, it shows how the load and the slip angle are applied in the machine.

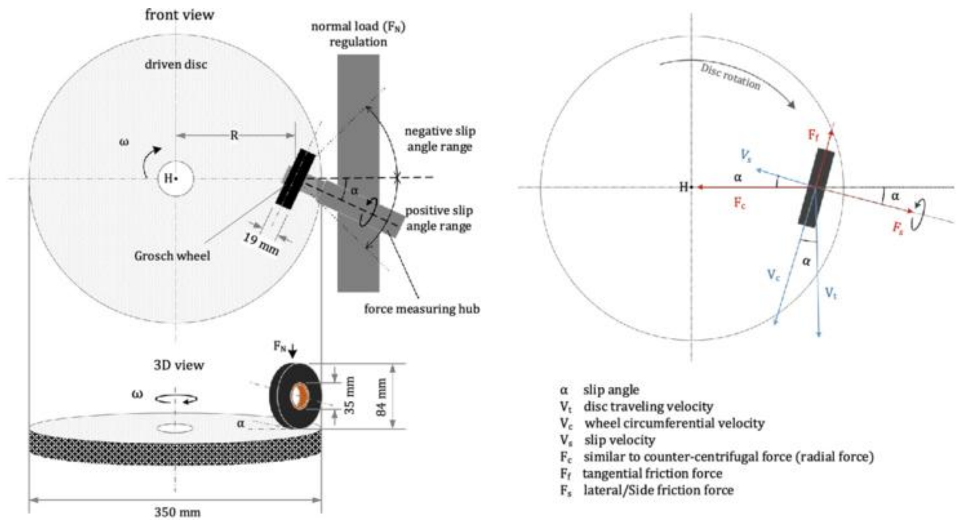


Figure 25. (Left) Schematic view of the LAT100 test set-up, (Right) The trigonometry of velocities and the resultant forces of the Grosch wheel sample on the LAT100 counter-surface disk at slip angle a [34]

Additionally, the machine can also be used with a dynamic mode, with this mode some input parameters can be dynamic inputs: the slip angle, the speed of the disc and the load. The idea with that was to simulate a track lap with a material point of view, by moving the sample and changing the load and the speed according to a track lap data (see Section 3.3.1).

3.1.4 Mass measurement

One of the main things to consider when studying tire wear in a quantifiable way is how to measure the loss of material during the test. For this, the mass of the sample is measured before and after the test protocol in order to determine the material loss. To be accurate and repeatable, a precise balance is used (see Figure 26) and a test protocol with specified temperature and treatment of the sample is necessary for reproducibility.

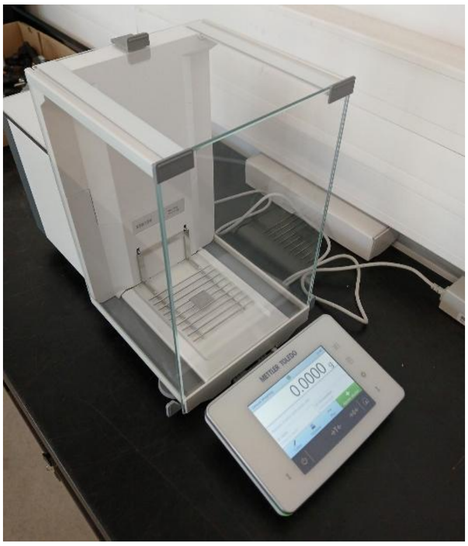


Figure 26. Precision balance used for mass measurement

After some tests to evaluate the repeatability of the measure, it was decided to measure the mass before and after at the same temperature because it impacts significantly the dispersion of the measure. Indeed, it is assumed that the material is sensitive to humidity due to the volatility of certain components. Moreover, it is important to avoid 'human errors' with the balance, therefore, the decision was made to measure the sample twice, spaced in time. This method successfully produced results with acceptable dispersion (see Chapter 4): the criteria used was to have the smallest dispersion possible. To quantify it, the coefficient of variation (CV) can be used. The CV indicates how much variation exists in a dataset relative to its average: CV values below 5% signal very low variability and excellent repeatability; values between 5% and 10% indicate low variability; 10-20% indicate moderate variability; 20-30% denote high variability; and values above 30% reflect very high variability and limited reliability. In the context of the study in this thesis, a CV below 10% can be considered acceptable.

This is one of the major elements of the method, because the measurement of mass is a crucial step for dispersion in the developed method. Since it is a human who takes the measure of the samples before and after the test, one needs to make sure that the protocol is well described and that the measurement is done in a repeatable and reproducible way.

3.2 Analysis of the specific test conditions

The first idea for creating a reliable protocol was to match reality: what the tire experiences on the track. By setting the protocol at specific operating points, it was expected to achieve accuracy and activate the correct wear mechanisms in the tested compound.

The data used in this section come from the World Endurance Championship (WEC) during the 2025 season. Each team conducted multiple runs with various tire sets, with each run ranging from 10 to 30 laps depending on the track. Each tire set can withstand three runs. The majority of the analysis relies on data from the Le Castellet track, where a testing session took place. This track features a combination of low-speed, medium-speed, and high-speed turns, making it a strong representative of a car's performance. Figure 27 presents the speed profile of the track for an LMH (Le Mans Hypercar) car.

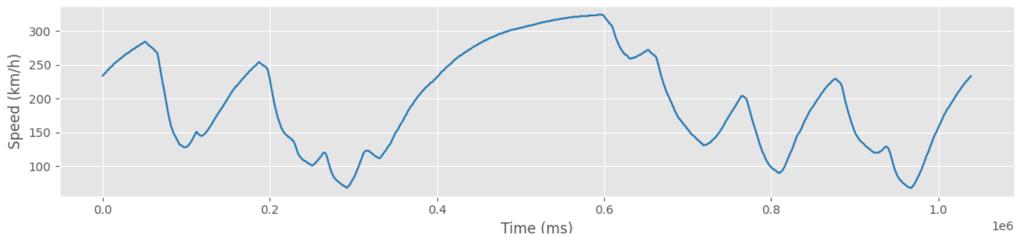


Figure 27. Example of speed profile for LMH Cars in Le Castellet

For all these parts, two datasets were used coming from TameTire Multirib model using two different cars (Car 1 and Car 2) on two different tracks:

- Spa-Francorchamps in Belgium
- Le Castellet in France

To avoid using a lot of datasets, the hypothesis that one lap can be representative of the whole run was made in the work.

3.2.1 Operating point analysis

"Operating points" refers to the triplet (P_c, V_g, T_s) that the tread compound experiences during a lap. The objective of this subsection is to estimate the appropriate ranges of operating points necessary for executing the protocol, in order to be representative of what the rubber experience in reality on the track. The idea here is to consider two main things when dealing with wear in motorsport:

- The level of wear that impacts the rubber instantly: the theoretical wear rate V_u.
- For how long this value of wear appears during a lap: the occurrence of the specific operating point.

Using these two numbers, the intention was to consider the intensity of wear at a given moment as well as the frequency with which that wear point occurs during a lap. For instance, a turn may be very demanding but appears infrequently during a lap, while a straight may be less demanding but occurs more often.

So, for each rib of each tire, two graphs were plotted.

- The first plot (Figure 28 left) represents the value "$V_{u,theoritical} * Probability_{occurence}$" in the $(P_c;\ V_g)$ plane. The $V_{u,theoritical}$ is calculated using a simple formula internal to Michelin, and the $Probability_{occurence}$ is equal to:

$$((Probability_{occurence})_a = \frac{\sum_{(P_c;V_g)_a} number\ of\ occurence}{\sum_{(P_c;V_g)_i}^{i\ \epsilon \mathbb{R}} number\ of\ occurence} \quad (5)$$

- The second plot (Figure 28 right) represents the average surface temperature for each couple $(P_c;\ V_g)$, also in the $(P_c;\ V_g)$ plane.

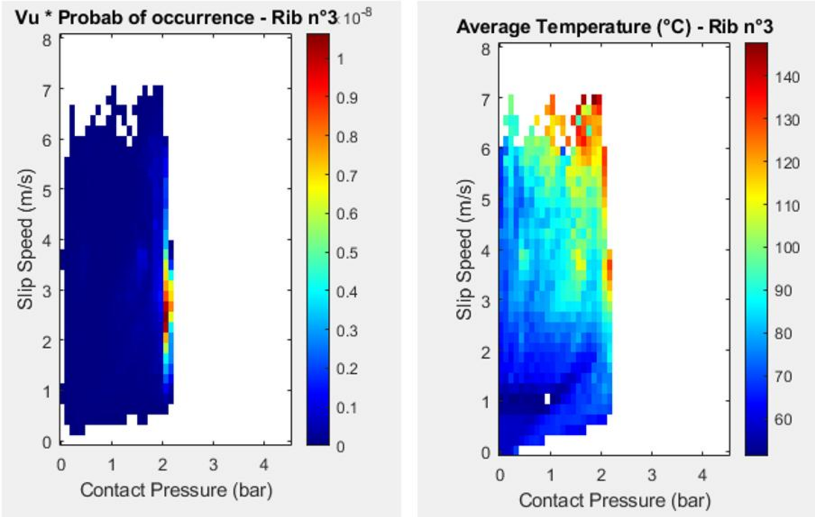


Figure 28. Example of operating point analysis for a front left tire - Rib 3 - Le Castellet

The whole analysis for each tire and each rib in Le Castellet and Spa-Francorchamps with the Car 1 is presented in Appendix A: Operating points analysis – Le Castellet track and Appendix B: Operating points analysis – Spa track. Furthermore, Figure 29 is showing an example for a front left tire, the value for each rib. Note that "Rib 1" always corresponds to the "inner rib", while "Rib 5" corresponds to the "outer rib" of the tire. The front left tire is just an example, but all four tires were used in the study.

From all these figures (Appendix A: Operating points analysis – Le Castellet track, Appendix B: Operating points analysis – Spa track), it is possible to deduce the most representative operating points for the intended use. Only the graphs corresponding to the middle ribs (2, 3, and 4) will be considered in the following analysis, as the shoulder ribs are not the most representative for typical usage.

- For the **front tires**: The highest probability occurrence for the three middle ribs are in the region between 2 and 2.2 bars of pressure, with slip speeds ranging from 1.5 to 3.8 m/s. The corresponding temperatures range from 70°C to 110°C.
- For the **rear tires**: The highest probability occurrence for the three middle ribs are in the region between 1.8 and 2 bars of pressure, with slip speeds between 1.5 and 3.5 m/s. The corresponding temperatures range from 70°C and approximately 100°C.

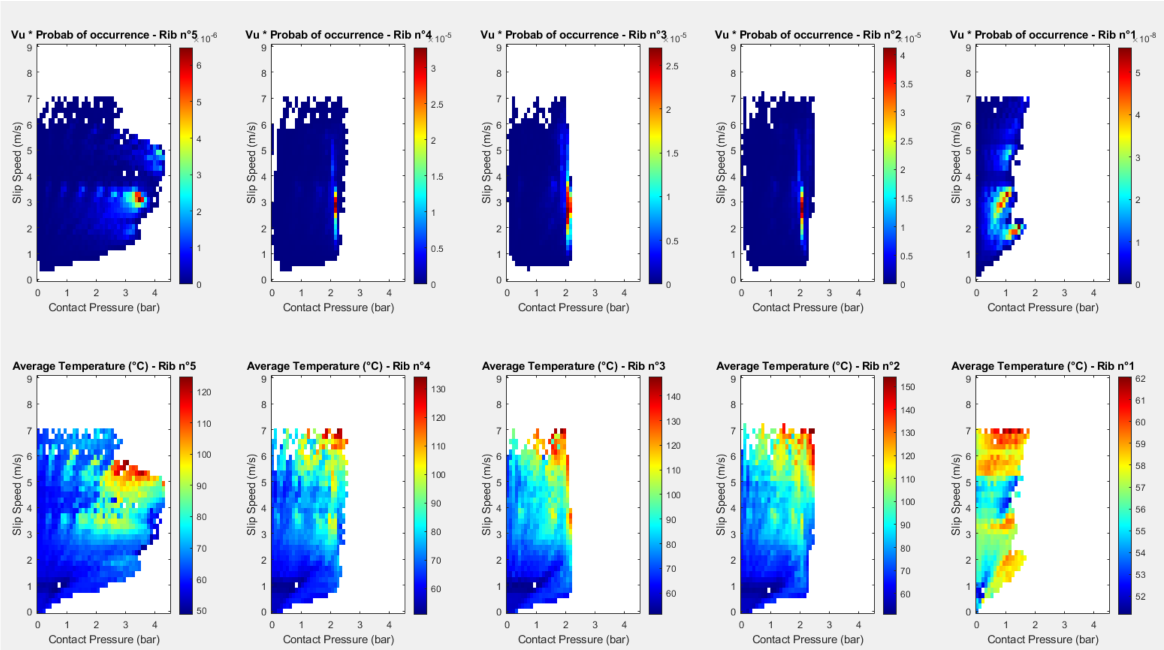


*Figure 29. Example of operating points analysis for a front left tire – Vu*Probability of occurrence (top graphs) and temperatures (bottom graphs) in the (Vg; P) plane – Le Castellet Car 1*

3.2.2 Sliding length l_g

The objective of this section is to estimate the order of magnitude for the total sliding length experienced by the tire during a lap. It is important to note that deriving a single value that uniformly applies to all parameters is not feasible, as the sliding length is highly influenced by factors such as the vehicle, the driver, the tire characteristics, the track, and the conditions. However, by employing a mean value for the sliding length, it is anticipated that the protocol will expose the rubber in a manner consistent with real-world usage.

Figure 30 and Figure 31 show the comparison of the sliding length per rib and per tire for both tracks. The calculated sliding distance corresponds to the total sliding distance experienced by the tire or by the rib of the tire.

Table 2 presents the key values for comparing the data from both tracks. By employing the analogy between sliding length and tire wear, it can be concluded that Spa-Francorchamps is more demanding on the tire than Le Castellet ("demanding" in this context means that it induces higher wear because of the track specificities). The rear tires exhibit more sliding than the front tires. Additionally, since both tracks involve more turns to the right, the left tires experience more sliding than the right tires, notably due to cornering load transfer.

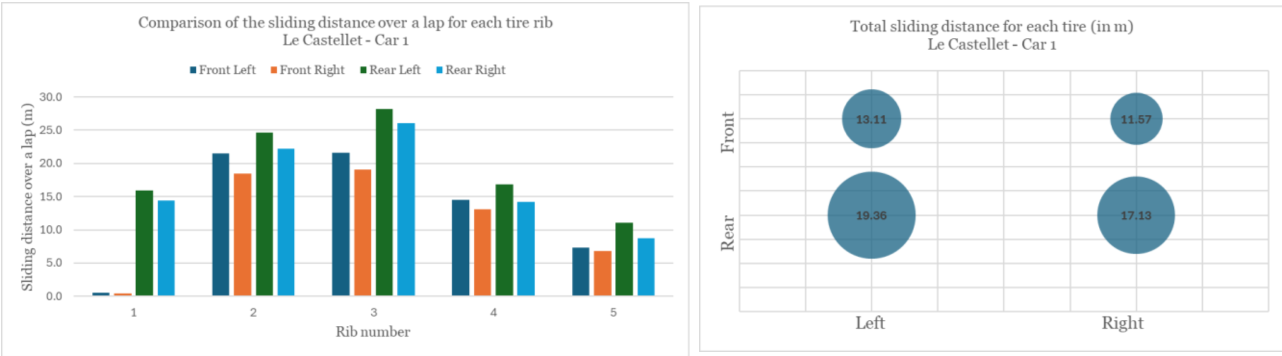


Figure 30. Sliding distance comparison for one lap a) per rib and b) per tire at Le Castellet

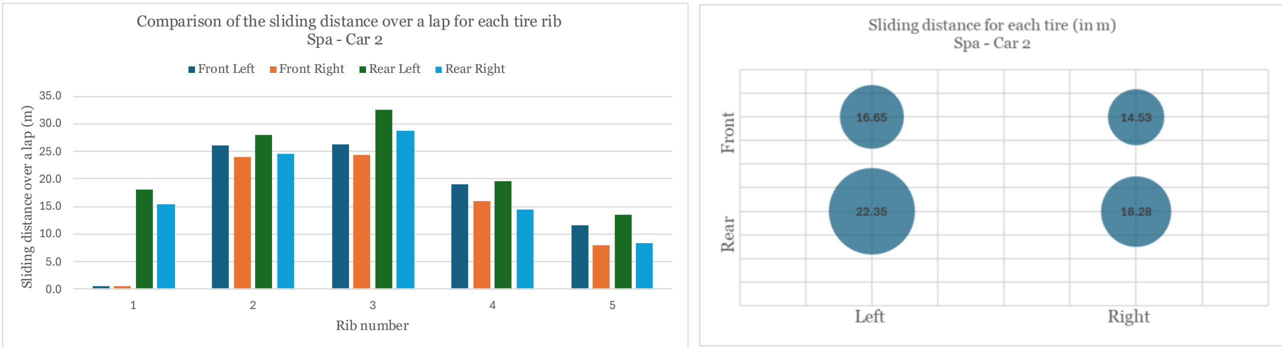


Figure 31. Sliding distance comparison for one lap a) per rib and b) per tire at Spa-Francorchamps

Table 2. Comparison of sliding length for two tracks

Name of the calculated mean	*Sliding length (in m)* *Le Castellet – Car 1*	*Sliding length (in m)* *Spa – Car 2*
3 ribs middle – Front tires	18.04	22.56
3 ribs middle – Rear tires	22.03	24.64
Front tires	12.34	15.59
Rear tires	18.24	20.31
For all tires, all ribs	**15.29**	**17.95**

3.3 Method of abrasion measurement

3.3.1 LAT100 Track lap simulation

The idea with the LAT100 protocol is to reproduce the conditions seen on track by the rubber tread from a material point of view.

To achieve this, a Python code was created to enable the transfer of a MATLAB table from a simulated lap using TameTire to a specific LAT100 file that contains the necessary information for the simulation cycle to take place. Given that the machine's speed is limited to 30 km/h for the specific conditions, a 'scaling factor' must be applied to reduce the speed during the lap. It was decided to simulate a circuit lap at a constant distance to keep this parameter consistent with a real lap. Thus, the time will be dilated in the emulation for the LAT100.

Figure 32 shows the input orders given, and the output of the machine in order to compare each data and see if the machine is capable to reproduce the track dynamics.

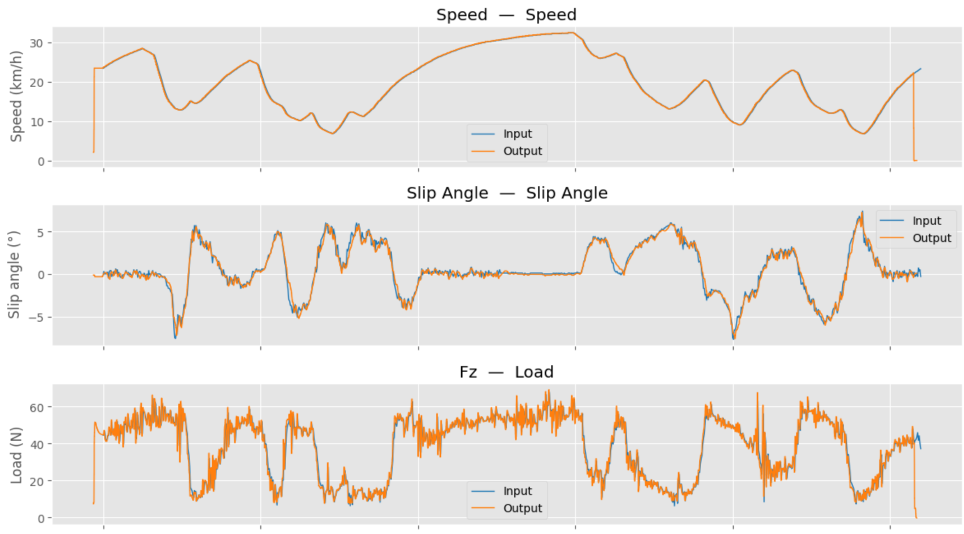


Figure 32. Input vs. output LAT100 protocol for the vehicle speed, slip angle and vertical load

Since the data are sufficiently close (see the differences in Figure 33), it can be concluded that the machine is able to follow the lap instructions provided. While some differences appear significant for the slip angle, this is due to the data being close to zero.

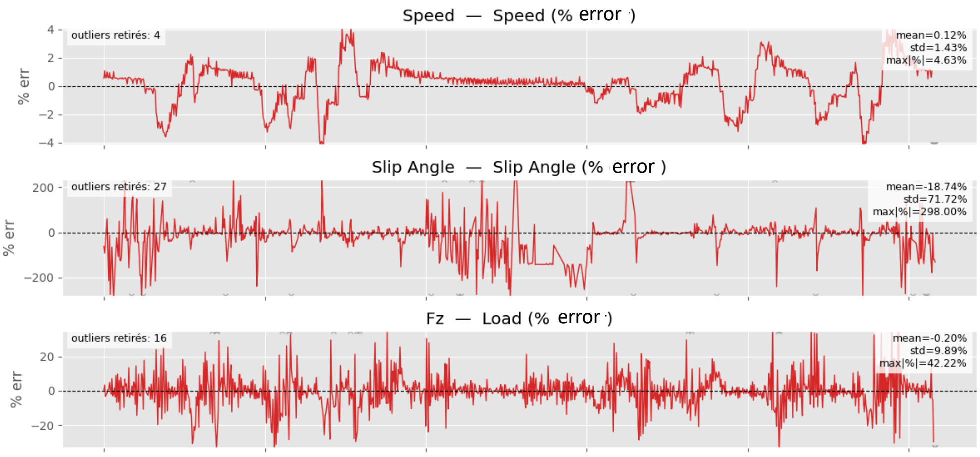


Figure 33. Differences between input and output LAT100 protocol

Moreover, the side force and the surface temperature can be extracted from the TameTire data and from the LAT100 output. The comparison between both data sets is exposed in Figure 34. Since it is challenging to reproduce the actual temperature changes on the machine, it was decided to calibrate the mean value of the measured surface temperature with the mean value from the TameTire data. Indeed, under real conditions, at high speeds, tires are cooled by the air blowing, while during braking the tires are heated by the braking system; which is challenging to reproduce with the LAT100 machine.

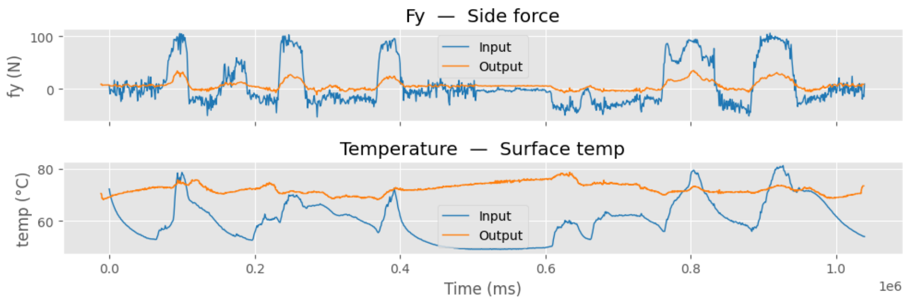


Figure 34. Input (TameTire output) vs. output LAT100 protocol

This protocol is not still fixed and approved, and it is currently under testing for repeatability and reproducibility of the mass loss (see results in the Section 4.1).

3.3.2 μPiste friction protocol

The initial concept for the protocol was to focus on realistic operating points based on the available track data. To achieve this, data from the analysis of the operating conditions were utilized (Section 3.2). Consequently, the sliding speed, contact pressure, and total sliding distance were selected. Given that the temperature cannot be fixed for comparing the different mixes (temperature are too important for comparing mixes), it was determined not to set a specific temperature and to conduct the same protocol at various temperatures. Indeed, since the mixes do not share the same glass transition temperature, it is unfair to rank them at a single temperature.

The protocol itself corresponds to several cycles with a fixe temperature and a fixed contact pressure, the sliding speed varies between 1.5 m/s and 4 m/s. A small cycle was added at the end in order to remove the rubber pellets created during the protocol, at low temperature and sliding speed.

The first step with this protocol, is to make sure it is highly repeatable, reproductible and reliable to what is to be measured. So, the facies were compared to tire wear facies, since the goal is to have something that is as close to how it looks like in reality as possible: not too much graining for example. Several protocol tests were carried out before reaching this phase. Sample's facies are exposed in Figure 35.

Figure 35. Example of sample's facies obtained with the µPiste's protocol

To ensure the reproducibility and repeatability of the protocol, several tests have been made using the same compound, the same protocol in the same conditions to compare the loss of mass obtained. Results are exposed in the Section 4.2.

3.4 Description of the compounds used

For all the tests of the thesis, specific rubber compounds have been made specifically for the needs of the thesis. These compounds are all analytical compounds meaning that they cannot be used to make real tires because of their proprieties. But these compounds are very useful to make comparison of rigidity or T_g for example.

Table 3 describes the compounds used during the thesis with the associated theoretical properties. The properties of the compounds are intentionally presented without units on a base of 100 to maintain the confidentiality of the mixes, as they are proprietary to MFP Michelin. However, the trends among the compounds remain consistent, allowing for effective comparison between them.

Table 3. Compounds general description

ID Compound	Effect	Tg (base 100)	Rigidity G* (base 100)
Mix 1	Reference 1	100.0	100.0
Mix 2	Tg+; Rig+	142.8	113.5
Mix 3	Reference 2	122.5	127.0
Mix 4	Rig+	126.1	151.4
Mix 5	Reference 3	103.6	110.8
Mix 6	Rig + A	124.3	145.9
Mix 7	Rig + B	124.3	148.6

There are three references mixes: Mix 1, Mix 3 and Mix 5. Each time, the mixes below the reference share the same base, with some change leading to higher or lower T_g/Rigidity. The "+" in the table stands for "higher".

The first two mixes (Mix 1 and Mix 2) share the same base and can be directly compared. Mix 2 shows both increased rigidity and T_g effect. To create this mix, method A and B were used together.

Mix 3 and 4 should be compared to each other. Mix 4 exhibits a higher rigidity (Rig+) obtained using method A, which corresponds to an increase in the number of crosslinking bridges.

Mix 5, Mix 6 and Mix 7 should be compared together. Mix 5 is the reference and the two other mixes have a higher rigidity but using two different methods (A and B) to get this higher rigidity. Both mixes have a similar rigidity G^* and the same T_g. Rig+A corresponds to an increase in the number of cross-links, and Rig+B corresponds to a decrease in the plasticizer volume fraction in the system. Comparing these mixes is particularly relevant since they have nearly identical mechanical properties.

4 Results and findings

This section aims to present the key findings and results derived from the various studies conducted throughout the thesis. The first subsection details the outcomes obtained with the LAT100 tribometer, focusing on the observed surface characteristics and mass loss during the tests. The second subsection highlights the significant results gathered from the µPiste tribometer, including insights from repeatability tests, analytical effects, and a comparative analysis of the different compounds. To conclude, a brief summary will encapsulate the overall wear performance and enhance the understanding of wear behavior based on the findings.

4.1 LAT100 results

The LAT100 results can be divided into two parts: the facies analysis and the material loss analysis. As mentioned earlier, the protocol is a success because it can, in some cases, reproduce the type of wear that the material experienced in real track conditions.

Figure 36 shows a comparison between the input (expected output for side force and temperature) and the output of the LAT100 tribometer. The side force and the surface temperature compare the expected output with the actual output. The gap in the side force corresponds to the fact that the load is reduced to fit the machine requirements and there is still a need to understand how to recalibrate the output side force. The average temperature is calibrated on the average calculated temperature (in blue on Figure 36), as explained in the method part.

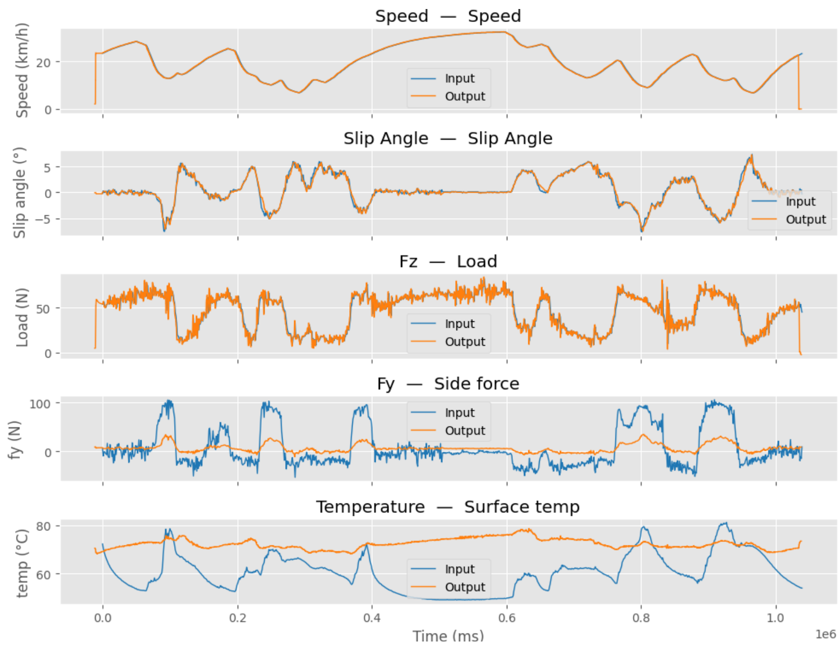


Figure 36. LAT100 input (end expected output) vs. output - Le Castellet Mix 1

Looking at the sample facies during the test in Figure 37 (specifically, at the midpoint of the protocol after completing a simulated lap, for example), it is clearly visible that a line of fluid material is above the 'healthy rubber'. This is what is called the FDSL, a characteristic that is seen on MSP tires used on tracks.

Figure 37. LAT100's sample facies during a test

Another thing to notice is the elevation of temperature during the test protocol, indeed since the rubber is rolling on the tribometer, the rubber sample heats up, and therefore not all laps are perfectly repeatable. All the temperature plots for one run and all the laps are exposed in Figure 38.

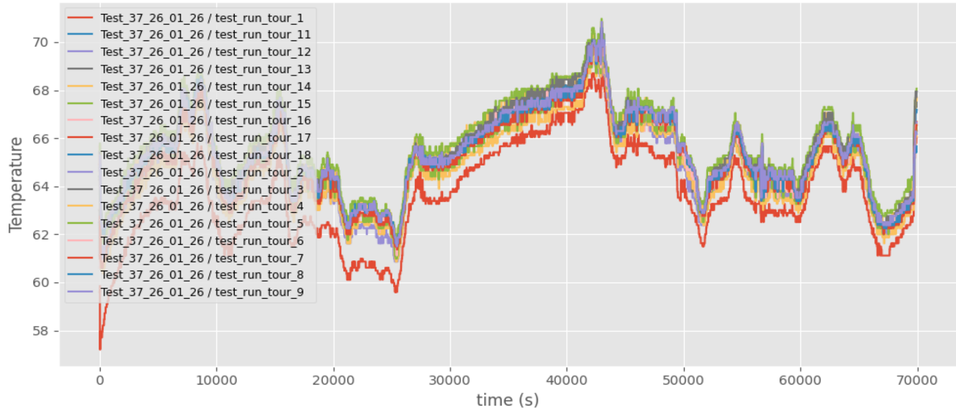


Figure 38. Temperature plots on 1 run - Le Castellet - Mix 1

As a conclusion of this subpart, a comparison of the mass loss has been made to see if the protocol can be repeatable and if it is able to rank different track simulation (Figure 39). For this the same compound (Mix 1) was used on two different tracks to study the repeatability: Le Castellet (France) and Spa-Francorchamps (Belgium). No clear trend can be identified from these graphs, apart from the decrease in mass loss over time observed in the Spa reproduction, which likely results from an unintended reduction in the distribution of the third body.

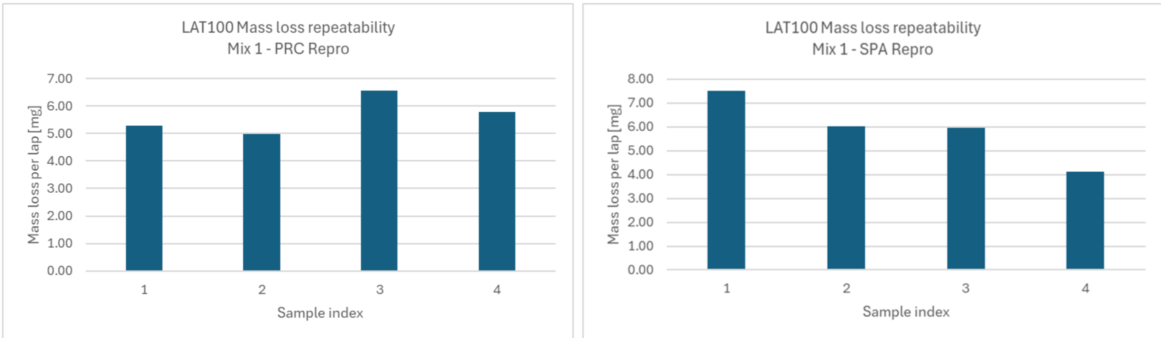


Figure 39. Mass loss - LAT 100 protocol - Mix 1 - Le Castellet (left) & Spa (right)

From that global mass losses, a corrected mean value and corrected standard deviation can be calculated (which are exposed in Table 4) by removing the furthest value for each track.

Table 4. LAT100 mass loss repeatability - Mix 1

Mix 1	Corrected mean value [mg]	Corrected standard deviation [-]	Corrected coef of variation [-]
Le Castellet	90.97	6.76	**7.44**
Spa	110.47	14.85	**13.44**

Both variation coefficients are below 15 which indicates a low dispersion but not sufficient to rank different materials since the effects are subtle. From this table, a ranking can be made between both tracks: Spa causes more wear than Le Castellet which is true according to what have been observed on track. This dispersion can result from temperature changes during runs, the amount and distribution of third-body material deposited during the run, and the timing of the mass measurements taken before and after the wear run.

Although some repeatability measurements are presented here, this protocol is not yet fixed or approved and is currently being tested for the repeatability and reproducibility of mass loss.

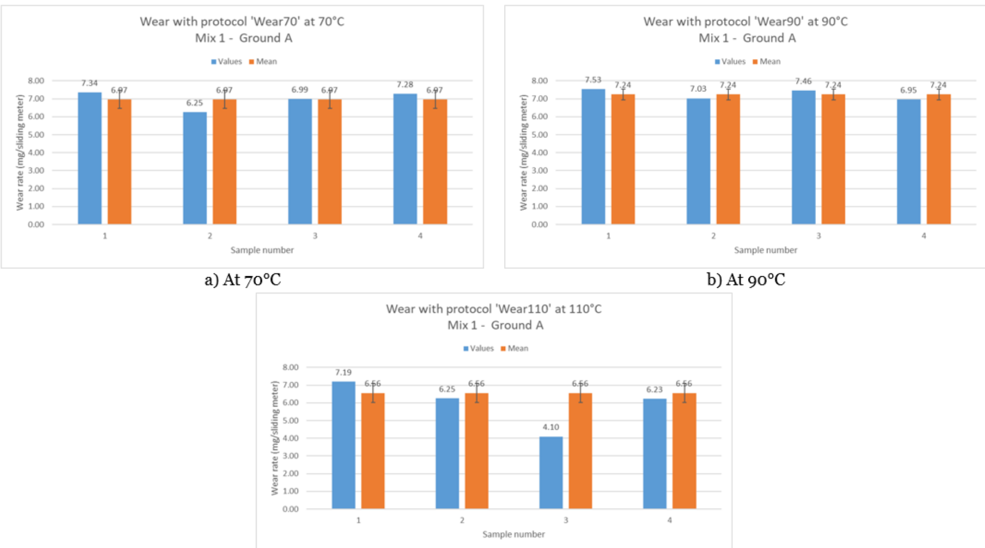
4.2 µPiste results

In the part below are display the results concerning the protocol using the µPiste machine, the description of the testing method is described in Section 3.3.2.

4.2.1 Repeatability tests

Figure 40 and Figure 41 show examples of several tests made with the same ground, the same compound and the same protocol to study the mass loss variation with the exterior conditions.

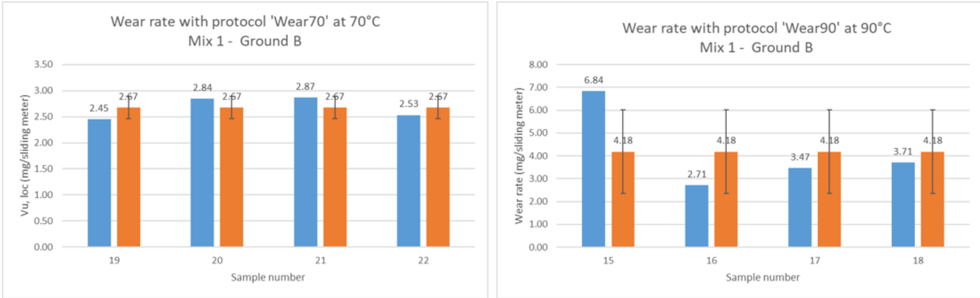
At 90°C and 70°C, the variations are very small, and the standard deviation is low with CV always below 10%, so the measure can be considered repeatable. But at 110°C, it is more difficult to have something repeatable. This experiment was repeated on another ground surface, yielding the same results.



a) At 70°C b) At 90°C

c) At 110°C

Figure 40. Repeatability experiment µPiste - Mix 1 - Ground A



a) At 70°C a) At 90°C

Figure 41. Repeatability experiment µPiste - Mix 1 - Ground B

The conclusion of the repeatability analysis was that to be sure of the measures it is better to make four measures each time than only one. Using this method, it is possible to draw a conclusion by using the corrected mean value and the corrected standard deviation. Indeed, it is very difficult to master all the exterior conditions such as the atmospheric pressure, the room temperature and the ground temperature.

To properly quantify the variation in measurements, the coefficient of variation (CV) can be calculated according to Equation 6. The lower this coefficient, the better the repeatability of the measurements.

$$CV = \frac{std}{mean} * 100 \ [\%] \qquad (6)$$

Table 5 shows some CV calculated during the repeatability tests. It displays the CV values before and after the process described below, which involves removing one sample to recalculate the mean and standard deviation. It is evident that this data processing reduces the CV, indicating that the method is effective. Furthermore, it can be observed that the tests conducted with Ground B are less repeatable than those with Ground A.

Table 5. CV before and after data processing - Repeatability tests examples

Mix	Temperature (°C)	Ground	Number of tested samples	CV value (before process)	CV value (after process)
Mix 1	90	A	4	**4.07**	**3.71**
Mix 1	110	A	4	**22.03**	**8.35**
Mix 2	70	A	4	**2.92**	**0.96**
Mix 2	110	A	4	**6.49**	**3.68**
Mix 1	70	B	4	**7.98**	**6.83**
Mix 1	90	B	4	**43.58**	**15.92**
Mix 4	90	B	4	**27.61**	**18.03**

Finally, to find one value for one compound, one ground and one temperature, the final method consists of:

- Running four samples with the same compound, at the same temperature on the same ground
- Calculating the mean value and standard deviation
- Eliminating the furthest value which is not in the range $[mean - std\ ; mean + std]$
- Recalculating the corrected mean value and standard deviation

Using this method allows for obtaining a reliable value for comparison with other compounds, as CV values for Ground A consistently remain below 10%, thereby reducing the likelihood of drawing false conclusions.

This method for determining the wear rate of a specific compound on a specific surface at a fixed temperature will be used for the remainder of this work.

4.2.2 Reproducibility over time

The goal was to study the protocol's reproducibility, that is, its repeatability over time. To do this, the same procedures were repeated with the same material on the same ground at different times to determine whether the mass loss remained within an acceptable range. The results are presented in Figure 42. Each bar corresponds to a sample of the same compound tested on the same ground using the same friction protocol. The measurements were performed at different times (October, December, and February) to evaluate the reproducibility of the test conditions.

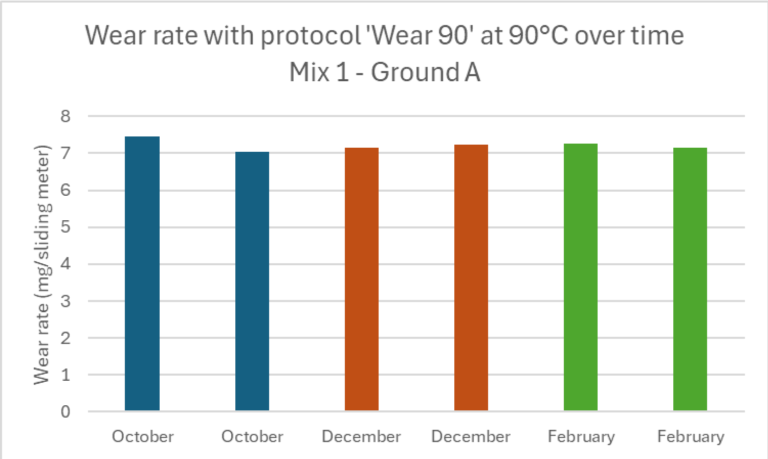


Figure 42. Mass loss over time for reproducibility - Mix 1 - Ground A

The wear rate values remain within a narrow range, with all measurements falling within the mean ± standard deviation. No significant variation is observed between the different testing periods.

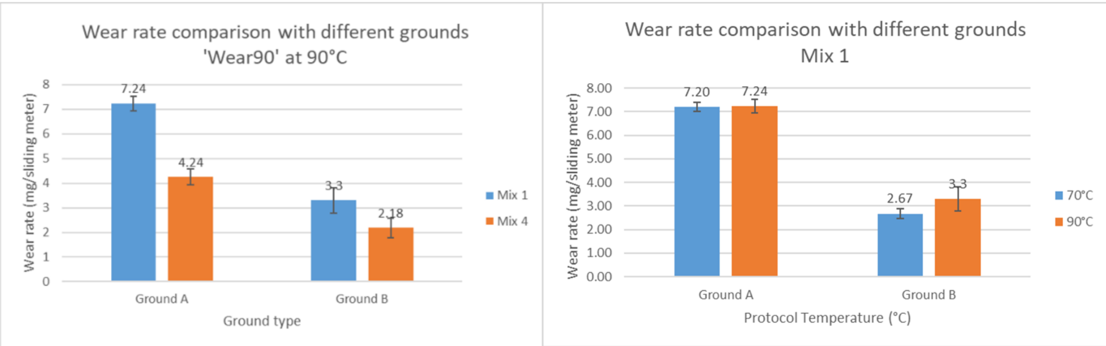
This consistency indicates that the testing methodology and conditions provide highly reproducible results for this compound-ground configuration. The protocol therefore appears reliable for assessing wear performance over time.

4.2.3 Analytical effects

In this part, analytical effects will be investigated to determine the impact of the specifical influent factor. The goal is to enhance the final protocol by using the appropriate settings.

a) Ground analytical effect

The analysis of the wear rate, as depicted in Figure 43, reveals the significant impact of ground type on the performance of different compounds at different temperatures.



a) b)

Figure 43. Wear rate comparison for different ground a) between two mixes and b) between two temperatures

In the left graph, comparing wear rates for different mixes at 90°C indicates that Ground A has the highest wear rate for Mix 1 at 7.24 mg/sliding meter, while Mix 4 on Ground B shows a notably lower rate of 2.18 mg/sliding meter. This clearly suggests that Ground A leads to increased wear compared to Ground B, highlighting the critical role ground type plays in determining the wear characteristics of the compounds.

The right graph explores the wear rates of Mix 1 across two temperatures for both grounds. At 90°C, Ground A maintains a wear rate of 7.24 mg/sliding meter, which is consistent with the results seen at 70°C (7.20 mg/sliding meter). However, Ground B significantly reduces wear rates at both temperatures, demonstrating values of 2.67 mg/sliding meter at 70°C and 3.3 mg/sliding meter at 90°C.

Note that in each case, the ranking remains consistent across both grounds, which is beneficial for comparing two values at different temperatures and/or with different mixes using various grounds.

These findings emphasize that Ground A is more effective at increasing mass loss across both mixes and temperatures, underscoring the importance of selecting the appropriate ground for reliably comparing different mixes. Indeed, to compare the mixes properly, it is preferable to have a greater mass loss, as this reduces the potential dispersion of values. Moreover Table 5 confirms this trend by showing that the CV values are lower with Ground A, indicating improved repeatability.

This analysis confirms that both ground type and temperature are critical factors in understanding wear behavior. The rugosities of both grounds are display in Figure 44.

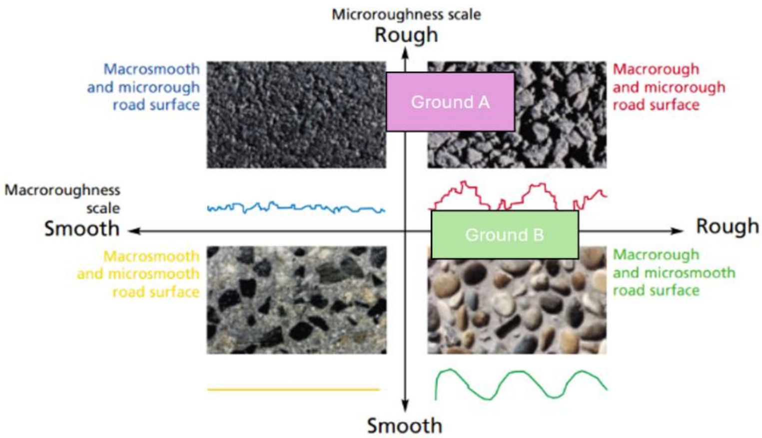


Figure 44. Ground rugosity comparison

For the remaining work, Ground A will be used to reduce dispersion and enhance the loss of mass repeatability.

b) ‘One-way’ and ‘back and forth’ comparison

The µPiste machine can operate in either 'back and forth' mode or 'one-way' mode, which means the rubber only moves in one direction against the ground, this is used to enhance the sliding length in one cycle. The aim is to compare these two modes to find out if they affect the wear rate and the facies of the sample. This comparison will consider the sliding length per cycle, as both tests are designed to cover the same total sliding length for a fair evaluation.

Figure 45 compares the wear rates between the 'one-way' mode and the 'back and forth' mode at 90°C for the Mix 1 on Ground A. The results show that the wear rate in 'one-way' mode is 32.6% lower than with the 'back and forth' mode. This indicates that the back-and-forth movement results in greater wear, likely due to increased friction and sliding distance per cycle. For the remaining work, the focus will be on using the back-and-forth mode to further investigate the wear characteristics, since it enables the detection of greater wear differences.

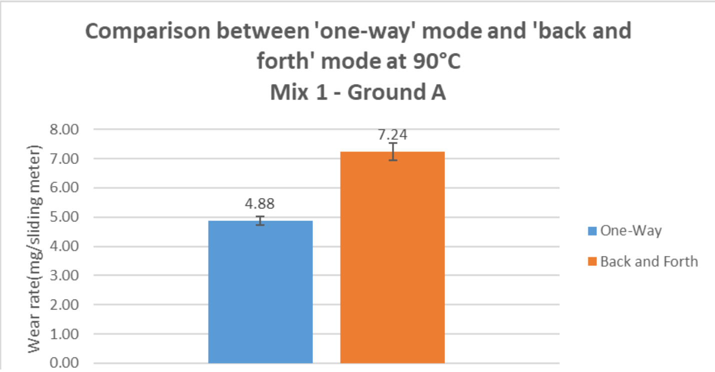


Figure 45. Wear rate comparison between 'one-way' mode and 'back and forth' mode at 90°C - Mix 1 - Ground A

Figure 46 illustrates the sample facies produced under both modes. The facies on the right appears more aggressive, exhibiting notable graining. When compared to tire facies, the right sample is more representative of expected wear. In contrast, the left sample suggests that the rubber has not performed as intended.

a) b)

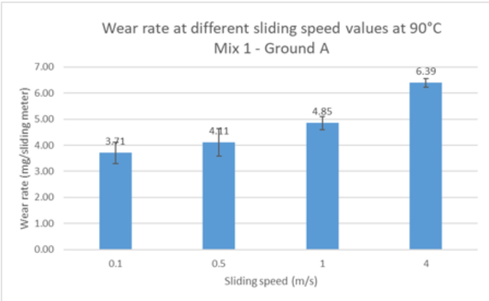
Figure 46. Facies comparison between a) 'one-way' mode and b) 'back and forth' mode at 90°C - Mix 1 - Ground A

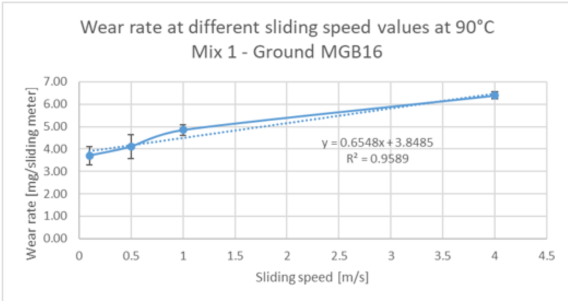
This facies very different on the left can be also linked to the fact that the machine is not regulating properly at 2 bars on the ‘one way’. Indeed, since the movement is really quick, it is challenging to regulate well in pressure. As a result, the contact pressure (load) may have been lower in the 'one-way' mode than in the 'back-and-forth' mode.

c) Sliding speed analytical effects

It is known that sliding speed has a huge impact on the wear rate, the goal of this part is to quantify this impact. For this, an analytical testing session has been made to measure the impact of the sliding speed without changing other parameters. For this, the temperature has been fixed at 90°C, Ground A was used as well as the Mix 1.

The analysis of the wear rates at different sliding speeds for Mix 1 on Ground A, as shown in Figure 47 a) and b), highlights the relationship between sliding speed and wear performance at 90 °C. In Figure 47 a), the wear rates increase with sliding speed, showing values ranging from 3.7 mg/sliding meter at 0.1 m/s to about 6.4 mg/sliding meter at 4 m/s, indicating that higher sliding speeds correspond to greater mass loss. Figure 47 b) provides a more detailed view, illustrating a linear trend with an R^2 value of 0.9589, indicating a strong correlation between sliding speed and wear rate. These results confirm that increasing sliding speed has a significant effect on the wear behavior of rubber compounds, even in the range [1.5; 4] mg/sliding meter in which the protocol acts.





a) b)

Figure 47. Wear rate analytical sliding speed effect - Mix 1 - Ground A a) with values b) correlation

d) Temperature analytical effects

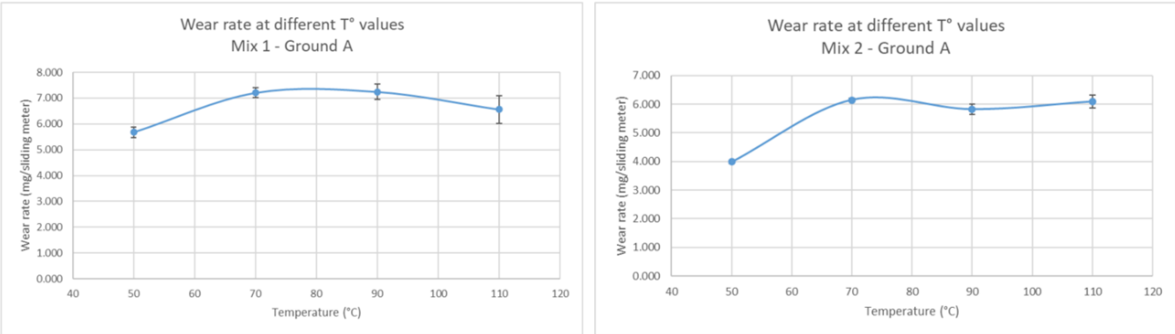
The goal in this part is to study the effect of the temperature on the wear rate. It is already known that it is a primordial factor when studying wear, especially with motorsport material (soft and sticky). But the objective here is to quantify this effect and see if there is a clear trend between the wear rate and the temperature.

For this, the classic protocol (described in the Section 3.3.2) has been used at different temperatures: 50°C, 70°C, 90°C, 110°C. Note that these temperatures are the setpoint temperatures and that the real surface temperature are lower depending on the temperature regulation and ground temperature.

To have a clear temperature effect, two compounds with different T_g were used in order to have a better idea and see if a trend can be clearly defined or not.

Figure 48 a) shows the trend of the measured wear rate in function of the temperature with the Mix 1 on the Ground A. It is clearly visible that the wear rate is increasing within the temperature until a certain maximum and then decreasing. This seems logical for the tested range of temperature: at 'low temperature' the rigidity is higher, so the wear rate is lower; and at higher temperatures the wear rate is maximum because the grip is optimum.

For high temperatures, as seen on the Figure 48 b), the wear rate is increasing since there is a lot of smearing creating a lot of rubber debris. Moreover, one can expect that at lower temperature than 50°C, the wear rate is highly increasing because the compound becomes highly fragile.



a) b)

Figure 48. Wear rate in function of the temperature for a) Mix 1 and b) Mix 2 - Ground A

In conclusion, within the range of interest (between 70°C and 110°C) the wear rate is not greatly affected, but a vague trend can be detected. This trend would shifts within the temperature range, depending on what the T_g of the compound would be. Therefore, it is important to consider the entire temperature range when comparing the compounds under the right conditions.

At this point: these results should be treated as indications of the relationship between temperature and the wear rate, rather than as a concrete law.

Moreover, this trend looks coherent to the precedent research on the subject as seen in Figure 49. Indeed, in 2022 at Michelin, the same trend had been detected with a different machine with similar compounds.

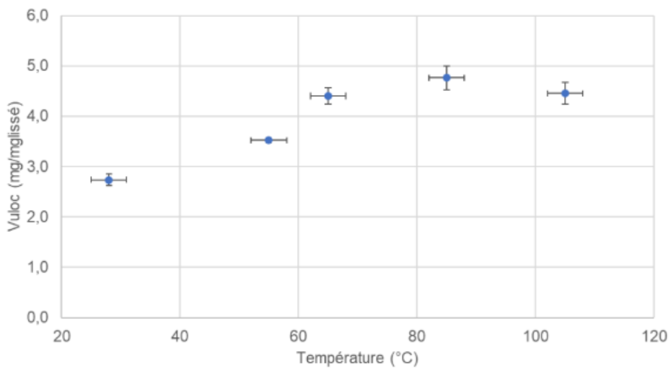


Figure 49. Influence of the temperature on the wear rate [13]

4.2.4 Compounds effects comparison

In this subsection, the aim is to verify whether the wear measurements and comparisons are accurate and match the expectations of the material designers. Several materials were tested (see Table 3). From these results, it is possible to conclude whether the protocol performs as intended and is capable of ranking different materials according to a wear criterion.

For each compound, 16 samples were used: 4 temperatures with 4 samples each time.

a) Mix 1 vs. Mix 2

The first comparison is the first two mixes, it is the reference (Mix 1) against a mix with a higher glass transition temperature and higher rigidity (Mix 2). Both temperatures curves for the mixes are exposed in Figure 50.

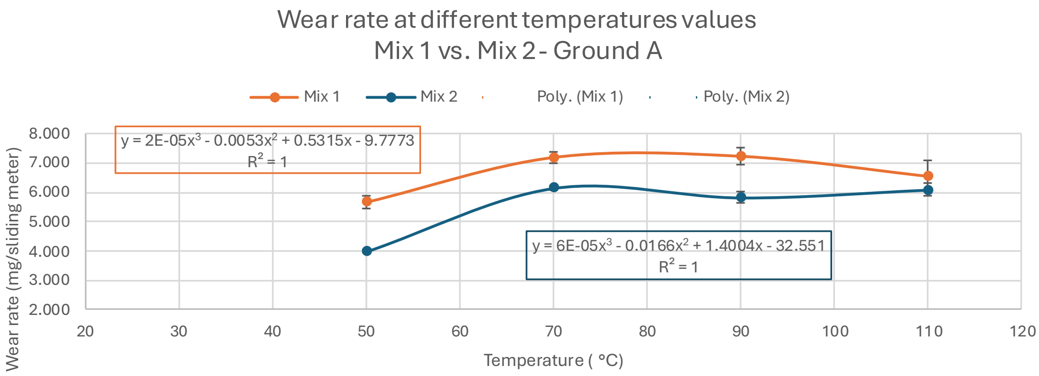


Figure 50. Mix 1 vs. Mix 2 - Ground A

The two temperature curves are distinct, and their standard-deviation ranges do not overlap, which means a ranking can be made between the two compounds. When comparing both curves, the Mix 2' curve is lower than the Mix 1' curve and shows an offset across the temperature range. Taking the maximum of each curve within the specified range yields a relative difference of 16.9%, which is close to the relative difference in rigidity (13.5%).

Between these two compounds, it is possible to conclude that Mix 2 is better in wear performance than Mix 1.

b) Mix 3 vs. Mix 4

These two compounds are a new reference (Mix 3) and a compound with an almost pure rigidity effect (Mix 4). Both temperatures curves for the mixes are exposed in Figure 51.

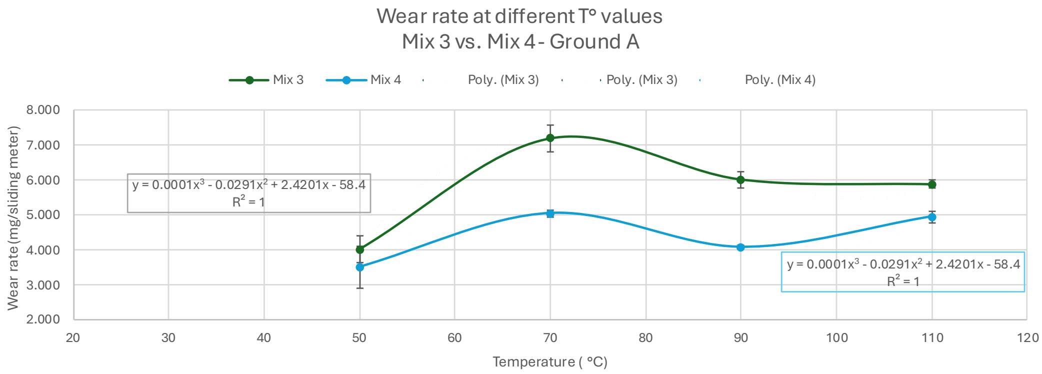


Figure 51. Mix 3 vs. Mix 4 - Ground A

Again, the two temperature curves are distinct and their standard deviation ranges do not overlap (apart at 50°C), which means that a ranking can be made between both mixes here.

Taking the maximum of each curve within the specified range yields a relative difference of 30.8%, which is close to the relative difference in rigidity (19.2%). But the glass transition temperature plays also a role here since it is not exactly the same for the two compounds.

c) Mix 5 vs. Mix 6 vs. Mix 7

These three compounds are a reference mix (Mix 5), and two mixes with a higher rigidity (Mix 6 and Mix 7). At the time of this report, not all temperature curves have been plotted due to time constraints; however, the available results are presented in Figure 52.

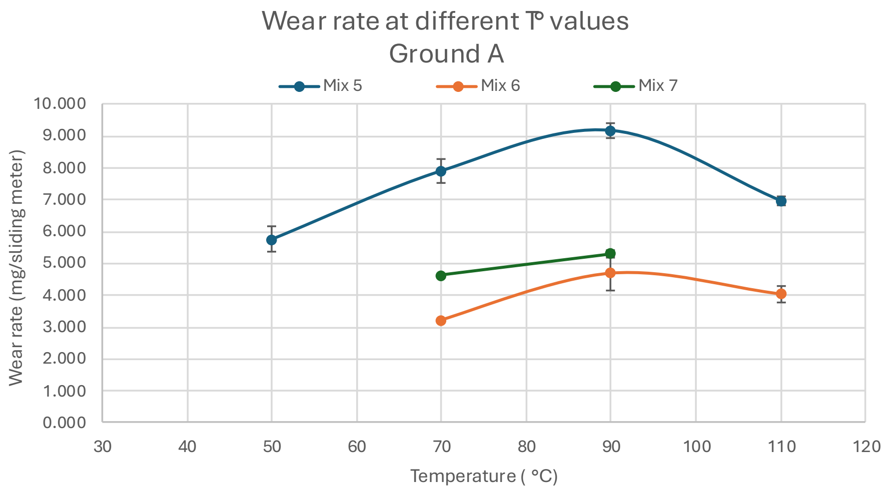


Figure 52. Mix 5 vs. Mix 6 vs. Mix 7 - Ground A

This comparison of Mix 6 and Mix 7 at two different temperatures is particularly insightful, as both mixes exhibit nearly identical mechanical properties but achieve their rigidity through different means.

Observing Figure 52 at 70°C and 90°C reveals a distinct offset in the wear rate curves, indicating that the wear performance is closely linked to changes in rigidity. For instance, at 90°C, Mix 6 demonstrates a 48% improvement in wear rate compared to Mix 5, while Mix 7 shows only a 42% improvement over Mix 5.

From the graph, it can be concluded that, despite having comparable properties ($G^*$and T_g), increasing the number of cross-links in the compound proves to be more effective in reducing wear than merely decreasing the plasticizer volume fraction in the formulation. This finding emphasizes the importance of cross-link density in optimizing wear performance, providing valuable insights for future compound development.

4.2.5 Wear performance comparison

It is also possible to compare wear performance with the experimental rigidity criterion measured by the µPiste machine. As shown in Figure 53, a clear trend exists between wear rate and rigidity: the higher the wear rate, the lower the rigidity. This was expected but this is one of the main results, the wear rate can be directly linked to the rigidity, to the conditions of taking into account the temperature in the protocol since the compounds have different T_g.

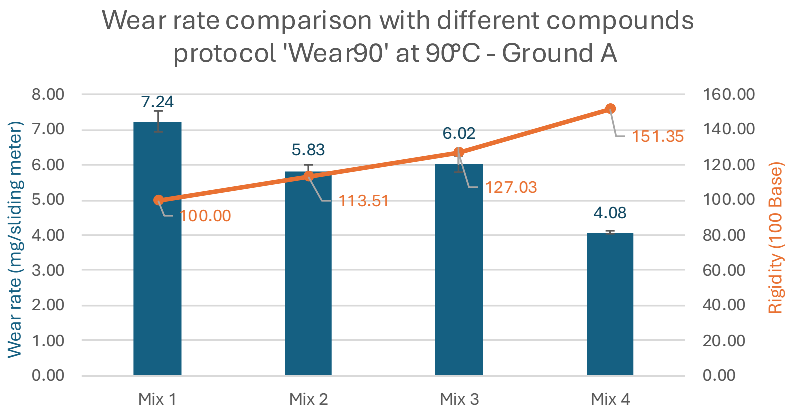


Figure 53. Wear rate vs. rigidity - all mixes

To check whether the rigidity-based ranking is valid, the graph shown in Figure 54 can be used. The dotted diagonal line represents the theoretical case where rigidity and wear performance are equal (both normalized to a 100 base). The x-axis shows rigidity (base 100) and the y-axis shows wear performance (base 100), which is directly related to the wear rate. Points above the line indicate

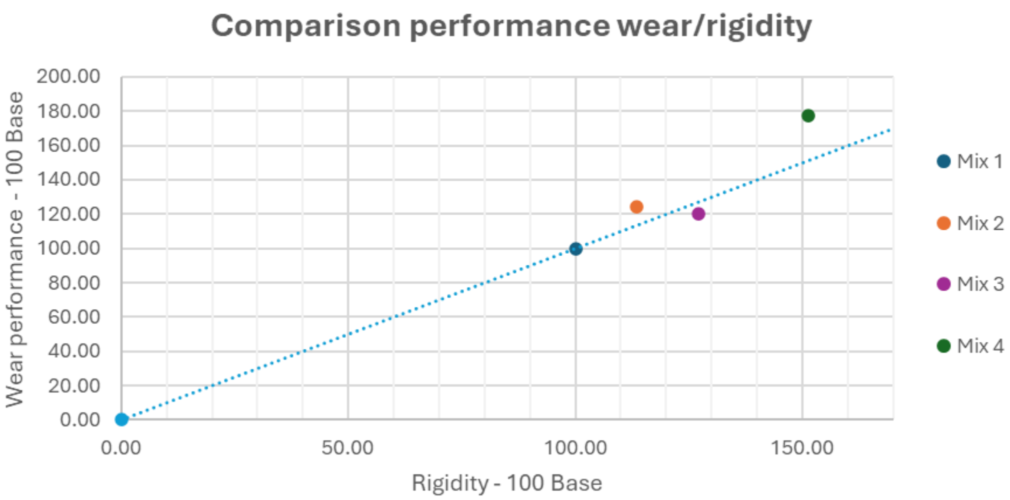


Figure 54. Comparison performance wear and rigidity - All mixes

materials that wear less than expected for their rigidity, while points below the line indicate materials that wear more than expected.

There is only one inversion in this graph: Mix 3 has higher rigidity than Mix 2 but lower wear performance. This may be due to differences in glass transition temperature between the mixes, which can also influence wear rate.

The same type of plot can be produced using glass transition temperature (T_g), normalized to a base of 100, on the x-axis (see Figure 55). In this representation, mixes 1-3 follow the expected trend: higher T_g corresponds to better wear performance and their positions nearly align with the diagonal trend line. Mix 4 is an outlier: despite its relatively low T_g it shows much better wear performance than the trend would predict.

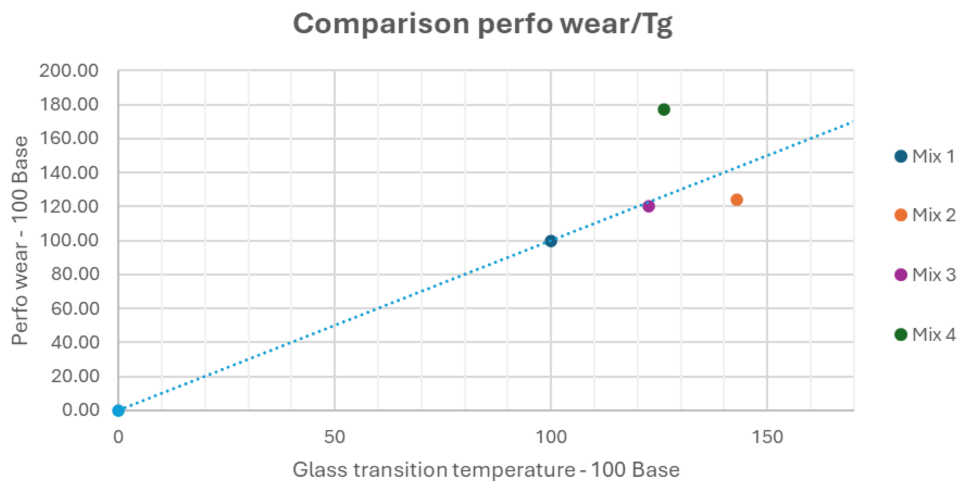


Figure 55. Comparison performance wear and glass transition temperature - All mixes

This suggests that factors other than T_g or rigidity alone (for example density, or thermal behavior during testing) influence the wear rate for the compounds, so neither T_g nor rigidity alone cannot fully explain mixes' wear performance.

5 Conclusions

The aim of this master's thesis was to develop an experimental protocol for conducting wear tests on tread rubber to evaluate their wear qualities, particularly for motorsport tires. Key to this process is ensuring repeatability, as well as the ability to replicate the specific wear patterns that occur on racing tires, which differ significantly from those on ordinary road tires for cars and trucks. Two experimental setups have been investigated: the LAT100 tribometer and the µPiste tribometer for which specific rubber samples have been created and evaluated. In order to set-up the experimental tests so it is similar to the settings on the track, measured track data is fed into the software TameTire to get the right operating points. This conclusion is structured into three brief subsections: conclusions from the LAT100 testing, conclusions from the µPiste protocol, and a comparison with on-track data. Each subsection summarizes key findings and limitations. The final subsection provides a more general conclusion on the work conducted and addresses the questions and objectives of the thesis.

5.1 LAT100 conclusion

The conclusion of the tests conducted during the master's thesis indicates that track wear has been approached with limited evidence, and measurable material loss has been observed. To ensure that this material loss is not attributable to other factors, conducting additional repeatability test sessions is essential.

In the long term, the objective can be to compare various track simulations, analyze different tire configurations (front/rear and left/right), and evaluate different rubber tread materials.

The first repeatability campaign conducted was promising but needs more tests to be accurate. It is possible to have a mass loss repeatable with some special conditions: repeatable 3rd body application, stable temperature for measuring mass, stable temperature over runs and laps during protocol.

During the course of this thesis, a protocol for comparing and ranking compounds was initiated but ultimately remains unfinalized and unvalidated due to the limited timeframe. However, several encouraging tests were conducted, demonstrating the machine's capability to accurately replicate track conditions and produce surface facies similar to those observed on actual tracks. Nonetheless, multiple steps are required to validate this protocol, including the attainment of perfectly repeatable results with a reliable mass loss that facilitates effective ranking of the compounds.

5.2 µPiste conclusion

The aim in this subsection is to highlights the main results and to conclude on the protocol developed for the µPiste tribometer: what works, its limitation and the key findings for the material sorting using the wear criterion.

This study aims to created and evaluated a wear-testing protocol using the µPiste machine and examined its repeatability, reproducibility over time, and sensitivity to key analytical factors (ground type, sliding mode, sliding speed, temperature) and compound properties. Here are the main conclusions.

<u>Protocol reliability and data treatment</u>

- The protocol demonstrates good repeatability at 70°C and 90°C, with coefficient of variation (CV) values generally below 10% for Ground A. Repeatability at 110°C is poorer and more sensitive to external conditions (such as ground temperature).
- A pragmatic data-processing routine (run four samples, remove the outlier outside [mean – std, mean + std], then recalculate the corrected mean and std) substantially reduces dispersion and produces robust average wear values suitable for comparison. Using this approach, results for a given compound, ground and temperature become repeatable enough for ranking purposes.

Reproducibility over time

- Repeating the same tests at different times showed that mass loss remains within the mean ± standard deviation range. This indicates good reproducibility of the protocol when the same conditions are maintained, even with some variability in the exterior conditions.

Influence of testing conditions

- Ground type strongly affects wear rates. Ground A produces larger mass loss and lower CVs than Ground B, making it preferable for laboratory comparative testing because it increases the signal-to-noise ratio.
- The machine's motion mode also matters: back-and-forth operation produces more wear and a sample facies that better resembles on-track behavior than the one-way mode. For this reason, the back-and-forth mode was adopted for the rest of the work.
- Sliding speed has a clear, almost linear effect on wear for the tested range, with higher speeds producing higher wear rates (strong correlation, $R^2 \approx 0.96$).
- Temperature affects wear in a non-linear way: in the tested range, wear increases with temperature up to a maximum and then decreases (for the majority); the position of this maximum depends on compound T_g. Within the motorsport-relevant range (70-120 °C) the effect is moderate but must be considered when comparing mixes.

Compound effects and material ranking

- The protocol is capable of ranking compounds by wear performance in most cases: the values differs from more than the standard deviation. Comparisons between mixes showed distinct temperature curves with non-overlapping standard-deviation ranges, allowing reliable ranking.
- A strong correlation between compound rigidity and wear was observed: generally, more rigid compounds has lower wear rates. However, some mixes (notably Mix 4 in this study) deviate from the rigidity or T_g trends, indicating that other material factors (e.g., density, elastomer type, crosslinking, or thermal behavior during testing) also influence wear.
- Therefore, neither T_g nor rigidity alone is sufficient to predict wear performance for all compounds; a combination of properties and controlled testing conditions is required.

- Comparing the last three mixes (Mix 5, Mix 6 and Mix 7) highlights that, despite similar mechanical properties, the method of increasing rigidity significantly impacts wear performance. These findings suggest that increasing the number of cross-links in the rubber compound is more effective for reducing wear than simply lowering the plasticizer volume fraction, underscoring the critical role of cross-link density in optimizing tire wear characteristics.

To evaluate the predictive capability and ranking accuracy of the established protocol, Figure 56 illustrates the pairwise comparisons for the first four mixes concerning the µPiste wear performance (depicted on the y-axis) and the theoretical rigidity (shown on the x-axis).

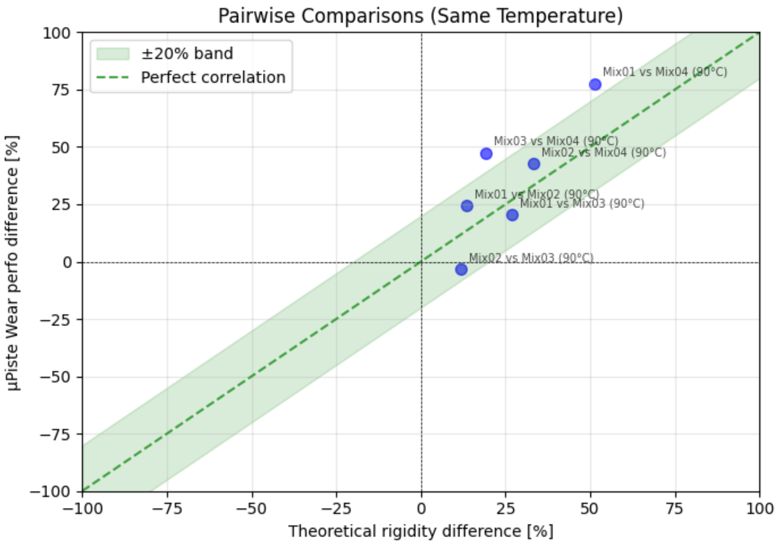


Figure 56. Pairwise comparisons µPiste wear perfo vs. rigidity difference

Figure 56 shows a clear trend, with most data points lying within the acceptable range, defined by a ±20% band around the line of perfect correlation (illustrated by the dashed green line). Notably, there is only one inversion among the comparisons, indicating that the protocol maintains a high level of consistency in its predictions. Considering these observations, it can be concluded that the protocol demonstrates strong validity, as the predictions align closely with the expected outcomes. The success in ranking and predicting the mixes reinforces the robustness of the method utilized, supporting its potential for further applications in similar research contexts.

Overall, the µPiste-based protocol, together with the recommended data-processing and operating choices, provides a reliable method to assess and rank compound wear performance under controlled laboratory conditions. While the protocol captures the main trends (rigidity and temperature effects), further work is suggested to quantify the influence of secondary material parameters and to link laboratory facies and wear rates more directly to on-track performance.

5.3 Final comparison (with track V_u)

A final comparison can be to compare some wear rate values with wear data from track tests. For confidentiality issues, the values will be given without any more precision on the track and the conditions.

Table 6 compares data from on-track measurements, a full-scale tire testing machine, and the µPiste tribometer, using wear rate per sliding meter as the common basis for comparison. To facilitate this comparison, the sliding length is utilized as an approximation for both the track and the tire testing machine, given that an exact measurement of the sliding length during tire/road contact is not feasible. It is important to note that the tire testing machine operates under less demanding conditions than those found on the track, while the µPiste tribometer is even less demanding (according to Table 6). Notably, the track wear deviation indicates that the tire testing machine underestimates wear by 11.6%, while the µPiste tribometer deviates even further by 37.4%.

Table 6. Wear rate comparison with track

	Track	Tire testing machine	µPiste tribometer
Mean wear rate [mm/cycle]	0.047	0.03	0.052
Sliding length [m/cycle]	9	6.5	16
Wear rate per sliding meter [mm/m]	0.00522	0.00462	0.00327
Track wear deviation	**-**	**-11.6%**	**-37.4%**

This significant deviation highlights the difficulty of reproducing true on-track behavior in the laboratory: track conditions combine higher temperatures and greater sliding energy, which drive substantially higher wear rates than either laboratory setup can fully replicate.

5.4 General conclusions

This subpart aims to address the questions outlined in Section 1.1, reflecting on the successes achieved in this thesis and identifying areas that require further work.

The optimal conditions for estimating tire wear under motorsport conditions have been established through the analysis of TameTire outputs and a comprehensive evaluation of the operating points. It has been identified that several key factors influence tire wear, namely sliding speed, contact pressure, and temperature (both of the rubber and the ground). To accurately reproduce the desired wear patterns in a laboratory environment, it was decided to omit the presence of a third body and adjust the settings of pressure, temperature, and sliding speed to effectively activate the mechanisms of fatigue and the formation of FDSL.

In order to develop a repeatable and reproducible protocol, a complete repeatability campaign was conducted using different grounds and compounds under the same experimental conditions, with efforts aimed at minimizing the CV. Additionally, a method was developed to reduce the standard deviation for increased reliability. Multiple comparisons were made using tire data to validate the protocol, regrouping both pairwise comparisons and the ranking of compounds based on their wear characteristics. A complete methodology has been developed to rank the compounds according to their wear capacities: take the maximum of the curve $V_u(T)$ to ensure equitable comparisons while accounting for any T_g shifts.

Ultimately, it was determined and proved that compound rigidity is the primary property influencing wear: higher rigidity correlates with lower wear rates. However, this factor alone is not sufficient for accurately quantifying wear, as other properties, such as T_g, also significantly impact the wear rate.

6 Reflections and future work

6.1 Remarks on the overall thesis

This thesis primarily involved experimental work using various machines that are not standard production models, but rather tribometers still under development. This implies that numerous challenges can arise during testing sessions, which can significantly prolong the time required to correct the data, resolve machine issues, and perform necessary repairs. Additionally, the experimental nature of the work means that results do not always align with expectations, necessitating adjustments and adaptations throughout the process. Consequently, the study often took longer than initially anticipated, particularly when unexpected findings emerged during the testing campaign.

The differences in mass loss used to compare the wear rates were subtle, often in the range of a few milligrams when evaluating two mixes. Therefore, every conclusion drawn in this thesis should be approached with caution. The results are not generalizable but rather specific to the compounds and materials studied at the time of this work. Every action and small details during the protocol can change the result.

6.2 Points of amelioration

All the work presented in this thesis serves as a foundation for further investigation to yield more precise results and conclusions. The established protocol on µPiste tribometer can be utilized to test compounds with formulations that are more closely aligned, assessing whether the protocol can effectively rank similar compounds.

Furthermore, investigating the analytical effects of pressure on the wear rate is essential for gaining a deeper understanding of how and when wear manifests on rubber samples. Expanding the temperature range of studies will also be beneficial in determining if the results align with the expectations of material designers. Additionally, examining the effects of ground properties on wear rates with various compounds is crucial. The ultimate goal of these analyses is to enhance our understanding of the mechanisms of tire wear from both material and physical perspectives. While the mechanisms are relatively clear in PC and TR applications, they become more complex in the context of slick tires, which exhibit high grip capacity and a pronounced tendency toward graining.

On the LAT100 tribometer, there remains considerable work to be done. Future campaigns should focus on enhancing the repeatability and reproducibility of mass loss measurements. However, the facies obtained during the initial testing sessions show promise for future developments.

References

[1] MFP Michelin, "L'histoire Michelin," [Online]. Available: https://www.michelin.com/groupe/histoire. [Accessed 08 12 2025].

[2] MFP Michelin, "Michelin: le groupe," [Online]. Available: https://www.michelin.com/groupe. [Accessed 08 12 2025].

[3] United Nations, "Sustainable transport | Department of Economic and Social Affairs," [Online]. Available: https://sdgs.un.org/topics/sustainable-transport#description. [Accessed 25 09 2025].

[4] Sustainable Mobility for All, "Global Mobility Report 2017: Tracking Sector Performance," Washington DC, License: Creative Commons Attribution CC BY 3.0, 2017.

[5] A. Ly and Z. El-Sayegh, "Tire Wear and Pollutants: An Overview of Research," Advanced Engineering Science, Volume 1-9, Pages 1-10, 2023.

[6] Wikipedia, "Tribology," [Online]. Available: https://en.wikipedia.org/wiki/Tribology. [Accessed 12 11 2025].

[7] M. Salehi, "LAT100, Prediction of tire Dry grip," University of Twente, Enschede, 2017.

[8] Cambridge university, "Cambridge dictionary," [Online]. Available: https://dictionary.cambridge.org/dictionary/english/friction. [Accessed 12 11 2025].

[9] Michelin, "Comment fabrique-t-on un pneu ?," [Online]. Available: https://www.michelin.ca/fr/auto/conseils/pneus-101/comment-fabrique-t-on-un-pneu. [Accessed 09 2025].

[10] MFP Michelin, "Course - Fundamentals of Rubber Technology," Internal document.

[11] MFP Michelin, *The tyre - Grip,* Internal document, 2001.

[12] M. Vantal, "Synthèse des connaissances de base de la performance usure - "L'usure en 60 pages"," MFPM, 2011.

[13] B. Paixão Peixoto de Vasconcellos, "Etude de l'usure de bandes de roulements de pneus compétition sur tribomètre," MFPM, Internal document, 2021.

[14] G. Lufau, P. Tregouet and P. Toulemonde, "Etude laboratoire des mécanismes d'usure représentatifs des conditions d'usage vus sur route," MFPM, Internal document, 2019.

[15] M. Godet, "The third-body approach: A mechanical view of wear," Wear, Volume 100, Issues 1-3, Pages 437-452, 1984.

[16] N. Fillot, I. Iordanoff and Y. Berthier, "Wear modeling and the third body concept," Wear, Volume 262, Issues 7-8, Pages 949-957, 2006.

[17] O. Ronsin, "Synthèse du projet MDMU: les mécanismes de départ de matière en usure," MFPM, Internal document, 2012.

[18] J. Veyrat-Durebex and G. Foyart, "L'usure des pneus dans le domaine de l'endurance," MFPM, Internal document, 2023.

[19] P.-A. Toulemonde and J. Parent, "Etude de l'effet de la température sur la prédiction de performance usure locale au CETR en protocole standard et en protocole ripage," MFPM, Internal document, 2019.

[20] O. Ronsin, M. Daude and E. Moreso, "Impact de la température sur la performance usure en TC : phénoménologie et premiers éléments de compréhension," MFPM, Internal document, 2013.

[21] J. Parent and P.-A. Toulemonde, "Effet de la vitesse de glissement et de la longueur glissée par événement," MFPM, Internal document, 2020.

[22] J. Parent, C. Khripin, L. Huet, L. Malosse and P.-A. Toulemonde, "Synthèse des activités exploratoires menées sur tribomètre CETR pour l'étude de l'usure en 2018," MFPM, Internal document, 2019.

[23] P.-A. Toulemonde and R. Jeanneret-Dit-Grosjean, "Document métier - Tribologie pour l'usure," MFPM, Internal document, 2021.

[24] G. Hatton, "Comment la dégradation des pneus affecte la stratégie de course : Stratégies, facteurs et techniques," 09 2024. [Online]. Available: https://www.catapult.com/fr/blog/comment-la-degradation-des-pneus-affecte-la-strategie-de-course. [Accessed 09 2025].

[25] MFPM - Michelin MSP, "Definition performances Graining," Internal document, 2024.

[26] Inconnu, "Suspension secrets," [Online]. Available: https://suspensionsecrets.co.uk/tyre-failure-graining-tearing-blistering-and-wearing/. [Accessed 09 2025].

[27] W. West and J. Limebeer, "Optimal Tyre Management of a Formula One car," IFAC-PapersOnline, Volume 53, Issue 2, Pages 14456-14461, 2020.

[28] MFP Michelin, "TameTire," [Online]. Available: https://simulation.michelin.com/tametire. [Accessed 01 2026].

[29] P.-Y. M. A. T. S. D. R. Jeanneret-Dit-Grosjean, "Définition et explication des nouvelles briques TamTire - Modèle d'usure," MFPM, Internal document, 2018.

[30] VMI Holland BV, "VMI LAT100 tire tread compound tester," [Online]. Available: https://vmi-group.com/specifications/vmi-lat100-tire-tread-compound-tester/. [Accessed November 2025].

[31] MFPM, "Euro 7, une nouvelle règlementation au service de la transition écologique et des manufacturiers responsables," 2025. [Online]. Available: https://www.michelin.com/publications/produits-et-services/reglement-euro-7-seule-une-methode-test-exigeante-

permettra-proteger-environnement-et-distinguer-les-manufacturiers-responsables. [Accessed 25 09 2025].

[32] TA Instruments, "Thermal Solutions," [Online]. Available: https://www.tainstruments.com/. [Accessed 07 10 2025].

[33] O. Ronsin, "Conference Boost Expert - Mécanisme d'usure et usure pneu," MFPM, Internal document, 2010.

[34] J. W. M. N. L. R. A. B. Marzieh Salehi, "Understanding Test Modalities of Tire Grip and Laboratory-Road Correlations with Modeling," Tribology Letters 69, 116, 2021.

[35] E. L. Deladi, "Static friction in rubber-metal contacts with application to rubber pad forming processes," Ph.D. dissertation, University of Twente, Netherlands, 2006.

Appendices

Appendix A: Operating points analysis – Le Castellet track

Figure 57 and Figure 58 provide a comprehensive analysis of the operating points discussed in Section 3.2. These graphs illustrate the outputs from the tire simulation software TameTire, which were essential for determining the appropriate operating points used to develop the protocol outlined in this thesis. The first figure focuses on the analysis for both front tires while the second figure addresses the analysis for both rear tires, on the "Le Castellet" track. Within each graph, the columns represent the five ribs of each tire, and the two rows correspond to the two plots generated for each rib, offering a detailed understanding of tire performance under simulated conditions.

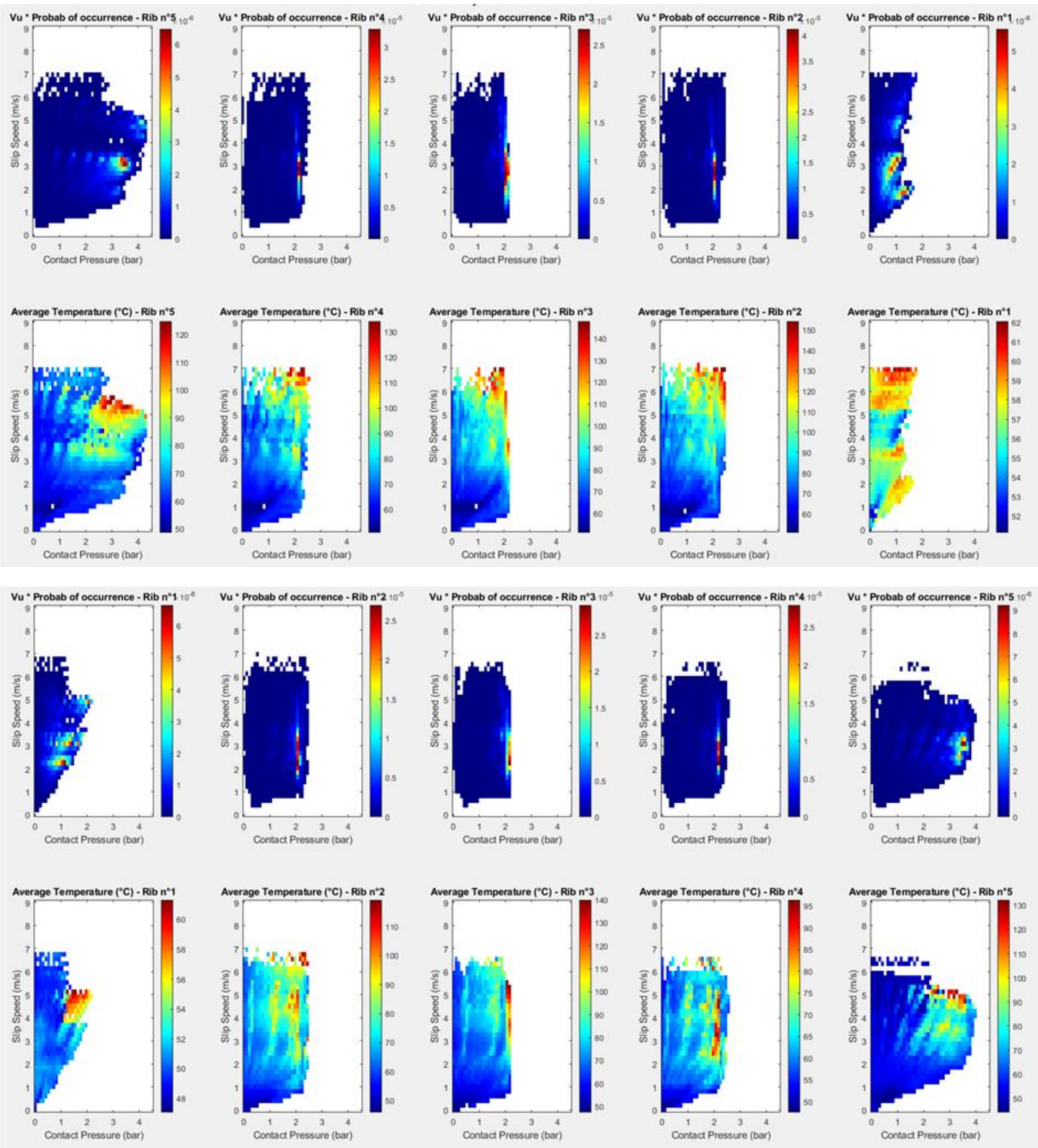


Figure 57. Operating point analysis - Le Castellet - Front left (above) & front right (below)

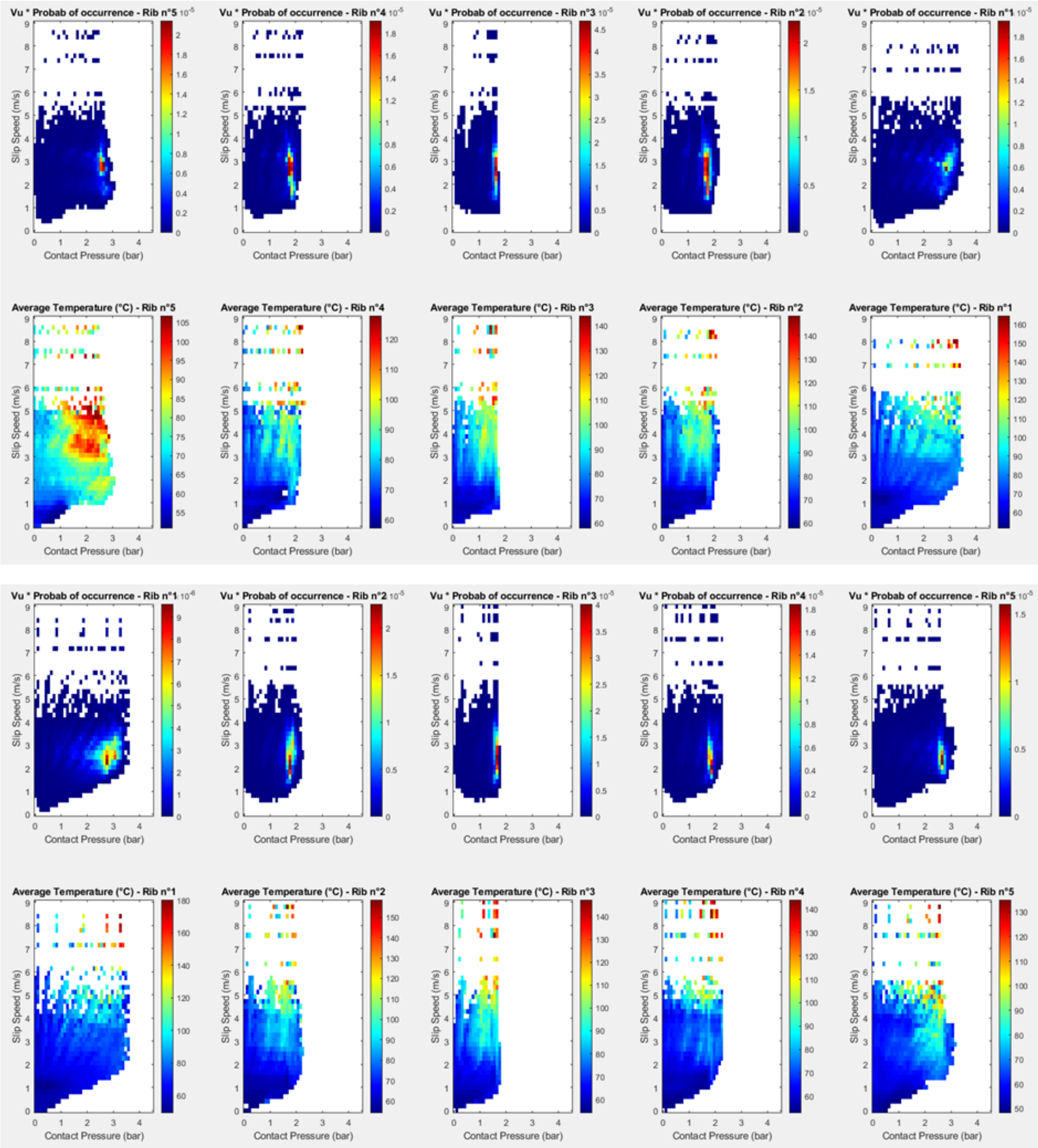


Figure 58. Operating point analysis - Le Castellet - Rear left (above) & rear right (below)

Appendix B: Operating points analysis – Spa track

Figure 59 and Figure 60 provide a comprehensive analysis of the operating points discussed in Section 3.2.These graphs illustrate the outputs from the tire simulation software TameTire, which were essential for determining the appropriate operating points used to develop the protocol outlined in this thesis. The first figure focuses on the analysis for both front tires while the second figure addresses the analysis for both rear tires, on the "Spa-Francorchamps" track. Within each graph, the columns represent the five ribs of each tire, and the two rows correspond to the two plots generated for each rib, offering a detailed understanding of tire performance under simulated conditions.

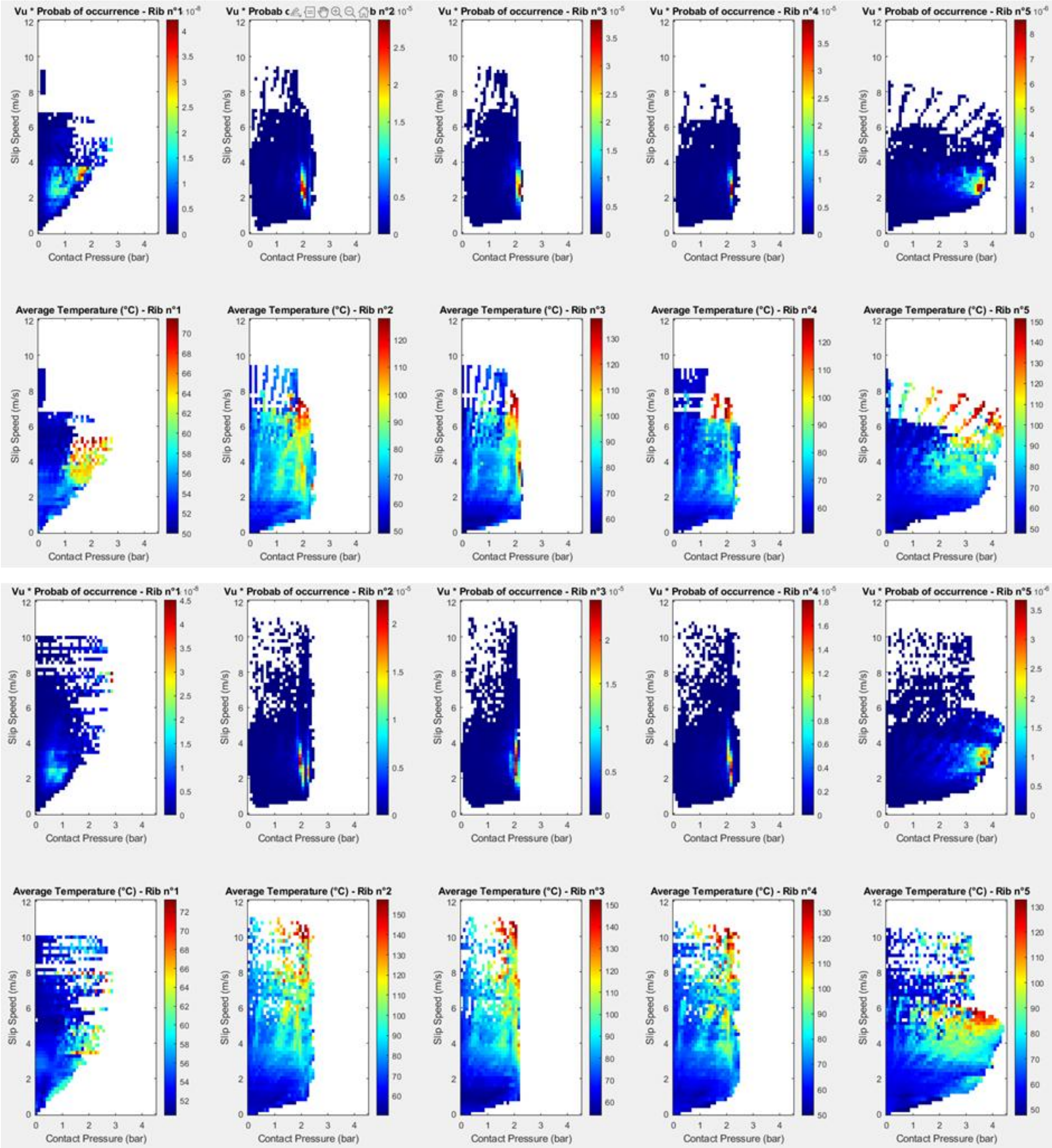


Figure 59. Operating point analysis - Spa - Front left (above) & front right (below)

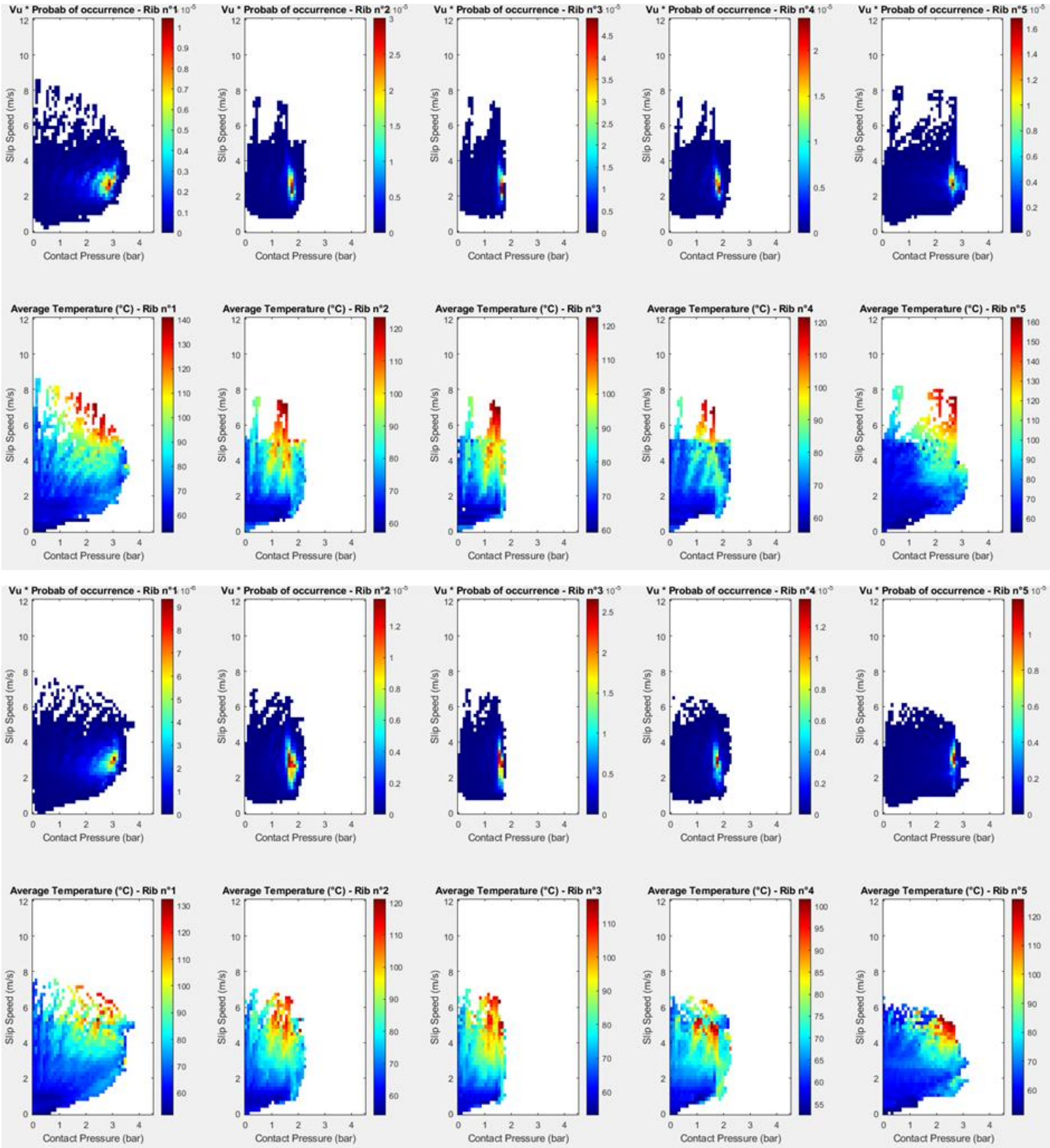


Figure 60. Operating point analysis - Spa - Rear left (above) & rear right (below)

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