Project *Life*-NEEVE:

Innovate technologies to monitor and reduce Non-Exhaust Emission, particles and microplastics of Vehicles and pavements to improve air quality and human health

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(Circular Economy and Quality of LIFE-Standard Action Projects (SAP))

Deliverable D2.6:

Properties and design of tyres with focus on rubber wear and non-exhaust particle emissions

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EXECUTIVE SUMMARY

Project NEEVE has the main purpose of suggesting measures to reduce non-exhaust emissions (NEE) from road traffic. An essential part of these emissions are particles from the tyre emitted as a result of forces acting in the tyre/road contact patch causing tyre rubber abrasion, which is increasingly recognized as a major source of microplastic pollution in the environment. As tyres wear down during regular use, particles commonly referred to as tyre wear particles (TWP) are released into the environment. These particles, composed of complex mixtures of synthetic- and natural rubber, fillers, and additives, range in size from several millimetres down to the nanometre scale, with the most abundant sizes around 20–100 µm. Once emitted, they contribute to pollution across all environmental compartments, including roadside soils, freshwater systems, marine environments, and the atmosphere.

In the European Union, the estimated annual emission of TWP ranges from approximately 500,000 to 1.3 million tonnes. Despite increasing scientific attention, the complete environmental and health implications of TWP are still not fully understood. However, there is wide agreement that the effects on human health are severe.

The generation of tyre abrasion particles is influenced by a wide array of factors, including tyre construction (tyre type, tread rubber compounds and additives), tread pattern, inflation pressure, vehicle characteristics (e.g., vehicle weight, wheel load, torque, and wheel adjustments), driving behaviour (speed, aggressive acceleration and braking), and external conditions such as road surface, traffic patterns, and ambient temperature.

The aim of this deliverable is to compile current knowledge on tyre properties and external factors affecting tyre abrasion and TWP emissions. It focuses exclusively on tyre abrasion during active use and does not address end-of-life tyre materials, such as rubber granules from recycled tyres used in rubber asphalt pavements, artificial turf or other applications. Although measurement methods are crucial for the study of rubber abrasion and TWP, the deliverable does not directly deal with measurement methods for TWP or for rubber abrasion as measurement methods are supposed to be part of another deliverable (D2.2).

The method used for collecting information in this deliverable, apart from using the authors' own experience and knowledge, is a literature survey, including Scopus, Web of science, and Google Scholar. AI (Chat GPT and Elicit) has also been used to find and compile references. Conclusions are based on syntheses of the collected information.

The main conclusions are as follows.

Despite tyre manufacturers are reluctant to publish their research, for commercial competition reasons, the open literature contains substantial information about how design, construction and material selections of tyres influences or potentially influences tyre abrasion. In this respect, it is mostly C1 tyres that have been studied.

The presented influences are, however, often unclear or inconsistent, making it difficult to make robust conclusions. A reason for such results may be that the measurement technology is challenging and still rather premature. Experiments therefore may give results that are over-interpreted since uncertainties are not enough considered, or that different methods emphasize various influencing parameters differently.

Tyres are designed and produced for various climates and regions. When comparing for example summer, winter and all-season tyres, the summer tyres have come out as giving lower rubber abrasion and winter tyres the most abrasion. This is because of the different rubber compounds used, where generally softer rubber is used in tyres constructed for lower temperature environments and vice versa. Tyres should be of the type optimized for the season and the region for many reasons: for example, regarding rubber abrasion, it is especially unsuitable to use winter tyres also in summer as that will accelerate wear.

Tyre temperatures have a profound influence on rubber abrasion, namely that higher temperatures give higher abrasion. However, it seems that the rate is not stable but changes with how much the tyre temperature differs from the glass transition temperature of the compound.

The abrasion rate is not the same during a tyre’s lifetime. Often the abrasion is higher when the tyres are new, which can happen because it is common that the outer tread layer has another compound than the main part of the tread, but becomes lower when the tyre has been operating for a while and. Later, when tyres become worn and possibly also chemically/thermally aged, abrasion will increase.

Tyre inflation has large influences on tyre wear, mostly by too low or too high inflation causing non-uniform wear across the tyre width. Poor wheel alignment causes irregular wear, such as the left and right parts of the tread being very differently worn. Consequently, both wheel alignment and inflation monitoring are important methods to prolong the tyre’s lifetime and mileage.

Tyre treads consist of numerous chemical substances and only a few are generally known. Although the physical structure of tyres is well understood, the chemical composition of the treads remains largely opaque, as manufacturers are not required to disclose detailed information, aside from limited assessments under the European REACH regulation, and they are not willing to do so either since the tread rubber is an important component in the commercial competition. Even if a certain line of a tyre brand is produced over a long time period and keeps the same designation and name, the rubber compounds are often changed due to progress in research or maybe availability of the substances.

There are two reinforcing agents which have been studied rather extensively in public literature, namely carbon black and silica. Carbon black has been the most common reinforcing agent, but today silica is also common, especially in passenger car tyres and for reasons of reducing rolling resistance. Carbon black has generally positive effects on rubber abrasion. Silica has been found to be superior to carbon black regarding wet grip and rolling resistance while its influence on rubber wear resistance is contradictory. Nevertheless, an increase in silica in the tyre has been found to influence the size distribution of the tyre wear particles: the number of emitted coarse particles decreased, while the number of fine particles increased.

The Euro 7 regulation, formally adopted in 2024 and soon to be implemented, introduces comprehensive measures to address non-exhaust emissions from vehicles. This marks the first instance of the European Union setting a framework to limit tyre abrasion emissions, aligning with methodologies developed by the United Nations Economic Commission for Europe [UNECE] under UN Regulation No. 117. Abrasion limits for new tyres are currently being discussed and may be implemented fairly soon for new tyres. This will require extensive and expensive testing of rubber abrasion by the industry with measurement methods that are likely to be burdened by flaws in the beginning as is common when new regulations are introduced. However, this development is desirable and necessary.

Recently, a model for predicting rubber wear on pavement surfaces has been published by world-leading experts on tyre/road contact and friction. They claim that they have successfully developed the world's first theoretical model for multiscale rubber wear behaviour on textured surfaces. This model may be useful for the design and construction of tyres with lower tyre abrasion and is already used by one of the major tyre manufacturers for this purpose. It is not yet clear whether the model will be available to other researchers or engineers.

Rubber abrasion and particle emissions are results of the interaction between tyre and pavement surface. It follows that both tyres and pavement surfaces must be considered when it comes to tyre wear and emissions. In the pavement, like for wet grip, both macrotexture and microtexture are known to influence tyre abrasion substantially; the more the rougher the textures are. Since roads must be safe, too smooth surfaces cannot be accepted. Especially smooth macrotexture is favourable also for noise and rolling resistance, so there is a win-win situation if it were not for traffic safety (wet skid resistance). Nevertheless, road authorities have a responsibility to make sure that textures are optimized as well as practical to reduce tyre abrasion and tyre particle emissions (and noise and rolling resistance), given that traffic safety is not jeopardized.

The present trend for vehicles becoming heavier; especially those for private use, means that tyres are increasingly loaded. This means that vertical, longitudinal and lateral forces in the tyre/road interface becomes larger when the vehicle is driven, which means that rubber abrasion will increase. Specifically, PM_{10} emissions have been found to be many times more sensitive to changes in load compared to $PM_{2.5}$, suggesting that larger particles are more strongly influenced by dynamic forces such as cornering or abrupt lateral movements. Since electric vehicles (EVs) due to their batteries are heavier than vehicles with internal combustion engines; especially the full-electric ones, while they allow much higher accelerations, it is often found that the electric or hybrid-electric ones are causing more tyre wear. However, the case is not entirely clear, since decelerations by those vehicles may be softer due to the regenerative system, accelerations can be limited, and EV tyres are often adapted for the higher torques. However, it is obvious that NEEVE should promote the idea of reducing vehicle weights by policy measures and public influence.

Driving behaviour is another factor strongly influencing tyre abrasion and particle emissions. Increasing speed means that higher tyre/road forces (torques) must be applied to overcome the air and rolling resistance; especially air resistance which increases by an exponent of 4 with speed. Speed also influences the proportion of particles being suspended in the air and also influences the proportion between the larger and smaller particles emitted. This does not mean that all is well in urban areas where average speeds are low, since then stop-and-go traffic will create more abrasion and more particles due to the intermittent changes in the acceleration and decelerations. Longitudinal slip is an important factor in rubber abrasion, but side slip by driving and steering in curves is even more important. Consequently, there is an interaction between speed, acceleration and deceleration, which gives a high potential for reducing rubber abrasion and particle emissions by driver education. It shall not be forgotten that driver behaviour which is favourable for low tyre rubber abrasion also is favourable for noise, rolling resistance and of course safety. Here, there is a clear win-win situation.

Tyres are always a result of compromises between various parameters. Tyre companies have always considered tyre wear as an important parameter, but with the new Euro 7 regulations it will receive more attention and requirements. Then, the question is: will it mean sacrifices of other essential parameters? To answer this question, one must consider one of the key parameters namely rubber hardness. In general, softer rubber (which is softer by higher temperatures) means more of both lower noise and lower rolling resistance, but higher tyre abrasion. Therefore, in general, low rolling resistance and low rubber abrasion are conflicting requirements. This is highly unwanted since both properties have severe environmental effects. Additionally, low rubber abrasion and high wet skid resistance are also essentially conflicting demands due to rubber hardness. Finally, a similar conflicting influence appears regarding rubber abrasion versus noise emission. Fortunately, there are other parameters such as “uniform” forces in the tyre/road contact patch and overall diameter which are mutually favourable to most of the parameters, but overall it is very challenging to produce tyres with low abrasion without having to sacrifice the other mentioned parameters.

Intensive work is taking place in a Task Force for Tyre Abrasion, which is part of the UNECE expert group on tyres (GRBP), to develop measurement method(s) for tyre abrasion and potentially also a “mileage” rating, but also to suggest limit values for tyre abrasion. One section in the Deliverable summarizes the TF TA work.

The deliverable also includes some recommendations for further work in NEEVE.

List of abbreviations and symbols

In this Deliverable abbreviations or symbols in the table below are often used.

Abbreviation	**Explanation**	**Comment**
Partners, companies or institutions related to this project		
VTI	Swedish National Road and Transport Research Institute	Partner
US	University of Sevilla	Partner
CIEMAT	Research Center for Energy, Environment and Technology	Partner
UN ECE	United Nations Economic Commission for Europe	
TF TA	Task Force on Tyre Abrasion	Under GRBP, under WP29 of UN ECE
Technical terminology		
C1 (tyres)	Tyres intended for passenger cars	
C3 (tyres)	Tyres intended for trucks and busses	
EV	Electric vehicle	
RR	Rolling resistance	
dB	Decibel	(Logarithmic) Unit for sound level
PM2.5	Particles with a smaller diameter than 2.5 µm.	
PM10	Particles with a smaller diameter than 10 µm.	
TRWP	Tyre and Road Wear Particles	
TWP	Tyre wear particles	
Ultra fine particles	Particles with an aerodynamic diameter between 5.6 nm and 560 nm.	
Tg	Glass transition temperature	
Measures and units		
phr	parts per hundred rubber	

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1. Introduction

Tyre abrasion is increasingly recognized as a major source of microplastic pollution in the environment [Baensch-Baltruschat et al., 2020; Kole et al., 2017; Wagner et al., 2018]. As tyres wear down during regular use, particles commonly referred to as tyre wear particles (TWP) are released into the environment. These particles, composed of complex mixtures of synthetic- and natural rubber, fillers, and additives [Rødland et al., 2023], range in size from several millimetres down to the nanometre scale, with the most abundant sizes around 20–100 µm [Järlskog et al., 2022; Kreider et al., 2010; Wilkinson et al., 2023]. Once emitted, they contribute to pollution across all environmental compartments, including roadside soils, freshwater systems, marine environments, and the atmosphere [Baensch-Baltruschat et al., 2020].

In the European Union, the estimated annual emission of TWP ranges from approximately 500,000 to 1.3 million tonnes [Giechaskiel et al., 2024; Wagner et al., 2018]. Despite increasing scientific attention, the complete environmental and health implications of TWP are still not fully understood. While studies have demonstrated acute toxic effects on aquatic organisms such as the mortality of Coho salmon due to specific chemical compounds in tyre leachates [Tian et al., 2021] a comprehensive picture of the long-term impacts on ecosystems and human health remains elusive.

The generation of tyre abrasion particles is influenced by a wide array of factors, including tyre composition (tyre type, rubber formulations and additives), tread pattern, inflation pressure, vehicle characteristics (e.g., vehicle weight, wheel load, drive train, torque, and tyre angles), driving behaviour (speed, aggressive acceleration, braking), and external conditions such as road surface, traffic patterns, and ambient temperature [Belkacem et al., 2022; Wagner et al., 2018]. Importantly, the nature of the tyre–pavement contact directly affects the wear rate and particle emissions, highlighting the need for a holistic understanding of how tyre properties interact with their operational environment. Currently, the EU tyre labelling system addresses wet grip, rolling resistance, external noise emissions and winter tyre classification. However, it does not yet include tyre abrasion, despite its environmental significance. With the upcoming EURO 7 regulation, tyre wear performance is expected to be addressed through standardized testing and labelling frameworks [Commission, 2022; Ydrefors, 2024].

In this deliverable, the primary focus is to review how specific tyre design and performance parameters influence abrasion rates, with particular emphasis on tyre material properties, tread design, and structural factors. Since these parameters also influence other important tyre characteristics such as rolling resistance, grip (wet friction), and noise generation, this analysis also considers the trade-offs between environmental performance and vehicle safety or efficiency. The aim is to identify areas where design goals may conflict and where potential synergies may be leveraged. Furthermore, since external factors might influence tyre abrasion as much or more than tyre materials and design, also these are reviewed and discussed.

2. Purpose, objectives and limitations

The aim of this deliverable is to compile current knowledge on tyre properties and external factors affecting tyre abrasion and tyre wear particle emissions.

This deliverable focuses exclusively on tyre abrasion during active use and does not address end-of-life tyre materials, such as rubber granules from recycled tyres used in rubber asphalt pavements, artificial turf or other applications.

The deliverable does not directly deal with measurement methods for NEE or for rubber abrasion as it is supposed to be part of D2.2.

3. Methods

The method used for this deliverable, apart from using the authors' own experience and knowledge, is a literature survey, including Scopus, Web of science, and Google Scholar. AI (Chat GPT and Elicit) has also been used to find and compile references. Syntheses of these are the basis for conclusions.

4. Tyre wear influencing parameters

4.1. Tyre/road interaction

The interaction between tyres and pavement is influenced by several interrelated factors, including tyre type, inflation pressure, tread pattern, wheel load, and rolling speed [Liu et al., 2024]. Also several pavement parameters influence the interaction. These parameters collectively determine the nature and extent of the tyre–pavement contact interface, which in turn significantly affects the rate of tyre wear and the generation of tyre abrasion particles [Gong et al., 2024]. For instance, under-inflated tyres or those subjected to exceptional wheel loads may experience increased deformation and friction at the contact patch, leading to accelerated abrasion. Similarly, variations in tread design and rolling velocity can alter the mechanical stress distribution and thermal conditions during operation, further modulating wear behaviour. Understanding these dynamics is essential for accurately assessing non-exhaust emissions and developing strategies to mitigate their environmental impact.

The tyre–pavement contact can be categorized into geometric and mechanical characteristics. Geometric characteristics pertain to the shape and size of the contact area, while mechanical characteristics involve the stresses and forces acting within the contact zone such as traction during acceleration, lateral forces during cornering, and braking forces during deceleration. These mechanical characteristics are influenced by both vehicle dynamics and pavement performance.

In recent years, due to mitigation of climate change and the increased use of electric vehicles (EV:s), the focus in the tyre industry has been on finding rubber compounds and additives which can reduce rolling resistance (and thus energy use and CO_2 emission while also enabling longer ranges of EV:s). This is often difficult to achieve simultaneously for wet grip (skid resistance); in fact, there is a common view that the optimum designs for rolling resistance and skid resistance are commonly incompatible. The various parameters that play a role in this are explored in the following sections.

4.2. Tyres

4.2.1. *Tyre types for different climates*

Tyres are engineered for specific climatic conditions, with their performance fundamentally influenced by the properties of the rubber compositions, filler content, and tread pattern aiming to optimise their performance regarding safety, fuel economy and noise emissions for the conditions they are built for. Tyres are commonly categorized into summer, all-season, and winter tyres, the latter comprising studded and non-studded variants, the latter often referred to as “friction tyres”. It is important to note that significant variation exists within each tyre category due to differences in quality, material formulations, and design approaches among different manufacturers and brands.

Summer tyres employ harder rubber compounds with higher glass transition temperature, Tg, ensuring durability and optimal performance on dry and wet roads above approximately 7°C. Below this temperature threshold, the rubber stiffens, resulting in decreased grip and increased braking distances.

All-season tyres offer a compromise between summer and winter tyres, with intermediate hardness and Tg values, designed to perform adequately across a range of conditions. Nonetheless, in Nordic climates characterized by prolonged sub-zero temperatures and icy roads, all-season tyres exhibit insufficient elasticity and lack the aggressive tread designs or mechanical traction features necessary for safe winter driving, leading to diminished handling and increased accident risk; see e.g. (Hjort et al. (2024).

Friction tyres (non-studded winter tyres) depend exclusively on rubber softness and tread pattern to achieve traction. Their compounds typically have high silica content and reduced Tg to preserve elasticity under cold conditions. These tyres balance performance and environmental impact by causing less road damage and particulate emissions compared to studded tyres, though their grip on smooth ice is comparatively reduced. Since the rubber mix and tread pattern is soft, using friction tyres in summer temperatures will reduce stability and friction [Leiss et al., 2013] as well as increase the wear rate [Liu et al., 2022].

Studded tyres are optimized for extreme winter environments such as icy and compacted snow surfaces. They incorporate metal studs to provide mechanical traction and utilize medium-soft rubber compounds with low Tg values to maintain flexibility at sub-zero temperatures. However, studded tyres contribute to increased road surface wear, elevated noise levels, and higher emissions of particulate matter, see e.g. (Gustafsson et al. (2009).

The misuse of tyre types poses significant safety and environmental concerns. The use of summer tyres in winter conditions results in rigidity and reduced traction, increasing the accident risk. Conversely, winter tyres used in summer suffer accelerated wear and increased rolling resistance, impacting fuel efficiency. Furthermore, inappropriate deployment of studded tyres outside designated conditions exacerbates road wear and air pollution. Therefore, understanding the material properties and selecting tyres appropriate for the prevailing environmental conditions is essential to optimize vehicle safety, performance, and minimize environmental impacts.

4.2.2. Tyre tread compounds

Tyre wear particles originate from the tyre tread, the outermost layer that comes into direct contact with the road surface. Consequently, in the context of tyre abrasion, the composition of the tread is more significant than that of the entire tyre. However, tyres contain numerous distinct chemical substances, and their compositions can vary significantly across different brands and models [Gieré and Dietze, 2023; Luo et al., 2021; Mattonai et al., 2022].

Although the physical structure of tyres is well understood, their chemical composition remains largely opaque, as manufacturers are not required to disclose detailed information, aside from limited assessments under the European REACH regulation [Mattsson et al., 2023]. Substantial quantities of tyre-derived materials are released into the environment through regular vehicle use, and mounting evidence links these emissions to pollution and ecological harm. While upcoming European regulations aim to address tyre wear rates, they do not encompass chemical composition.

Highly aromatic (HA) oils were previously used in tyre manufacturing to facilitate rubber mixing and enhance the tyre’s technical performance, particularly its road grip. As such, they played a direct role in tyre quality and road safety. However, since 1 January 2010, their use has been prohibited in the European Union under the REACH Regulation (EC No 1907/2006, Annex XVII, Entry 50), which restricts the content of polycyclic aromatic hydrocarbons (PAHs) in extender oils [EC, 2006]. In contrast, the California Environmental Protection Agency introduced a regulation in 2023 requiring tyre manufacturers to evaluate and disclose alternatives to the toxic antioxidant 6PPD. However, this compound represents only one of hundreds of organic substances typically found in tyres, many of which remain chemically uncharacterised and environmentally unassessed [Obanya et al., 2024].

All tyre treads consist of the following compounds, the exact composition varies between brands and tyre types [Gieré and Dietze, 2023; Johannessen et al., 2022; Sommer et al., 2018]:

- Polymeric materials: generally natural rubber (NR) and synthetic rubber (styrene-butadiene- rubber, SBR, and butadiene rubber, BR) (40–50%)
- Fillers: e.g., carbon black or silica (30–35%)
- Softeners: often used as processing aids, such as soil and resin (15%).
- Vulcanization agents: curatives, accelerators and activators to vulcanize or cure the rubber, through the creation of crosslinks between the polymer chains e.g., zinc oxide, stearic acid, and organic sulphur (2–5%)
- Additives: e.g., anti-degradants for protection against deterioration due to oxygen, heat etc, specific chemicals to increase strength and stability (5–10%).

4.2.3. Influence of rubber hardness and ambient temperature

One important tyre material property is hardness, which affects both skid resistance, rolling resistance, noise emission and abrasion. A harder tyre will have less dry and wet skid resistance, but lower rolling resistance than a softer, due to lower rubber deformation energy losses. In recent years, as a result of increased interest on fuel economy, greenhouse gas emissions and driving range of battery electric vehicles, there has been a focus on finding rubber compounds and additives which can reduce rolling resistance. This is often difficult to achieve simultaneously with a good wet grip (skid resistance); in fact, there is a common view that the optimum designs for rolling resistance and skid resistance are incompatible, in accordance with the “magic tyre triangle” (Figure 1).

The hardness of the tyres has, in several studies, directly or indirectly, been shown to be related to tyre abrasion and TWP emissions. For example, Schläfle et al. (2023b) used an internal drum with asphalt and investigated the effect of temperature, which affects tyre hardness, on particle emissions from a summer, a winter and an all-season tyre. Since rubber gets softer at higher temperatures and vice versa, summer tyres need to have harder mixes and winter tyres softer mixes. The results showed that the particle emissions from the summer tyre were slightly larger at higher (25 °C) than at lower (5 °C) temperature, while the winter tyre showed a reversed correlation, i.e. had lower emissions at the higher temperature.

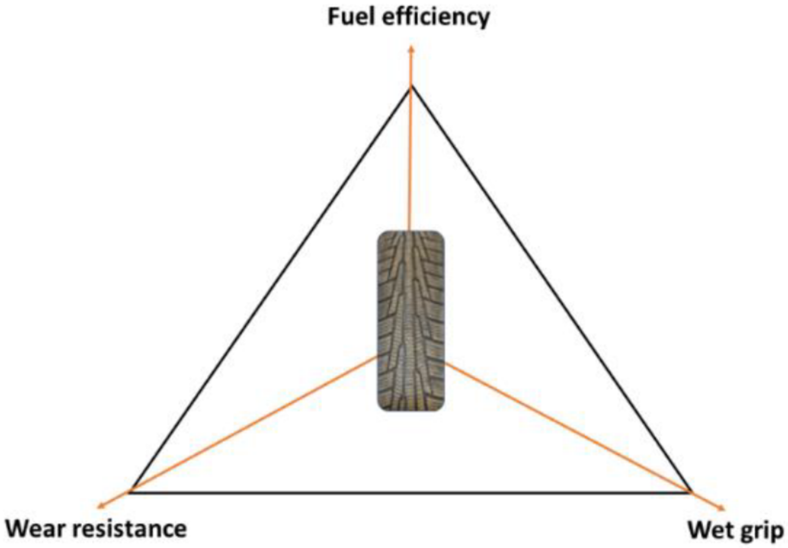

Figure 1: Magic tyre triangle. Source: [Ydrefors, 2024].

The all-season tyre differed by having both lower and higher emissions depending on load condition. In two different projects involving in total 14 summer, studless winter and all-season tyres, Mathissen et al. (2024) showed that PM10 concentration in a road simulator set-up, is linearly dependent on tyre rubber hardness, resulting in the softer winter tyres emitting higher amounts of PM10 than the harder summer tyres (Figure 2). Mathissen et al. (2024) showed that PM10 concentration in a road simulator set-up, is linearly dependent on tyre rubber hardness, resulting in the softer winter tyres emitting higher amounts of PM10 than the harder summer tyres (Figure 2). For each set-up the initial temperature was the same for all tyres (10 ºC), but different pavements were used. The same study also demonstrated a higher tyre abrasion at higher temperatures for a summer and a winter tyre within the temperature range -5 to +25 ºC.

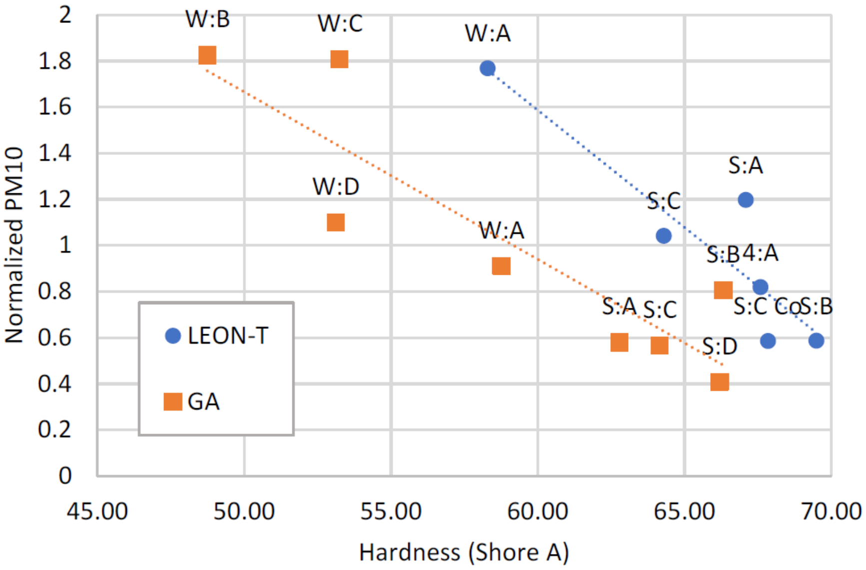

Figure 2: Normalised PM10 concentrations as function of tyre rubber hardness in a road simulator set-up [Mathissen et al., 2024].

4.2.4. Influence of reinforcing agents

The choice and amount of reinforcing agent can influence the tyre hardness. Carbon black (CB) has been the most common reinforcing agent, but today silica is also common, especially in passenger car tyres. The amount of reinforcing CB in the rubber mix was shown to increase the hardness and decrease the tyre wear without affecting the grip coefficient [Purboputro et al., 2020]. The amount of CB was shown to be more important than the type used in a study by [Chung et al. 2002] while [Gamlath et al. 2024] showed that the type of CB has influence as well (e.g., better tear strength, tensile properties, hardness, and abrasion resistance). Further, [Ha et al. 2023] indicate that modifying the type of carbon black can reduce the generation of particulate matter in the 2.5 µm size range. Specifically, using CB with a lower average surface diameter and a lower exposed surface area compared to conventional CB seems to reduce the tread block removal rate. In contrast, larger CB particles increase the internal stress gradient within the rubber matrix, which facilitates the formation of tire wear particles.

The influence of carbon black on abrasion resistance depends on its surface area, i.e. particle size, its dispersibility and surface properties. This is also true for another reinforcing agent, silica, which is found to be superior to carbon black regarding wet grip and rolling resistance [Wang, 2008]. However, silicas influence on wear resistance is contradictory. Some researchers [Wang, 2008] described silica as inferior to carbon black in regard to wear resistance while other researchers [Gehrke et al., 2023] described that replacement of silica rather than carbon black improves the wear resistance to a greater extent while improving the rolling resistance by decreasing the energy losses and at the same time not changing the wet grip ability.

Furthermore, [Gehrke et al. 2023] also reports that often there is an inverse correlation between abrasion rate and particle size, the amount of emitted finer particle increases as the total abrasion rate decreases. This implies that the total mass of emitted tyre particles can decrease while the amount of emitted fine particles increases. An increase in silica in the tyre influenced the size distribution of the tyre wear. The number of emitted coarse particles decreased, while the number of fine particles increased [Yan et al., 2021].

Another study showed that an increase in silica loading caused a decrease in wear rate until reaching at a silica loading of approximately 50 phr after which the abrasion rate seems to be unaffected by further silica loading. This may be a percolation limit, and a further filler increase will reduce the interaction between filler and polymer [Sridharan et al., 2019].

Besides, carbon black and silica, some less common reinforcing agents have been tested, e.g., multiwalled carbon nanotubes (MWCNT) and reduced graphene oxide sheets (RGO). The wear resistance was increased in the tests when part of the carbon black was replaced with multiwalled carbon nanotubes [Zhu et al., 2019]. However, the health effects of inhaling MWCNT are not well known. If single MWCNTs are released and inhaled, the damage may be more profound compared to a larger amount of tyre particles. In a test, RGOs were added to silica loaded SBR/BR mix. The wear resistance was shown to improve by increases in the RGO loading [Sae-oui et al., 2017].

The influence of the filler on the wear resistance is also affected by the polymer it is combined with. In [Sae-oui et al. 2017], tests with different combinations of polymer and filler were performed, with styrene butadiene rubber and butadiene rubber (BR), combined with either carbon black or silica as filler. In these tests, the abrasion resistance was better with carbon black than with silica. The authors explain it with a stronger filler-filler interaction (Payne effect). However, the rolling resistance and the wet grip is estimated to be improved by using silica. These estimations are done based on the ratio of loss modulus to storage modulus at low temperatures around 0 °C and high temperatures around 60 °C which are expected to give a good representation of the wet grip and the rolling resistance. The presence of BR resulted in poorer wear resistance in most systems tested, but in one system, in which BC was used, wear resistance increased. For all systems tested, the pure BR mix showed the best wear resistance and rolling resistance but the poorest wet grip among the measurements. The inclusion and increase of SBR in the mix resulted in a better wet grip and poorer rolling resistance. The relationship between mix composition and wear resistance was not linear between the different mixtures.

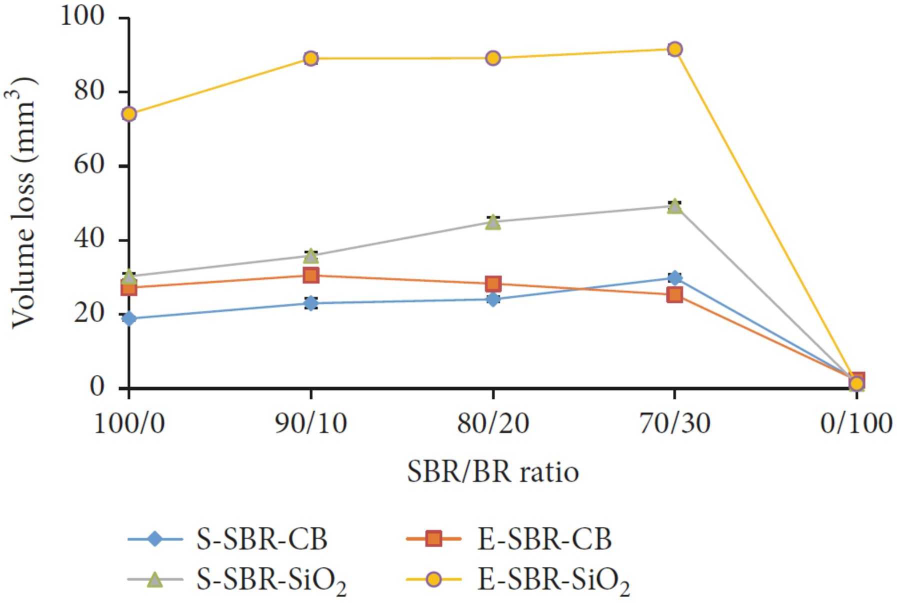

Figure 3: Effect of SBR/BR blend ratio on abrasion resistance for four rubber mix systems, with carbon black or silica enforcement [Chae et al., 2022].

4.2.5. Size and properties of the wear particles

The rubber mix composition not only affects the wear rate, but also the properties of the wear particles produced. [Chung et al. 2002] could show that a rubber mix with only natural rubber resulted in a coarser size distribution than mixes with 20 and 40 % synthetic butadiene rubber.

The influence of the curative on the abrasion rate has also been tested. The choice of curatives showed a stronger influence on the wear rate than the amount of reinforcing carbon black, with a lower wear rate for a conventional curative compared to the more efficient ones [Chae et al., 2024b]. The tested cure systems based on natural rubber (NR), differed in terms of their ratio between sulphur and the accelerator TBBS (tert-butyl-benzothiazole sulfonamide), which affects the rubber network. The sulphur accelerator ratio was larger for the conventional system, reduced for the semi-efficient system and lowest for the efficient cure system.

The incorporation of hydrocarbon resins, such as dicyclopentadiene (DCPD), has been shown to reduce rubber abrasion across four types of laboratory abrasion test equipment. However, the presence of DCPD led to the generation of coarser tyre wear particles (TWPs), with most particles found in the >1000 µm size fraction [Gehrke et al., 2023]. This suggests that while hydrocarbon resins may positively influence the wear rate, they could also affect the particle size distribution of TWPs under environmental conditions. It should be noted, however, that the particle size distribution obtained from laboratory abrasion tests may not accurately reflect real-world conditions, where mechanical forces, environmental variables, and road surfaces differ significantly.

As mentioned above, [Yan et al. 2021] reports that often there is an inverse correlation between abrasion rate and particle size, the amount of emitted finer particle increases as the total abrasion rate decreases. This implies that the total mass of emitted tyre particles can decrease while the amount of emitted fine particles increases. An increase in silica in the tyre influenced the size distribution of the tyre wear particles. The number of emitted coarse particles decreased, while the number of fine particles increased [Gehrke et al., 2023].

4.2.6. Tyre production

Vent spews are hair-like rubber residuals, found on a new tyres' surfaces which originate from the production procedure. These particles are emitted from the tyre during the first driven kilometres. The tyre manufacturers should be held responsible to stop these production residues from being emitted in the environment [Egaji et al., 2019; Mathissen et al., 2011].

4.2.7. Tyre dimensions

For functional parameters such us noise emission, wet grip and rolling resistance, larger tyre width is negative while higher diameter is positive, for similar loads and adjusted inflations. It is a complicated interaction between load, inflation and tyre dimensions. But given the same load, quite probably, it may be the same influence of tyre dimensions for rubber abrasion. At least, higher diameters will reduce the sudden tyre deformations in the edges of the contact patches, which logically should be positive for all the mentioned parameters. Increased widths will expose a wider tread to the unavoidable deformations in the leading and trailing edges of the tread.

Egaji et al. (2019) shows that larger tyre dimensions with higher loads will emit more wear particles, even though their tread depth decrease is slower. Nevertheless, if the same wheel load is used for all tyres, the larger tyre dimensions will emit slightly less wear particles and have a clearly slower reduction in tread depth. Here, one would need to separate the effects of tyre width and diameter while keeping loads the same to get a clear picture.

4.2.8. Tyre inflation and ageing

Tyre wear is influenced by a combination of factors, including maintenance practices, ageing, and inflation pressure. Ageing, particularly thermal ageing, has been shown to increase the abrasion rate of rubber compounds. [Chae et al. 2022] attribute this effect to an increase in cross-link density and a reduction in antidegradants, leading to a stiffer rubber matrix that is more prone to wear. Additionally, aged tyres tend to produce smaller wear particles.

Inflation pressure also plays a critical role in determining tyre wear patterns and overall tyre lifespan. Under-inflation leads to an elongated contact patch and increased loading on the shoulder areas, resulting in accelerated wear on both edges of the tread. In contrast, over-inflation concentrates the contact area at the centre of the tread, causing excessive central wear. While inflation pressure has a more direct impact on tyre longevity than on the quantity of wear particles generated [Buschmeier and Oelze, 2022], improper inflation, particularly under-inflation, can increase fuel consumption by up to 2 % and reduce tyre life by approximately 25 % [Schläfle et al., 2023b]. Optimal tyre pressure is vehicle- and load-specific, and dependent on tyre type. Manufacturers typically provide recommended inflation values, often indicated on the tyre sidewall or within the vehicle's specifications. Regular monitoring and adjustment of tyre pressure in accordance with these guidelines are essential, especially for commercial vehicles subject to varying load conditions. Proper inflation is thus crucial not only for minimising irregular wear and extending tyre life but also for maintaining fuel efficiency and overall vehicle safety [Zhang et al., 2024].

4.2.9. Temperature influence

The ambient air temperature, the road temperature, the weather and the driving condition together determines the tyre temperature which in turn influences the tyre wear. A tyre whose temperature is near its compound's glass transition temperature[1] has a poor wear resistance, but the wear resistance improves as the temperature increases, wear in this temperature range is often called plastic deformation wear. As the temperature increases, the temperature's influence on the wear rate decreases. Lastly, the temperature reaches a level where the wear increases at further temperature increases. Wear in this temperature range is often called elastic deformation wear [Zhang et al., 2023].

The tyre temperature influence on wear depends on the constituent material and varies between tyres. In a study with an all-season tyre, a summer tyre, a European and a Nordic winter tyre, they were driven the same test route at 4 °C and 12 °C ambient air temperature. The tyre wear rating order changed between the two different test temperatures [Kipscholl and Stoček, 2023].

In another study, a winter tyre, a summer tyre and an all-season tyre were run at different wheel loads and at two different ambient air temperatures, 5 °C and 25 °C. A comparison between tyre wear measurements on the tyres performed at different loads and 25 °C for the summer tyre, 5 °C for the winter tyre, and both temperatures for the all-season tyre was performed. The summer tyre showed the lowest emission rates at all tested wheel loads, while the winter tyre had the highest emission rates for the tested loads [Wilkinson et al., 2023].

Besides the ambient air temperature and the weather, the tyre temperature will also be affected by the driving style, where large slip angles or high torques will contribute to a heat-up effect on the tyre. Tread temperatures heavily affect the emission of ultrafine particles. As the tread temperature increases, the emission of ultrafine particles increases due to volatilization and

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[1] The glass transition temperature (Tg) is the point at which a polymer changes from a hard, brittle state to a soft, rubbery state, influencing flexibility and grip. Winter tyres are for example formulated with rubber compounds that have a lower Tg than summer tyres, allowing them to remain soft and effective in cold conditions.

nucleation of organic compounds with the tire tread [Mathissen et al., 2024]. The size of the tyre wear particles decreases as the air humidity increases [Mathissen et al., 2024].

Temperature also plays a significant role in the formation of tyre wear particles, particularly through the manifestation of smearing abrasion, wherein particles adhere to the pavement surface. This smearing is likely attributed to thermal degradation and oxidation processes affecting the rubber compounds in tyres. Such phenomena have been documented in several studies e.g. [Mattonai et al., 2022; Yusupov Umidbek et al., 2022]]. When testing one summer tyre and one winter tyre under three different temperature conditions (-5, 10 and 25 °C), Ma et al. (2017) found that both mass and number concentration of particles increase with increasing temperature, implying softer rubber mix.

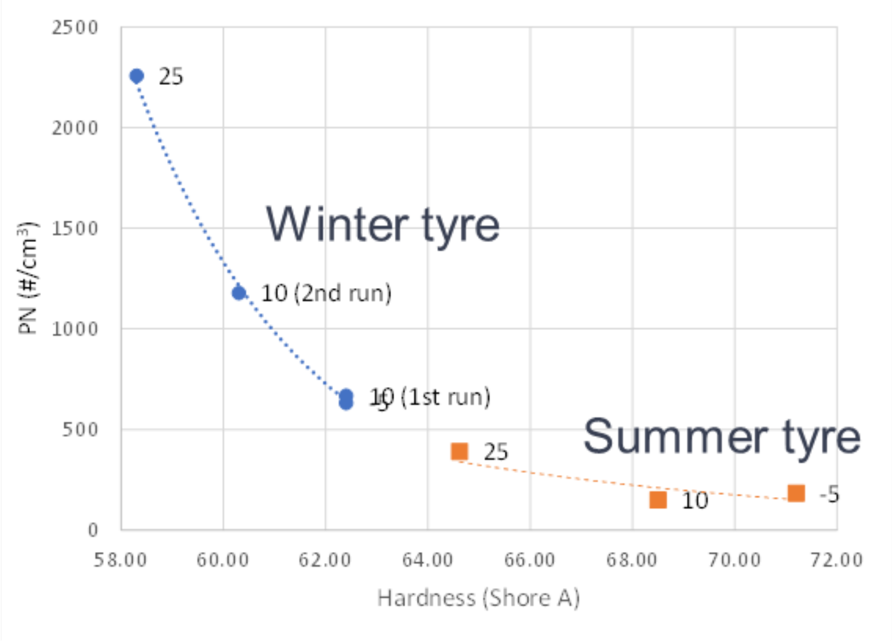

Figure 4: Particle number concentration as a function of rubber hardness and temperatures for a winter and a summer tyre [Ma et al., 2017].

The tyre temperature will also be influenced by wet driving conditions, since it will cool the tyre down and hence influence the temperature effect on the wear rate. Another influence is that the water will reduce the contact between tyre and road and therefore influence the friction and consequently the wear rates on the tyre. The direction of the influence of the wet conditions differs between tyres, for two tested tyres the wear rates were reduced in wet driving conditions, while the other two showed the opposite trend [Zhang et al., 2023]. Tyres of an average vehicle operating on highways can attain temperatures ranging from 60 to 70 °C. Elevated thermal conditions promote the evaporation of volatile compounds and facilitate the formation of finer tyre and road wear particles, characterised by smaller particle sizes in comparison to the coarser fraction [Pohrt, 2019].

Pohrt (2019) suggests that tyre wear increases the further away the ambient air temperature is from the tyre's optimal temperature. However, their measurements rather show that the tyre wear increases as the ambient air temperature increases. In a recent review, [Müller et al. 2025] examine the relationship between climate change and particulate tyre wear emissions, concluding that direct empirical evidence remains limited. However, several studies suggest potential indirect links through environmental factors such as rising temperatures, extended dry periods, and increased stormwater events. Seasonal variation in tyre emissions has also been reported, with some studies observing higher concentrations during summer months, while others found elevated levels during winter or monsoon seasons, for example [Kang and Kim 2023; [Nguyen et al. 2024]; [Schläfle et al. 2023]; [Srimuruganandam and Shiva Nagendra 2012], all of which may influence tyre wear rates and the dispersion of particulates. These inconsistencies point to the complex interplay between climatic conditions and emission dynamics but may also partly be due to neglected uncertainties in the experiments. The impact of temperature on tyre wear emissions is particularly contested, with findings ranging from increases to decreases in emission levels, likely reflecting methodological differences across studies. Overall, the current body of research lacks standardised, harmonised data, thereby limiting the ability to draw definitive conclusions and highlighting the need for further investigation in this area [Müller et al. 2025].

4.2.10. Particles from worn tyres vs new tyres

Hägg made a statement in 2025 that worn tyres produce significantly more tyre-wear particles than new ones [Hägg 2025]. Laboratory measurements revealed that when a tyre is brand new, the outermost layer wears off quickly during a short initial phase, resulting in elevated particle emissions—commonly referred to as the "break-in" period. This may be more significant for tyres which have a different compound in the outer part than further inside the tread. After this phase, tyre wear emissions stabilize at a relatively consistent rate until the tyre becomes severely worn, typically beyond 70 % of its usable tread. As mentioned above, ageing by time and use may amplify this effect. At this stage, the tyre's structural integrity is compromised, causing it to break down more rapidly. As a result, the emission of tyre-wear particles increases significantly, reaching levels two to three times higher than those of brand-new tyres, according to statements by [Hägg, 2025].

Here is then another conflict with rolling resistance (RR), as worn tyres produce more TWP but RR decreases when tyres are worn [Sandberg & Glaeser, 2008].

4.3. Vehicle properties

4.3.1. General issues

Two Chinese studies evaluated tyre wear quantity and difference (TWQD) based on mathematical theorical model using coupling algorithm of vehicle dynamic model and road properties [Zhang et al., 2023; Zhong et al., 2024]. The researchers analyzed factors of vehicle speed, steering angle, braking forces and road features. The results revealed that vehicle speed, braking force and road surfaces have a significant effect on TWQD. Among the investigated features, the vehicle speed had the highest impact on TWQD. On the other hand, the impact of steering angels on TWQD was so weak that it could be neglected. Higher speed led to higher kinetic energy and intense frictional interaction between tyre and road surfaces which in turn led to higher heat and more mechanical stresses on tyre tread, hence, higher tyre wear. For braking forces, the stronger braking led to an increase in the longitudinal slip ratio and frictional interaction between tyre and road surfaces. The process led to heating and abrasion, especially in the front tyres of vehicles.

The company Emissions Analytics recently conducted tests on eight different brands and types of tyres. Full sets were mounted on the same test vehicle with wheel alignment and tyre pressures properly adjusted. Each tyre set was driven for over 1,000 miles, with approximately 90 % of that distance covered on motorways. To assess wear, the tyres remained mounted on their rims to avoid damage, and the complete wheels were weighed before and after testing. From this, the distance-specific mass loss was calculated. On average, the vehicle lost 64 mg/km across all four tyres. Notably, the rear tyres accounted for 71 % of total wear, largely due to the car's rear-wheel drive configuration.

Tyre wear rates varied significantly between brands. The fastest-wearing tyre lost mass at 2.3 times the rate of the most durable one, highlighting the substantial impact tyre selection can have on particulate emissions. Wear was observed to be highest when tyres were new, particularly during the first few thousand miles, after which the wear rate declined in a pattern approximating a logarithmic curve. Based on an average annual mileage of 16,000 km, this equates to roughly 0.5 kg of tyre material shed per vehicle per year [Beji et al. 2020]; [Belkacem et al., 2022]; [Foitzik et al., 2018]; [Muresan et al., 2024]; [Schütte and Sextro, 2021]; [Wei et al., 2020].

4.3.2. Wheel alignment (toe and camber angles)

Toe-in and camber are two important parameters in the design of four-wheel vehicle and can significantly affect tyre wear [Leister, 2018]. The accurate matching of the toe-in and camber angle settings can be chosen to minimise the sideslip. The precise calculation of the matching is difficult due to complexity of tyre cornering properties. [Liu et al. 2022] suggests a formula, considering the cornering characteristics of tyres and the structure parameters of vehicles, to calculate the optimal toe-angle at a given camber angle. Adjustments according to this formula are expected to reduce the tyre wear rate.

The design of the wheel suspension will influence the camber and toe angles and can be performed in a way that minimises the camber and toe angles. [Liu et al., 2022; Union, 2009] investigated the interaction between wheel suspension kinematics and tyre wear based on a flexible multibody simulation model for a rear axle system. Camber and toe angles, kinematics of wheel and distribution of mass loss of tyre tread materials per unit contact width were studied to evaluate their impact on the interaction between tyre and road. The simulation model included a complete vehicle model. The results showed that a theoretical wear rate for the suspension with the most advantageous tyre angles was less than 50 % of the wear rate in the same setting with a traditional series suspension, which means tyres with new setup can be used twice as long as the traditional setups [Union, 2020].

The toe angle has a large influence on tyre wear [Trudso et al., 2022; Union, 2024]. They established a 3 degree of freedom nonlinear vehicle dynamic mathematical model to analyse the effects of different initial toe angles on tyre wear. The initial toe angle was set to be 0 °, 0.5 °, 1° and 1.5 °. The results showed that if the toe angle is too big or unreasonable, the tyre wear is abnormally more. If toe angel increases to 1 °- 1.5 °, the tyre wear may occur 3 to 10 times more, comparing with normal design.

A study by UN ECE found that the relationship between slip angle and the tyre’s total amount of measured wear particles was best described as a second-grade polynomial [UNECE, 1968]. A big part of these emitted particles was found to be ultrafine particles. When both the slip angle and the speed was varied the found relationship was closer to an exponential curve, when only changing the speed, a linear curve was the best description.

4.3.3. *Wheel load*

A dependency of wheel load, with higher wear at higher load, was shown by [UNECE, 2016] for the wear rate. However, this wheel load dependency is small compared to the influence of slip angle and speed.

4.3.4. *Vehicle type*

Autoily, an interest organization, reported in 2025 that front-wheel-drive (FWD), four-wheel-drive (4WD), and all-wheel-drive (AWD) vehicles, even though all axles contribute to traction, the front tyres tend to wear out faster than the rear ones. This is primarily because the front tyres handle most of the braking and steering and are subjected to greater lateral forces. In rear-wheel-drive (RWD) vehicles, where the rear wheels are responsible for traction and acceleration, the rear tyres typically wear faster. However, the difference in wear between the front and rear tyres is not always significant and can vary depending on driving behavior. For trucks, tyre wear is more influenced by which axle bears more weight rather than by acceleration forces. Furthermore, [Autoily, 2025] noted that the side of the road a vehicle drives on can also affect tyre wear. For example, in countries like the United States, where vehicles drive on the right side of the road, the right-side tyres tend to wear faster. This is due to more frequent left turns, which shift more weight onto the right-side tyres. Even though this is an interesting result, it needs further evaluation through controlled scientific studies.

The EU Commission has evaluated the tyre wear on the front and rear of FWD vehicles [Commission, 2023]. They found that the wear on the front tyre was 1.7 times more than that on the rear tyre due to following factors: more weight and higher acceleration applies to front tyre as well as toe angle of the front tyre, in which the front tyre is aligned slightly inward to improve steering. Moreover, [Andrew and Wright-Williams, 2018] studied the effects of vehicle types on tyre wear under real driving conditions. They studied two types of vehicles, Skoda-Octavia (a conventional internal combustion engine vehicle) and Toyota-Auris (a hybrid electric vehicle). They found that, on average, the hybrid vehicle had 36 % more tyre wear than the conventional internal combustion engine vehicle, which can be related to faster acceleration and higher instant torque at start.

A survey and interview study on users' experience of tyre wear on electric vehicles, Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs) was conducted by [Mirzanamadi and Gustafsson, 2022]. The results showed that approximately 33 % of private vehicle drivers reported a faster tyre wear in their EV/PHEV/HEVs vehicles, comparing with tyre wear in a conventional internal combustion engine vehicle (ICEV). Two main reasons for faster tyre wear in EV/PHEV/HEVs were reported to be their higher acceleration and heavier vehicle loads, compared to ICEVs. In addition, it was noted that the driving behaviour in electric vehicles can led to slower tyre wear, compared to tyre wear in ICEVs.

In a modeling study by [Foroutan et al., 2025] the authors project that total PM10 and PM2.5 emissions from tyre wear particles will increase over the next two decades in the US, primarily driven by the expansion of the vehicle fleet and the growing prevalence of electric vehicles. A key contributing factor is the higher weight of EVs compared to conventional vehicles. Notably, when the authors conducted simulations excluding the additional weight of EVs, PM2.5 emissions from TWPs decreased by over 40 %, and the projected contribution of EVs to total PM2.5 emissions in 2044 dropped from 40 % to below 31 %. These findings underscore the importance of reducing vehicle weight, particularly through advancements in battery technology, as a strategy to mitigate TWP emissions associated with EV adoption.

Electric vehicle tyres differ from conventional tyres in several ways as they need to support more weight, reduce rolling resistance, resist abrasion from higher torque, minimize noise, and often feature narrower tyre designs with special tread patterns. They also partly replace deceleration by applying brakes to a “softer” deceleration by regenerative braking for the purpose of charging the battery. This could balance out some of the wear-increasing effects but of course depends largely on how the driver handles the vehicle. These design changes affect tyre performance, but there is currently no original data showing how these differences impact particulate tyre wear emissions as the vehicle fleet becomes more electrified. Although it's often assumed that EVs will increase particulate tyre emissions due to their weight and torque, this conclusion is not fully supported by existing evidence. The topic is complex and requires consideration of additional factors like future traffic trends and regional socio-economic developments [Müller et al, 2025].

4.4. Tyre labelling

4.4.1. The EU tyre label

When tyres are placed on the market within the European Union, they must comply with the requirements outlined in the *General Safety of Motor Vehicles* regulation (Regulation (EC) No. 661/2009) [Rødland et al., 2024]. In addition, a tyre labelling framework has been in place since 2009, originally established under Regulation (EC) No. 1222/2009 and subsequently revised by Regulation (EU) 2020/740, which came into effect in 2021 [Rødland et al., 2024]. The objective of this labelling scheme is to enhance consumer awareness and decision-making by providing standardized information on key performance indicators, including fuel efficiency (via rolling resistance), safety (wet grip), and external rolling noise [Grigoratos et al., 2018]. As of 2021, two additional performance criteria were introduced to address extreme weather conditions: the Alpine symbol (3PMSF) for snow performance and the ice stalagmite symbol, specific to Nordic markets, for icy conditions. All labelling information is recorded in the European Product Database for Energy Labelling (EPREL), where manufacturers are responsible for uploading and maintaining relevant product data.

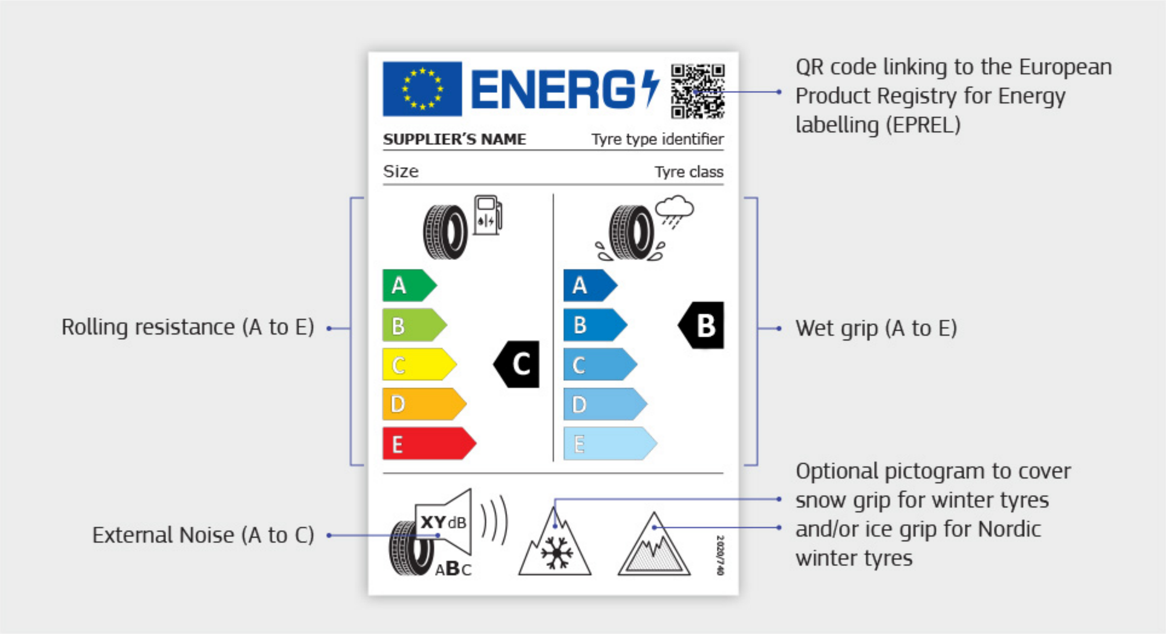

Figure 5: The EU tyre label which is to be stuck on each tyre. From [European Union, 2020]. The tyre manufacturers usually add own information above and/or below the formal label.

While there is not yet any formal decision to include a tyre abrasion label, provisions exist to include tyre abrasion and durability metrics on labels once standardized testing methods are established. The proposed approach involves measuring tread depth loss during abrasion tests to project tyre service life, akin to the treadwear index used in the United States [Jeong et al., 2022].

The Euro 7 regulation, formally adopted in April 2024, introduces comprehensive measures to address non-exhaust emissions from vehicles [Woo et al., 2022]. This marks the first instance of the European Union setting a framework to limit tyre abrasion emissions, aligning with methodologies developed by the United Nations Economic Commission for Europe [Woo et al.] under UN Regulation No. 117 [Pohrt, 2019]. See further about expected regulations in 8.1.

While the European REACH regulations do restrict certain toxic chemicals in tyre manufacturing (e.g., polycyclic aromatic hydrocarbons, (EC, 2006 #837)), the scope of tyre wear particle restrictions remains limited as tyre wear particles are classified as unintentionally released microplastics and are therefore exempt from the microplastic restriction under REACH (Annex XVII, Entry 78 of Regulation (EU) 2023/2055) [Guo et al., 2025(ECHA, 2025 #5003]). Further, tyres are treated as complete products, classified as 'articles'. While polymers are exempt from REACH registration requirements, they are still subject to authorization and restriction provisions [Lowne, 1971].

In a study by [Lowne, 1971] the chemical composition of nine tyres marketed as "green," and seven conventional tyres was analyzed to assess whether "green" tyres are environmentally safer. Despite marketing claims, no significant differences in overall chemical composition were found between green and conventional tyres. In fact, some green tyres contained higher concentrations of 6PPD, a compound known for its environmental toxicity, than conventional ones. The study also revealed that tyre classification based on seasonal use better explained chemical variation than sustainability labels. For instance, tyres with lower rolling resistance, often promoted as more sustainable under EU Tyre Labelling, were associated with higher levels of synthetic rubber and 6PPD. These results disprove assumptions that "green" tyres contain fewer hazardous substances or form a distinct, less harmful chemical group.

It was concluded by [Muresan et al., 2024] that current sustainability labelling lacks transparency and does not adequately reflect the chemical risks of tyres. They recommend including chemical composition in environmental assessments as the findings suggest that "green" tyres, as currently marketed, may pose similar or even greater environmental risks than conventional ones.

4.4.2. *Treadwear rating*

Already in the 1970's a system named Uniform Tire Quality Grading (UTQG) was introduced in the US. It included a "Tread wear rating". It means that tyre manufacturers test and rate their own tyres and submit reports to the US DOT's National Highway Traffic Safety Administration (NHTSA). An UTQG treadwear rating means that the manufacturer took the tyres to a testing facility, put it on a test vehicle and measured it against a standard tyre with a 100 treadwear rating. If a tyre is rated 300, that means it is expected to wear three times faster than the 100-UTQG rated tyre. TWR values range from 100 to 700.

A study by [Muresan et al., 2024] investigated the Treadwear Rating (TWR) provided on the sidewalls of tyres as an indication to predict the amount of physical wear and particle emissions (PM10, PM2.5, and particle number) from tyre use. The study tested five summer tyres from different brands at a constant speed of 70 km/h in a controlled laboratory pavement environment. The results showed that tyres with the same TWR but from different manufacturers behaved differently in terms of material loss and particulate emissions. This suggests that TWR alone cannot reliably predict emissions when comparing tyres across brands. However, within the same brand, the tyre with a higher TWR did show reduced wear and lower PM10 emissions.

The study highlights the complexity of tyre wear emissions. Despite TWR being a durability indicator, it does not universally correlate with particle emissions, especially across different brands. [Muresan et al., 2025] investigated the chemical leaching behaviour of TWPs from tyres with varying treadwear ratings. They found that TWPs from tyres with a treadwear rating of 700 contained significantly higher concentrations of marker compounds (benzothiazoles) compared to those with lower ratings of 250 and 500. The authors noted that a higher treadwear rating generally reflects a longer-lasting tire. This would typically suggest that such tyres generate fewer TWPs. However, the elevated concentrations of leached compounds observed in TWPs from high-rating tyres contradict this assumption, implying that longevity does not necessarily correlate with lower environmental impact in terms of chemical emissions.

The effects of TWR on the generation of tyre PM was investigated [Muresan et al., 2025] through laboratory tests and real-world driving measurements. Tyre wear simulator (from NEOPLUS Inc., Korea), installed in a chamber, was used to perform the laboratory measurement. Furthermore, a mobile sampling vehicle, driving on an asphalt road, was used to measure the particle mass concentration of tyre-road wear particles. Tyres used for tests were all-season tyres with the same sizes and tread pattern, but their number of TWR were different including 250, 350, 500 and 700.

The results of both laboratory and real-world driving measurements showed that PM emissions generally decreased as the TWR of the tyre increased, except for the tyre with the highest TWR

(700), which produced higher PM emissions than the tyres with TWR numbers of 350 and 500. Tyres with TWR number of 250, 350 and 500 were developed for passenger vehicles and primarily used silica as the filler material. For these tyres, as the number of TWR increases, the strength of rubber increases which leads to less treadwear and in turn reduction in the PM emissions. While tyre with TRW number of 700 was mostly developed for commercial vehicles and its filler material was only carbon black. This tyre could easily produce fine particles due to lamellar peeling, especially under high-speed conditions, rather than tearing or curling of tyre treads [Veith, 1973].

The treadwear rating is often connected to an estimation of how long distance a tyre will roll until it is worn-out; what is referred to as “Mileage”. Tyre companies offer a “guaranteed” milage for a certain tyre. An often used conversion is to multiply the treadwear number by 1000 to get mileage in miles. For example, a tyre rated 400 should last for 40,000 miles (64,000 km). But this of course depends a lot on the driver and there is at least one (commercial) actor in the field that offers a “Treadwear mileage calculator” that is claimed to take this into account [Atlib, 2025].

There has been wide disappointment in the US about the treadwear indicator, yet it is still there. It is recognized of being fairly ok within a certain tyre manufacturer’s product range but giving strange results when comparing tyres between manufacturers. The reason is not so much the system and its criteria itself, but that there is a lack of control that the ratings from manufacturer to manufacturer is consistent. The main problem is that tyre manufacturers can select their control tyres (which give the rating 100), so the reference tyre may greatly differ between brands. Furthermore, both conditions and test track surfaces are not sufficiently specified and controlled. The problem is similar to that of noise measurements, where track-to-track differences may be equally high as differences between tyres. Thus, the problem cooks down to inadequate specifications in the measurement method, reference tyre, calibrations and proper standardization.

4.5. Road surface properties

The characteristics of road surfaces, particularly their texture, play a significant role in influencing tyre wear rates [Zhang et al., 2023]. Asphalt pavements are composed of aggregate particles bound together with bitumen. The size of the aggregates and its grading give a distinction between macrotexture defined by the size, distribution, and spatial configuration of the aggregate. Microtexture, on the other hand, pertains to the surface roughness of individual particles with dimensions less than half a millimetre. Over time, the loss of bitumen binder and the smaller aggregates can lead to an increase in macrotexture, but the opposite is also possible; all depending on the properties of the aggregates. Conversely, microtexture tends to diminish due to surface polishing [Pohrt, 2019], but it may also increase due to the action of studded tyres where such are used in wintertime. Zhang et al. (2023) investigated the effects of road surface texture on tyre wear. The result showed that driving on rough and harsh road surfaces can lead to three times more wear on tyre rather than driving on smooth and polished road surfaces. Pohrt (2019) reported that that microtexture roughness played the main role on tyre wear, compared to the effects of macrotexture.

Extremely high differences in tyre wear were measured in a number of Swedish tests in 1977-1980. Around 70 % more tyre weight loss was recorded on a surface dressing (designated Y1) with high macrotexture compared to a smooth-textured asphalt (AC 11). Results were similar irrespective of whether the surface dressing was new or medium worn [Kihlgren, 1980].

Nevertheless, in a study by [Pohrt, 2019], the role of Mean Profile Depth (MPD) in relation to Tyre and Road Wear Particles (TRWP) emissions were explored. Findings indicate that MPD alone is not a reliable predictor, as pavements with higher MPD sometimes yielded emission levels comparable to those with lower MPD. This suggests that other parameters such as microtexture and the physical properties of the pavement materials can obscure or override the effects of MPD. Moreover, [Zhang et al., 2023] emphasize that optimizing pavements solely for mechanical durability, safety, or noise reduction may inadvertently exacerbate TRWP emissions. Instead, a multi-criteria approach to pavement design accounting for emission mitigation may offer a strategic opportunity to enhance urban air quality in the context of increasing vehicle electrification.

In another study by [Zhong et al., 2024], the direct emissions of TRWP under varying road surface types and driving conditions were investigated. The study encompassed five road categories: urban, suburban, beltway, rural, and highway. Results showed that TRWP emissions per kilometre were significantly higher on urban, suburban, and rural roads, and lower on beltways and highways. Driving on beltways and highways, characterized by steady high speeds (>60 km/h), exhibited low emission variability. In contrast, urban, suburban, and rural driving typically involving variable speeds (<50 km/h), degraded pavements, and elevated dust levels displayed substantial variability in emissions. The findings suggest that while average vehicle speed largely governs the mean intensity of TRWP emissions, instantaneous emission rates are more strongly influenced by speed fluctuations and the condition and cleanliness of the road surface. Particle size distribution also varied: urban and suburban areas produced higher proportions of fine particles, whereas rural, highway, and urban areas generated more coarse particles. This could be attributed to enhanced resuspension of super-micron dust and localized detachment of larger tire fragments due to elevated mechanical stresses at the tire–road interface [Belkacem et al., 2022].

The case for cement concrete pavements is similar to asphalt, but the binder is cement instead of bitumen. However, cement concrete pavements are generally known to wear slower than asphalt pavements and be much more durable, but with respect to wear of tyres, it is uncertain whether cement concrete is better or worse than asphalt. Various results are reported but are inconsistent. This is probably because the important thing is not the binder but the texture of the pavement surfaces and this may be highly different both on asphalt and cement concrete pavements.

It is worth mentioning that the rain on the pavement led to a decrease in the tyre wear. A common reason is that the water may somewhat decrease the contact between tyre rubber and surface microtexture, but it may also be that water mixed with dirt may act as a lubricant in the tyre/road interface. However, the after-effect of the rain can lead to an increase in the tyre wear due to an increase in chemical surface etching. The increase in the tyre wear after rain decreases as the traffic polishes away the abrasive character of the pavement [Muresan et al., 2024] .

Lastly, the influence on the wear of rubber compound’s composition also depends on the road surface. [Beji et al., 2020] compared two tyres with different rubber mix composition, where composition B had the lowest wear on asphalt and composition C on concrete.

4.6. Driving behaviour

4.6.1. Speed

To maintain a constant speed, the forces in the interface between the tyre and the road need to be equivalent to the resistive forces acting on a car. At high-speed, air resistance is the dominant force and could impact the speed influence of the tyre wear [Muresan et al., 2024]. The tyre wear is estimated to be proportional to the square of the resistive forces or slip and the relationship between vehicle weight and wear is estimated to be roughly linear [Schläfle et al., 2023a; Schläfle et al., 2023b]. This relationship implies that large acceleration, high speed and sharp turns will result in a high wear rate. Drag resistance is proportional to the fourth power of speed which implies that the increase in drag resistance might explain a higher wear rate at high speeds.

Many studies report a higher wear rate at higher speeds, but in some studies the shown influence has been negative or non-existent. A possible explanation is that an increase in speed causes the wear rate to increase but this increase is not always seen in the measurements due to factors such as the placement of the inlet or other driving conditions being present in the slower driving, such as more starts and stops [Foitzik et al., 2018]. Different relationships between speed and tyre wear are reported, ranging from an undisturbed background concentration, a linear relationship, to a quadratic relationship between speed and tyre wear [Gehrke et al., 2023]. Belkacem et al. (2022) states that it is important to note that some studies report a markedly weaker, or even negligible, dependence of tire wear on rolling speed. However, such findings often do not account for the increased drag resistance associated with higher speeds, which can influence wear.

Moreover, several studies indicate a negative correlation between average trip speed and tire wear rate, suggesting that vehicles traveling at lower speeds tend to exhibit higher tire wear. This apparent contradiction is typically attributable to confounding variables, particularly the driving environment. Lower average speeds are often associated with urban driving conditions, which involve frequent acceleration, braking, and cornering factors that significantly contribute to tyre abrasion. In contrast, higher average speeds are more characteristic of long-distance highway travel, where driving patterns are steadier and less abrasive. Thus, the observed relationships are not due to speed per se, but rather to the nature of the driving context in which different speeds occur [Kim and Lee, 2018].

The speed could also influence the size distribution of the tyre wear particles, as the ratio between PM2.5 and PM10 increased with speed in some studies [Kim and Lee, 2018]. The influence of speed is however dependent on both which tyres and vehicles that are used [UNECE, 1968].

It was claimed by [Belkacem et al., 2022] that motorways exhibit the highest non-exhaust emissions (NEE) compared to urban, rural, and motorway areas, and that the particle number concentrations increase with vehicle speed, and to some extent, specific pavement materials. Further, the authors conclude that acceleration and de-acceleration clearly affect the NEE, as the emissions decreased significantly when the speed were stable, and the road flat, without bumps, potholes, and curvature.

The influence of vehicle speed, pavement type, and surface texture on Tire and Road Wear Particle (TRWP) emissions, quantified as rear-of-wheel particles (RoWP) were examined by

[Muresan et al., 2024]. These emissions encompass particles generated from tyre and road surface wear, resuspension, and third-body interactions at the tire–road interface. The study evaluated several pavement types, including asphalt concrete, porous asphalt, stone mastic asphalt, high- and low-macrotexture surfaces, and asphalt concrete modified with 2 % crumb rubber. Tests were conducted using a vehicle equipped with Michelin Energy Saver 195/60 R15 tires at speeds of 30, 50, and 90 km/h.

Consistent with prior literature, for example [Pirjola, 2010] and [Beji et al., 2020], the results by [Muresan et al., 2024] demonstrated that TRWP emissions increase with vehicle speed, particularly for circum-micron particles (0.5–2.5 µm). For example, TRWP with a diameter of 1.0 µm exhibited exponential increases between 30 and 90 km/h, surpassing the linear trends observed for ultrafine and coarse particles. This finding suggests that not only the quantity but also the size distribution of TRWP emissions is speed dependent. Further, three primary size-based TRWP categories were identified, each associated with distinct emission mechanisms: (1) ultrafine particles (<0.01–0.5 µm) generated by continuous wear, (2) circum-micron particles (0.5–4 µm) emitted via resuspension mechanisms such as lift forces and wake vortices, and (3) coarse particles (up to several hundred microns) resulting from the detachment of tire fragments.

Importantly, vehicle speed disproportionately affects resuspension-driven emissions rather than those generated by interfacial wear mechanisms. While higher speeds exacerbate circum-micron emissions, pavement characteristics particularly at lower and intermediate speeds have a significant impact on coarse and ultrafine TRWP emissions. This underscores the potential for pavement design to mitigate particulate emissions, particularly in urban environments and within the framework of electrified mobility.

4.6.2. Lateral and longitudinal forces

The lateral and longitudinal acceleration and deceleration influences the tyre wear, where influences from the lateral acceleration are reported to be the larger. In tests performed in 60 km/h and 80 km/h, the lateral acceleration and following side slip was shown to correlate well with PM2.5 emissions [Chae et al., 2024a]. This correlation was however not seen in 30 km/h, nor was a corresponding correlation between emissions and longitudinal acceleration found in this study. The former may be due to the much lower side slip caused at 30 than at 60 or 80 km/h.

In another study, measurements of tyre wear at different combinations of longitudinal and lateral forces were performed on a summer tyre. The relationship between emitted particles and both longitudinal and lateral force was found to fit a fourth order curve well. The force had a small influence on the tyre wear at small loads and increased fast at higher loads. Increases in the lateral force caused more tyre wear than for the longitudinal force. The authors speculate that this may be due to the tread pattern of the tyre [Schläfle et al., 2023a]. Reports about a much higher increase in total particle mass than in total number of particles could indicate that changes in loading could also influence the size distribution of the tyre wear particles [Schläfle et al., 2023b].

One study showed that a negative longitudinal force, i.e. braking resulted in more emitted tyre particles than a positive longitudinal force, acceleration [Foitzik et al., 2018].

Accelerations increase the frictional forces in the interface between tyre and road, which leads to higher stress and temperature there, and increases the tyre wear. The stress and temperature in the interface are particularly high at high slip values, which occurs in a spinning wheel in acceleration or a locked wheel in braking. These conditions can be avoided through using traction control systems which prevents the tyre from spinning and with anti-lock braking systems (ABS) [Gehrke et al., 2023] .

A significant increase in non-exhaust particle concentrations associated with sharp positive and negative acceleration events was reported by [Belkacem et al., 2022]. This finding indicates that aggressive driving behaviour characterized by rapid acceleration and braking substantially elevates the generation of tire and road wear particles compared to more moderate, fuel-efficient driving styles (i.e., Eco-driving). The results highlight the critical influence of driving dynamics on the intensity of non-exhaust emissions, underscoring the potential environmental benefits of promoting smoother and less aggressive driving patterns. [Kim and Lee, 2018] showed that an increase in lateral loads at a constant driving speed led to an exponential decline in the $PM_{2.5}$ to PM_{10} emission ratio. This indicates a disproportionate rise in coarse particulate matter generation under higher lateral stress. Specifically, PM_{10} emissions were found to be 3.8 times more sensitive to changes in load compared to $PM_{2.5}$, suggesting that larger particles are more strongly influenced by dynamic forces such as cornering or abrupt lateral movements [Kim and Lee, 2018].

See also the study by [Muresan et al., 2025], mentioned in the previous section on road surfaces, where results showed that TRWP emissions per kilometre were significantly higher on urban, suburban, and rural roads, and lower on beltways and highways. Driving patterns on those two categories of roads would be quite different, which would explain the results.

5. Modelling tyre abrasion

Recently, a model for predicting rubber wear on pavement surfaces have been published [Persson et al, 2025]. They claim that they have successfully developed the world's first theoretical model for multiscale rubber wear behaviour on textured surfaces (one concrete and three sandpapers). Experiments measuring rubber wear behaviour when sliding in dry and wet conditions at different contact pressures and sliding speeds showed that the theoretical model's predictions of wear rates (mass loss per unit of sliding distance) and size distribution of wear particles aligned rather closely with the experimental results, confirming that the model could be used for such predictions. The surface topographies were scanned mechanically with a resolution of around 1 µm; i.e. clearly well into the microtexture range.

Dr Perssons model was developed in cooperation between his company Multiscale Consulting, a Chinese institute and tyre manufacturer Yokohama. It is claimed to have a groundbreaking potential focused on tyre wear predictions. Although it is published in an extensive article, it is not yet known if it is sufficient to be used by other researchers, but Yokohama reports that it will be used in developing their future tyres.

Figure 6 shows an example of how predictions of wear rate (in red symbols) compared to measurements (blue symbols). The logarithm of the wear rate (in mg/m) for rubber blocks sliding on concrete and on the sandpaper surfaces P80, P100, and P180 are shown. The load on concrete is FN = 250 N, and the results for the wear rate for the sandpaper surfaces were scaled by 250/118 so they can be compared to the theory and the results for concrete. Note that the ranking of the three sandpapers is not the same by prediction as by measurement. Persson admits that the results may differ from time to time despite specimens and conditions are assumed to be the same, so small deviations in certain parameters may have significant effects.

This reflects the experience that measurements of rubber abrasion are very challenging.

Another very advanced tyre wear model that has been presented recently is that of [Sakhnevych, A.; Genovese, A. 2024].

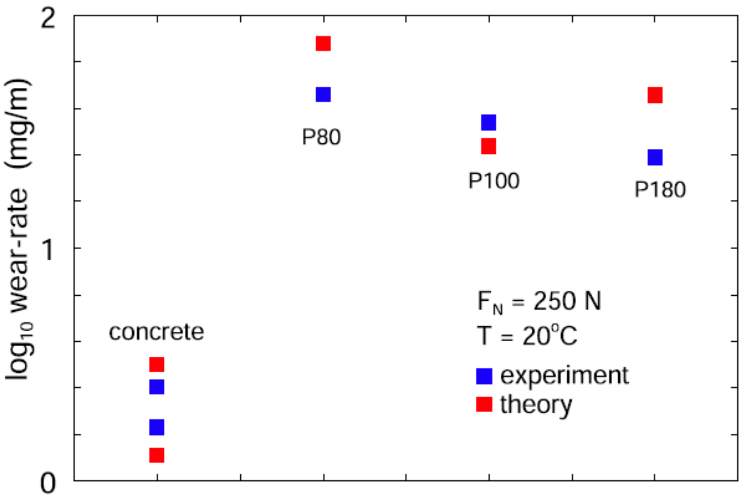

Figure 6: Comparison of predicted versus measured wear rates using Person's model. From [Persson et al, 2025]. See text for explanations.

6. Abrasion in relation to noise, friction and rolling resistance properties

6.1. Noise

Rubber abrasion versus noise emission properties of tyres have never been experimentally tested as far as the authors are aware. However, a study investigating the effect of various tread depths is related to the topic. Sandberg & Glaeser [2008] presented research in the European project SILENCE with the purpose to study how much tyre/road noise and rolling resistance change when car tyres are worn down from the original 8 mm tread depth to 2 mm, and when chemical ageing of the tyre rubber is simulated by exposure to heat. Six car tyres of different types were selected for the study, which were worn on a wear machine at Continental in Germany in steps of 2 mm tread depth. Before, between and after these wear sessions tyre/road noise and rolling resistance were measured on two drum facilities with different surface textures. Additionally, coast-by and CPX measurements were made on outdoor ISO test tracks.

The results regarding the noise emission for the differently worn tyres showed that the effect of tyre wear on tyre/road noise emission very much depends on what kind of road surface that one considers. The effect ranges from a substantial noise decrease for a tyre worn from new condition to "fully worn" when tyres run on a very smooth-textured road surface, to a very substantial noise increase for the same wear when the tyres run on a rough-textured road surface. The noise changes due to (even) tread wear may amount to a decrease of 3-4 dB on very smooth-textured surfaces and an increase of 4-5 dB on rough-textured surfaces. The effect of (artificial thermal) ageing seems to be additional and may add one extra dB to the smooth-surface effect and two extra dB to the rough-surface effect.

The conclusion is that the relations between noise emission and tyre tread wear (the latter represented by treads worn down from 8, to 6, 4 and 2 mm tread depth) strongly interacts with the pavement surface texture and shows a complicated pattern. This, however, does not say anything about how rubber abrasion and noise properties are related [Sandberg & Glaeser, 2008].

Nevertheless, it is known that softer tread rubber makes low noise properties possible [Sandberg & Ejsmont, 2002]. This is an opposite effect to rubber abrasion vs noise; i.e., low noise tyres using softer rubber will cause more rubber abrasion. This appears to be a quite clear effect. Another effect is that tyres with larger diameter generally give lower noise (for the same load), which is the same as for rubber abrasion.

6.2. Friction

Unfortunately, there is a conflict between skid resistance (aka wet grip) and rubber wear in tyres. Tyres with high skid resistance often wear down faster because the compounds and tread patterns designed for good grip tend to be softer and then are more easily abraded. Conversely, tyres designed for low wear with harder rubber compounds and less aggressive tread patterns will commonly have lower wet skid resistance. It is notable that there is a general view that requirements for high skid resistance and low rolling resistance are challenging to meet.

6.3. Rolling resistance

The study mentioned under the heading Noise [Sandberg & Ejsmont, 2002], also addressed rolling resistance (RR). Tyre wear and tread depth were found to have a dramatic effect on rolling resistance. When tyre treads are worn from new condition (8 mm) to 2 mm tread depth, the rolling resistance may decrease by about 20 %, generally on all six tyres.

As for noise, soft rubber treads and shoulders are favourable for RR since the rubber more easily deforms in an optimum way. This is commonly unwanted with regard to rubber abrasion since this becomes worse for softer rubber. Temperature has a similar effect; i.e. it is good for rolling resistance but bad for abrasion. However, interaction with other parameters may make the relations more complicated since also the carcass and the rubber hysteresis properties cannot be neglected.

Therefore, in general. low rolling resistance and low rubber abrasion are conflicting requirements. This is highly unwanted since both properties have severe environmental effects.

7. Tyre choice in WP3

In task T.3.4. the objective is to select and test tyres with the aim to reduce NEE. The selection will be based on tyre studies in Task T.2.6 (Deliverable D2.6). Based on the contents of this deliverable and the experience of its partners, the following recommendations are made. First, one should consider what measurement methods that shall be used, as this will influence the number of tyre samples needed and possible to include within the budget. If one or more test vehicles will be used (such as in a convoy) a choice of vehicle type and its tyre dimension will need to be done. The project should decide on one common car tyre dimension that is easy to fit on the test vehicle(s) while simultaneously being used by tyres having different estimated or previously tested treadwear or rubber abrasion.

Second, one must decide on how many types that should be included in the tyre sample to be tested. Summer tyres seem to be natural, but can we also include a set of winter tyres? Should also all-season tyres be included? Budget reasons may perhaps not allow the all-season tyres to be included.

Third, knowing the dimension of the test tyres, one shall decide on a number of tyres in each category (summer and winter) and it shall be the aim to select tyres which are supposed to cover a wide range of rubber abrasion rates. This should use statements by the tyre manufacturers (tyres claimed to have low wear plus tyres that have no statements about wear but are common on the market). One of the authors (Sandberg) has already noted some tyres that are claimed by its manufacturer to have low-wear and high-mileage properties.

Fourth, similar to the third point, we shall look for tyres that have a treadwear rating on the sidewall. Most European summer tyres have this rating on the sidewall despite it is not required in Europe, since the tyres may be offered both on the US and European markets. Tyres with the widest possible treadwear rating should be included for testing. Winter tyres do not have treadwear ratings, not even in the US, but all-season tyres should have it.

The situation in Task 3.4 will determine how many (different) tyres that can be tested, but tentatively it is suggested that six “low-wear” tyres and six “normal-wear” tyres should be included (of those six, 3-4 should be summer tyres and 2-3 should be winter tyres), supplemented by one reference tyre. The measuring method will decide on how many samples of each tyre that are needed.

The reference tyre should be included in all tests and its abrasion rating should be used for “normalizing” the other test results, to minimize the effect of weather and other uncontrolled parameters.

8. Future outlook

8.1. Work with regulations and preparations for them (TF TA)

While the Euro 7 is directed towards the vehicle regulations, the vehicle manufacturers delegated the tyre industry to develop methods and limit values for tyre abrasion and/or particle emissions. Much of this technical work is organized within the UNECE's WP on vehicles (WP29) which has a Working Party on Noise and Tyres (GRBP). The GRBP has established a Task Force on Tyre Abrasion (TF TA) to deal with this issue. The members are from member states of the European Union, the European Commission, and the tyre and vehicle industries. The latter include very active industries in Japan, but also industry organizations in China, South Korea, India, Canada and USA. Its key activities include developing standardized measurement methods. The TF TA is thus working on creating a standardized method for measuring tyre abrasion, which includes defining test conditions and methods to quantify the emissions from tyre wear. It is also working on regulatory proposals and assessing their environmental impacts.

The latest objectives of TF TA are reading [TF TA, 2025]:

"*The UN Regulation will address the tyres abrasion performance by determining a standardized measurement method which will allow for the quantification of the microplastic emissions in the environment. At the same time, TF TA will investigate the inclusion of abrasion rate in the proposed UN Regulation and a characterisation methodology for the mileage potential index, based on the abrasion measurement method.*" It is noted that "*The future UN Regulation will apply to new pneumatic tyres*". This means that C1, C2 and C3 tyres are all included (when they are new) but retread tyres will not be included. Also, (at least some) winter tyre types will be excluded.

It is further stated that what TF TA shall do is the following [TF TA, 2025]:

A. Develop a robust procedure for measuring the abrasion of tyres: Test conditions and methods;

B. Define the acceptable uncertainty for the tyre abrasion test method(s) and assess the uncertainty of the tyre abrasion test method;

C. Based on the abrasion test method, define a characterisation of relative mileage potential index (e.g. by measuring the tread depth reduction of the tyres and other metrics/calculations, in the context of the abrasion test method, even considering potential needs of integration to the abrasion test method needed for this study);

D. Evaluate the abrasion performance and tread depth reduction of a wide range of tyres available in the market;

E. Define abrasion limits for tyres in order to limit the emission of microplastics to the environment; and

F. Develop a proposal of amendment to UN Regulation No 117 for the type approval of tyres in respect to their abrasion.

The regulators and the industry have agreed that using particle emissions as the parameter on which to base tyre limits is not practical and would require much more research. Instead, the decision has been to use tyre abrasion as the regulated parameter [Sandberg, 2025]. This is reflected also in this deliverable. It is interesting to note that JASIC (Japan Automobile Standards

Internationalization Center) is leading a drafting group on an indoor drum method, while the currently most preferred field method is the convoy method.

The TF TA works with high intensity and frequency; for example, with the 7 first months of 2025, nine meetings have been held. The reader can follow the work at the following web address: https://wiki.unece.org/pages/viewpage.action?pageId=160694352&src=contextnavpagetreemode

The expected regulations for tyre rubber abrasion, which may be published already in 2025 and may be put in force in 2026 for C1 tyres, are essential to follow-up; in particular to the limits that will be set and to the measurement method(s) that will be required.

After experience of the regulation is collected and if it is positive, it is time to promote the introduction of the rubber abrasion or “mileage” measure in the EU labelling system. This will require more elaborate measurement methods since it will mean that more tyres must be tested.

8.2. Other topics

It is important to follow-up the usefulness of the rubber wear models, especially the most recent and comprehensive ones by [Persson; et al, 2025] and [Sakhnevych, A. & Genovese, A. 2024]. It is crucial whether they will really be fully operable by other researchers based on the publications so far. They should then be adapted for predictions of rubber abrasion from full-scale tyres, be compared to check if results are similar, and also compared to measurements by methods required in upcoming regulations. By varying parameters in the model one may be able to see how much various parameters and not the least certain pavement surfaces may influence the results. Unfortunately, neither one can be used already in NEEVE.

The concept of “digital twin” has in the latest years gone from concept to reality. Tyre manufacturers have for many years used mathematical and physical models to improve their tyres, but this has now advanced to producing a digital version of a tyre, which is represented by highly composite multi-layered structures, consisting of a multitude of different materials. The physical model structure of the tyre is described by a three-dimensional array of interconnected nodes by means of tension and rotational stiffness and damper elements. The latter are attached to the rim which is modelled as a rigid body [Farroni, 2025]. This concept is not possible to use in NEEVE as the project lacks such resources, but the R&D of tyre manufacturers is expected to benefit largely from this in the near future. It will be easier to play with the components of the digital twin to see how one can achieve a certain compromise performance or an enhanced performance in terms of, for example, low rubber abrasion.

9. Discussion

If and when the tyre label is supplemented by a rubber abrasion label or a corresponding “milage” rating, with different classes congruent with the energy label, the EU tyre label will have a strong focus on environment, by labelling three of the globally most important environment parameters. So far, the consumer interest in the label has been mild. The economic incentives to pay a little more for higher quality tyres have been too small. But when two major parameters with profound influence on the economy of the vehicle owner—energy consumption and tyre mileage—are labelled the effects on the private economy will double and may be much clearer to the vehicle owner potentially influencing his/her tyre purchase. Such informed purchase decisions will then benefit both the vehicle owner and the public. Reduced climate impact and improved global health will be a bonus. Therefore, NEEVE should point out this possibility of influencing the tyre market by supplementing the tyre label system, for the benefit of all.

10. Conclusions

A synthesis of the findings presented in this deliverable results in the following conclusions.

Despite tyre manufacturers are reluctant to publish their research, for commercial competition reasons, the open literature contains substantial information about how design, construction and material selections of tyres influences or potentially influences tyre abrasion. In this respect, it is mostly C1 tyres that have been studied.

The presented influences are, however, often unclear or inconsistent, making it difficult to make robust conclusions. A reason for such results may be that the measurement technology is challenging and still rather premature. Experiments therefore may give results that are over-interpreted since uncertainties are not enough considered, or that different methods emphasize various influencing parameters differently.

Tyres are designed and produced for various climates and regions. When comparing for example summer, winter and all-season tyres, the summer tyres have come out as giving lower rubber abrasion and winter tyres the most abrasion. This is because of the different rubber compounds used, where generally softer rubber is used in tyres constructed for lower temperature environments and vice versa. Tyres should be of the type optimized for the season and the region for many reasons: for example, regarding rubber abrasion, it is especially unsuitable to use winter tyres also in summer as that will accelerate wear.

Tyre temperatures have a profound influence on rubber abrasion, namely that higher temperatures give higher abrasion. However, it seems that the rate is not stable but changes with how much the tyre temperature differs from the glass transition temperature of the compound.

The abrasion rate is not the same during a tyre's lifetime. Often the abrasion is higher when the tyres are new, which can happen because it is common that the outer tread layer has another compound than the main part of the tread, but becomes lower when the tyre has been operating for a while. Later, when tyres become worn and possibly also chemically/thermally aged, abrasion will increase.

Tyre inflation has large influences on tyre wear, mostly by too low or too high inflation causing non-uniform wear across the tyre width. Poor wheel alignment causes irregular wear, such as the left and right parts of the tread being very differently worn. Consequently, both wheel alignment and inflation monitoring are important methods to prolong the tyre's lifetime and mileage.

Tyre treads consist of numerous chemical substances and only a few are generally known. Although the physical structure of tyres is well understood, the chemical composition of the treads remains largely opaque, as manufacturers are not required to disclose detailed information, aside from limited assessments under the European REACH regulation, and they are not willing to do so either since the tread rubber is an important component in the commercial competition. Even if a certain line of a tyre brand is produced over a long time period and keeps the same designation and name, the rubber compounds are often changed due to progress in research or maybe availability of the substances.

There are two reinforcing agents which have been studied rather extensively in public literature, namely carbon black and silica. Carbon black has been the most common reinforcing agent, but today silica is also common, especially in passenger car tyres and for reasons of reducing rolling resistance. Carbon black has generally positive effects on rubber abrasion. Silica has been found to be superior to carbon black regarding wet grip and rolling resistance while its influence on rubber wear resistance is contradictory. Nevertheless, an increase in silica in the tyre has been found to influence the size distribution of the tyre wear particles: the number of emitted coarse particles decreased, while the number of fine particles increased.

The Euro 7 regulation, formally adopted in 2024 and soon to be implemented, introduces comprehensive measures to address non-exhaust emissions from vehicles. This marks the first instance of the European Union setting a framework to limit tyre abrasion emissions, aligning with methodologies developed by the United Nations Economic Commission for Europe [UNECE] under UN Regulation No. 117. Abrasion limits for new tyres are currently being discussed and may be implemented fairly soon for new tyres. This will require extensive and expensive testing of rubber abrasion by the industry with measurement methods that are likely to be burdened by flaws in the beginning as is common when new regulations are introduced. However, this development is desirable and necessary.

Recently, a model for predicting rubber wear on pavement surfaces has been published; led by a world-leading expert on tyre/road contact and friction (Dr Bo Persson). It is claimed that they have successfully developed the world’s first theoretical model for multiscale rubber wear behaviour on textured surfaces. This model may be useful for the design and construction of tyres with lower tyre abrasion and is already used by one of the major tyre manufacturers for this purpose. Another model focused on tyre wear was published almost simultaneously by Italian researchers. Although the models are described in articles, it is not yet clear whether they will be fully useful for studies by other researchers or engineers.

Rubber abrasion and particle emissions are results of the interaction between tyre and pavement surface. It follows that both tyres and pavement surfaces must be considered when it comes to tyre wear and emissions. In the pavement, like for wet grip, both macrotexture and microtexture are known to influence tyre abrasion substantially; the more the rougher the textures are. Since roads must be safe, too smooth surfaces cannot be accepted. Especially smooth macrotexture is favourable also for noise and rolling resistance, so there is a win-win situation if it were not for traffic safety (wet skid resistance). Nevertheless, road authorities have a responsibility to make sure that textures are optimized as well as practical to reduce tyre abrasion and tyre particle emissions (and noise and rolling resistance), given that traffic safety is not jeopardized.

The present trend for vehicles becoming heavier; especially those for private use, means that tyres are increasingly loaded. This means that vertical, longitudinal and lateral forces in the tyre/road interface becomes larger when the vehicle is driven, which means that rubber abrasion will increase. Specifically, PM_{10} emissions have been found to be many times more sensitive to changes in load compared to $\mathrm{PM}_{2.5}$, suggesting that larger particles are more strongly influenced by dynamic forces such as cornering or abrupt lateral movements. Since electric vehicles (EVs) due to their batteries are heavier than vehicles with internal combustion engines; especially the full-electric ones, while they allow much higher accelerations, it is often found that the electric or hybrid-electric ones are causing more tyre wear. However, the case is not entirely clear, since decelerations by those vehicles may be softer due to the regenerative system, accelerations can be limited, and EV tyres are often adapted for the higher torques. However, it is obvious that

NEEVE should promote the idea of reducing vehicle weights by policy measures and public influence.

Driving behaviour is another factor strongly influencing tyre abrasion and particle emissions. Increasing speed means that higher tyre/road forces (torques) must be applied to overcome the air and rolling resistance; especially air resistance which increases by an exponent of 4 with speed. Speed also influences the proportion of particles being suspended in the air and also influences the proportion between the larger and smaller particles emitted. This does not mean that all is well in urban areas where average speeds are low, since then stop-and-go traffic will create more abrasion and more particles due to the intermittent changes in the acceleration and decelerations. Longitudinal slip is an important factor in rubber abrasion, but side slip by driving and steering in curves is even more important. Consequently, there is an interaction between speed, acceleration and deceleration, which gives a high potential for reducing rubber abrasion and particle emissions by driver education. It shall not be forgotten that driver behaviour which is favourable for low tyre rubber abrasion also is favourable for noise, rolling resistance and of course safety. Here, there is a clear win-win situation.

Tyres are always a result of compromises between various parameters. Tyre companies have always considered tyre wear as an important parameter, but with the new Euro 7 regulations it will receive more attention and requirements. Then, the question is: will it mean sacrifices of other essential parameters? To answer this question, one must consider one of the key parameters namely rubber hardness. In general, softer rubber (which is softer by higher temperatures) means more of both lower noise and lower rolling resistance, but higher tyre abrasion. Therefore, in general, low rolling resistance and low rubber abrasion are conflicting requirements. This is highly unwanted since both properties have severe environmental effects. Additionally, low rubber abrasion and high wet skid resistance are also essentially conflicting demands due to rubber hardness. Finally, a similar conflicting influence appears regarding rubber abrasion versus noise emission. Fortunately, there are other parameters such as “uniform” forces in the tyre/road contact patch and overall diameter which are mutually favourable to most of the parameters, but overall it is very challenging to produce tyres with low abrasion without having to sacrifice the other mentioned parameters.

11. Recommendations

It should be checked whether the rubber wear model proposed by [Persson et al, 2025] is or will be available for use in NEEVE. If it is available, it should be used for finding new ways to reduce rubber abrasion.

The measurement methods and equipment for testing rubber abrasion and particle emissions from tyres should be further studied. The recent observations in [Sandberg, 2025] should be further explored and compared to the technical resources available to NEEVE.

The work with upcoming regulations in the EU and in the UN ECE should be followed as closely as possible and NEEVE should consider how the project can improve the expected regulations. Especially, NEEVE should point out the possibility of influencing the tyre market by supplementing the tyre label system with tyre abrasion or “milage” rating, for the benefit of all.

Finally, this deliverable includes some recommendations regarding selection of tyres for testing their rubber abrasion in a later Task of NEEVE.

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