Environmentally Optimal Tyres and Brakes

Phase 1 Report for National Highways

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Executive summary

In recent years, the UK Government has been developing policies to transition road transport to zero tailpipe emissions, reducing pollutants and noise in the process, improving the environment around Britain's roads. However, all road vehicles use tyres and brakes, and these have their own environmental impacts. When in use, both tyres and brakes are sources of particulate emissions as they wear, sometimes known collectively as non-exhaust emissions (NEE), which are a source of both air and water pollution. Tyres and brakes are also responsible for emissions during their manufacture and end-of-life disposal, and through their rolling resistance, tyres can have an impact on the energy use of the vehicle and so its greenhouse gas (GHG) emissions. Tyres are also responsible for road noise, and the importance of tyre noise increases as adoption of hybrid, electric, and fuel-cell vehicles reduce powertrain noise. Of course, both tyres and brakes perform a safety-critical role enabling the vehicle to steer and stop effectively, and optimising their environmental performance must not compromise safety.

The objective of this study is to improve understanding of the environmental impacts of the manufacture, use, and disposal of tyres and brakes used commonly in the UK. This aligns with a wider aim to reduce particulate, carbon, and noise emissions along the Strategic Road Network through improvements to tyre and brake technologies. This report covers Phase 1 of the study and aims to determine the optimal environmental characteristics of tyres and brakes. The parameters considered are noise emissions, particulate emissions to air and water, and rolling resistance which affects fuel efficiency and greenhouse gas emissions from conventionally fuelled vehicles or from electricity generation for BEVs. The report also considers how vehicle type and driver choices influence these resulting emissions. The analysis in this report is based on the findings from the literature, engagement with stakeholders, market research, and an evaluation of past consumer engagement.

The analysis finds that the resulting significant environmental impacts of tyres for the different phases of a tyre's life and potential routes for reduction are:

- **Tyre manufacture** use of energy, carbon-intensive fossil-based materials, and scarce resources such as natural rubber which risks land use change. Product development needs to move towards sustainably sourced, low GHG impact materials and low-carbon energy.
- **Tyre use** rolling resistance impact on GHG emissions, and abrasion of both tyre and road leading to microplastic tyre and road wear particles (TRWP) entering watercourses and airborne particulate pollution. Reducing both involves optimising tyre materials' composition and tread design while considering any trade-off against wet grip (safety) and noise. Emerging technologies may enable further optimisation. Eliminating vent spews removes unnecessary microplastic particles.
- **Tyre end-of-life** carbon release and pollution. Circular economy strategies for tyres should minimise unwanted environmental impacts and exploit emerging technologies, including maximising the use of tyres through safe part worn and re-treaded tyres, recycling of tyre carcases and materials, and maximising the energy extracted with minimal environmental impact at disposal.

And similarly for brakes:

- **Brake component manufacture** currently use energy and carbon-intensive fossil-based materials. Product development needs to move towards sustainable production through minimising the use of scarce resources and energy, and developing products that use sustainably sourced, low GHG impact materials.
- **Brake use** causing particulate emissions, with airborne pollution being a threat to human health and the risk of particles poisoning water courses. Particulate emissions reduction can use a range of technologies including alternate pad materials, disc coatings, and regenerative braking, while meeting safety requirements and driver demands for braking performance and minimising the use of toxic substances of concern. Emerging technologies may enable lower emission and more sustainable friction materials.
- **Brake end-of-life emissions**. While a high proportion of brake components by mass are already recycled, further circular economy strategies for brakes could utilise emerging technologies including remanufacture of discs, pad material extraction and recycling, and maximising the energy extracted with minimal environmental impact at disposal.

As well as the attributes of the tyres and brake components themselves, achieving optimum environmental impact from their use relies on other factors including:

- Consumer understanding and choice influencing informed buying decisions. While there is good information provided for tyres covering rolling resistance, wet grip, and noise; abrasion or manufacture are not covered and there is no standard information for brakes. Consumer choice may also be limited by garage stock.
- Correct use and maintenance. Incorrect tyre pressure or wheel alignment (camber and tracking) can increase GHG emissions and abrasion rate. Maximising the life of tyres and brakes requires regular checks so they can be changed at the optimum time.
- Driving style. Hard braking events increase brake and tyre temperatures and abrasion rates, while harsh acceleration and cornering and even high speeds increase tyre abrasion. Road layout and traffic management may also affect tyre, road, and brake wear by introducing additional braking and cornering.
- Road surface. Tyre abrasion and rolling resistance as well as grip and noise were found to be highly dependent on road surface, and optimum use of tyres will be dependent on suitable road surfaces.
    - Minimising surface unevenness, macro and microtexture, and aggregate hardness are beneficial for minimising TRWP while minimising surface unevenness and macrotexture also benefit rolling resistance, but there may be a trade-off to maintain adequate skid resistance and drainage, or reduced tyre noise for roads in built-up areas.
    - However, optimising the properties of the road surface to minimise TRWP and rolling resistance is a topic with limited existing research, and further work would be required to establish how this could be achieved.
    - Both TRWP and rolling resistance are generally seen to increase with higher road temperature.

The GHG emissions from the use phase of tyres relate to vehicle energy use which can be addressed through zero-tailpipe emission powertrains (such as electric vehicles) and energy decarbonisation. Particulate and microplastic emissions of the tyres and brakes relate to their abrasion. Figure 0-1 summarises the particle emission pathways from literature. Around half of brake emissions are thought to become airborne particles of less than 10 micrometres in size (PM_{10}), while most tyre particles end up in soil or waterways with only a small proportion small enough to become airborne. Most road transport PM_{10} emissions now originates from non-exhaust emissions, while some literature suggests that up to 70% of microplastics found in oceans originate from tyres and road transport.

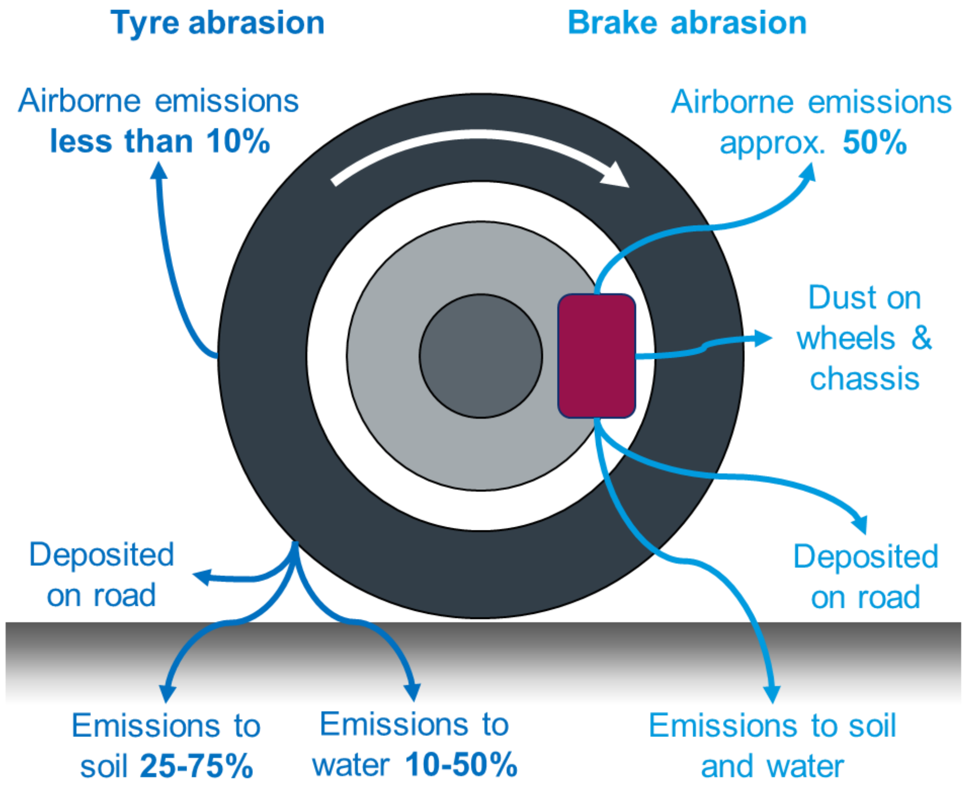


Figure 0-1: Tyre and brake abrasion and particle emission pathways from literature

An approximate quantification of the abrasion emissions is illustrated in Figure 0-2. This estimates the average and range of tyre and brake mass lost on the Strategic Road Network (SRN) in 2022. The data is from literature estimates of abrasion rates, and the total PM_{10} airborne emissions from non-exhaust sources using the SRN in 2022 from NAEI emission factors, both plots using traffic and freight data from DfT[1]. The high degree of uncertainty is clear from the range of literature estimates of abrasion rate which suggests abrasion could be double or half the indicated average.

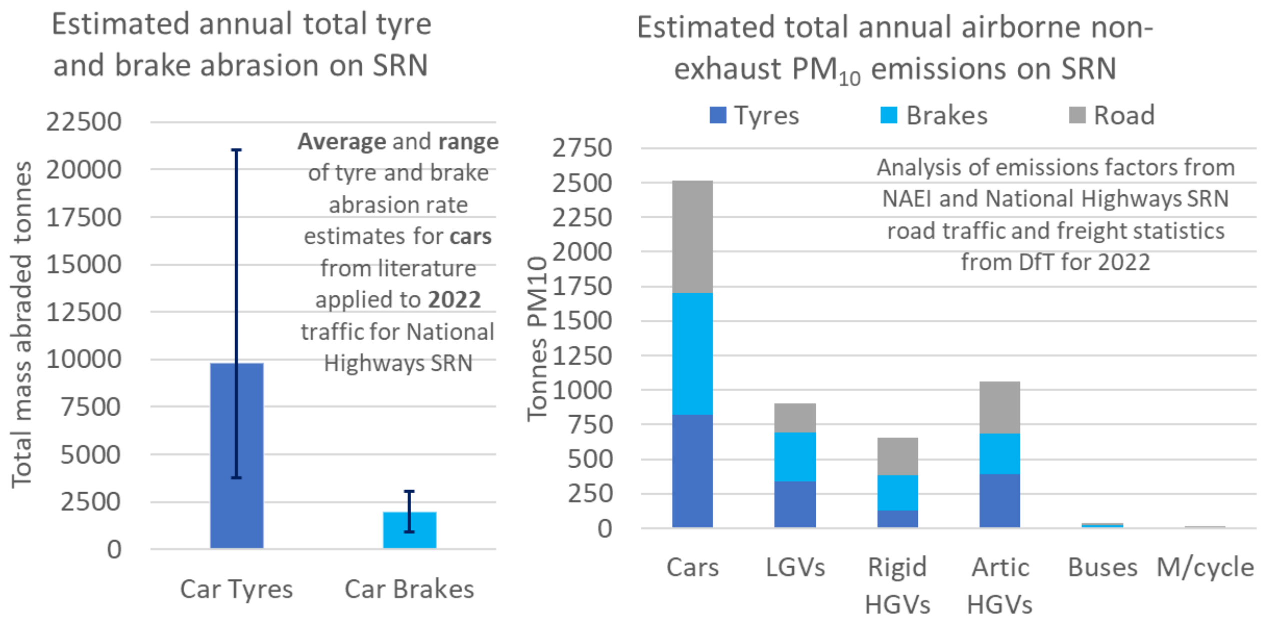


Figure 0-2: Estimated tyre and brake abrasion and PM10 emissions on Strategic Road Network (SRN) in 2022

The impact of the transition to the use of electric vehicles as the phase-out of petrol and diesel vehicles from 2035 approaches is considered. Their use of regenerative braking is expected to significantly reduce the emissions from brakes, and potentially reduce manufacturing and disposal impact through fewer replacement parts. However, their increased weight and ability to produce high torque from rest is likely to increase tyre abrasion compared to conventional vehicles. A shift from air pollution to water pollution is possible since a large proportion of tyre particles enter water courses compared to a small proportion (by mass) becoming airborne, whereas brake particles are more likely to be airborne.

Tyre and brake use regulations currently focus on safety of performance and limiting toxic material use, and for tyres, standard labelling covering rolling resistance, wet grip, and noise. UN ECE standards are being established for brake emissions (PM_{10}) measurement and are in development for measuring tyre wear. This will facilitate the implementation of labelling and/or limiting regulations, and the proposed Euro 7 regulations are expected to limit both tyre wear and brake emissions. It is noted that the UN standards and Euro 7 proposals use measurements of mass emissions, but it is the ultrafine particles that pose the largest threat to human health, and it is not well understood how these relate to total mass lost. Therefore, a deeper understanding of the number and size distribution of the particles is needed. However, regulating tyres by mass loss will be effective at minimising microplastic emissions to soil and water. Specific regulations apply to the disposal of vehicle components including tyres and brakes although manufacturing is covered only by general industrial regulation, and regulation to ensure sustainable use of materials is not yet mature.

It is expected that Phase 2 of this work will identify and investigate mechanisms which can build on these findings to promote the development of environmentally optimum tyres and brakes, their deployment by vehicle manufacturers, and their purchase by consumers and fleet operators.

[1] Abrasion rate estimates from https://www.eng.auth.gr/mech0/lat/PM10/, NAEI emission factors from https://naei.beis.gov.uk/data/ef-transport, traffic data for 2022 from https://www.gov.uk/government/statistical-data-sets/road-traffic-statistics-tra Table TRA4115

Glossary

Term	Meaning
μm	Micrometres (10^{-6}m)
ADAC	Allgemeiner Deutscher Automobil-Club
Al	Aluminium
AP	Acidification potential
AQEG	Air Quality Expert Group
ARD	Abiotic Resource Depletion
ARD_FE	Abiotic Resource Depletion Fossil Energy
ARD_MM	Abiotic Resource Depletion Metals and Minerals
BEV	Battery electric vehicle
BIIR	Bromobutyl rubber
BOM	Bills of materials
BTMA	British Tyre Manufacturers' Association
CaSO4	Calcium sulphate
CBAM	Carbon Border Adjustment Mechanism
CBp	Pyrolytic carbon black
CC	Carbon–ceramic
CED	Cumulative Energy Demand
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
CoF	Coefficient of friction
CSRD	Corporate Sustainability Reporting Directive
Cu	Copper
dB	Decibels
DfT	Department for Transport
EEA	European Environment Agency
ELT	End of life tyres
EMEP	European Monitoring and Evaluation Programme
EoL	End of life
EP	Eutrophication potential
EPD	Environmental Product Declarations
EPR	Extended Producer Responsibility
eq	Equivalent
ELT	End-of-Life Tyres
ELV	End-of-Life Vehicles
EPA	Environmental Protection Agency
ER	Energy recovery
ESPR	Eco-design for Sustainable Products Regulation
ET	Ecotoxicity
ETS	Emissions Trading System
ET_FW	Freshwater Ecotoxicity
ET_Ter	Terrestrial Ecotoxicity
EU	European Union
EV	Electric vehicle
Fe	Iron
FEHRL	Forum of European National Highway Research Laboratories
FRC	Forest risk commodities
FNC	Ferritic nitrocarburising
GB	Great Britain

Term	Meaning
GCI / GCR	Grey cast iron
GHG	Greenhouse gas emissions
GJ	Gigajoules
g/km	Grams per kilometre
GPSDR	Global Platform for Sustainable Natural Rubber
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HD	High dispersion / highly dispersible
HD-HS	High-dispersion- high surface area
HDV	Heavy duty vehicle
HGV	Heavy goods vehicle
HD-HS silica	High-dispersion high surface area silica
HMC	Tungsten carbide-coated
HTP	Human Toxicity Potential
HVAF	High Velocity Air Fuel
HVOF	High Velocity Oxygen Fuel
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine vehicle
ISO	International Organisation for Standardisation
JATMA	Japan Automobile Tyre Manufacturers Association
JRC	Joint research centre
kg	Kilogram
kN	Kilonewton
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCV	Light commercial vehicle
LGV	Light goods vehicle
LULUC	Land use and land use change
mg	Milligrams
MMC	Metal matrix composite
MnS	Manganese sulphide
MOT	Ministry of Transport
N	Newton
NAEI	National Atmospheric Emissions Inventory
NAO	Non-asbestos organic
NEE	Non exhaust emissions
NH_3	Ammonia
Ni	Nickel
NO_x	Nitrogen oxides
NPT	Non-pneumatic tyres
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PAHs	Polyaromatic hydrocarbons
PBB	Polybrominated biphenyls
PCR	Product Category Rules
PEO	Plasma electrolytic oxidation
PET	Polyethylene terephthalate
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
PM_{10}	PM sampled with an inlet of 50% efficiency at 10µm

Term	Meaning
$PM_{2.5}$	PM sampled with an inlet of 50% efficiency at 2.5µm
PMF	Particulate Matter Formation
PN	Particulate number
PTI	Periodic Technical Inspection
RAC	Royal Automobile Club
REACH	Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals
RBS	Regenerative braking systems
R&D	Research and development
RTC	Recycled tyre crumb
SAL	sulphuric acid lignin
SBR	styrene-butadiene rubber
SiC	Silicon carbide ceramic
SL	Soda lignin
SO_2	Sulphur dioxide
SO_x	Sulphur oxides
SPS	Suspension Plasma Spray
SRN	Strategic Road Network
TfL	Transport for London
TIP	Tyre Industry Project
TPO	Tyre pyrolytic oil
TRWP	Tyre and road wear particles
TSP	Total suspended particulate
TWR	Tyre treadwear rating
UK	United Kingdom
UN ECE	United Nations Economic Commission for Europe
US	United States
US EPA	United States Environmental Protection Agency
UTQG	Uniform Tyre Quality Grading
VOCs	Volatile organic compounds
VTI	Swedish National Road and Transport Research Institute
vkm	Vehicle-kilometre
WHO	World Health Organisation
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
wt%	Weight percentage
Zn	Zinc

1. Introduction

1.1. Background and context of the study

In recent years, the UK Government has been developing policies to transition road transport to zero tailpipe emissions, reducing pollutants and noise in the process, improving the environment around Britain's roads. However, all road vehicles use tyres and brakes, and these have their own environmental impact. When in use, both tyres and brakes are sources of particulate emissions as they wear, sometimes known as non-exhaust emissions (NEE), which are a source of both air and water pollution. Data from the National Air Emissions Inventory (NAEI) suggests that vehicle exhausts, brakes, tyres, and associated road wear contribute approximately equally to airborne emissions of particulate emissions of less than 10 micrometres (PM_{10}).

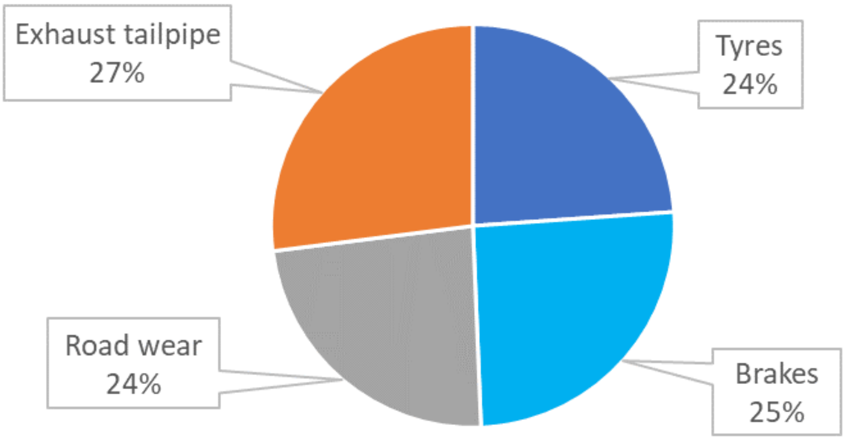


Figure 1-1: Sources of PM10 from UK road traffic (Source: NAEI)

Tyres and brakes are also responsible for emissions during their manufacture and end-of-life disposal, and through their rolling resistance, tyres can have an impact on the energy use of the vehicle and so its greenhouse gas (GHG) emissions. Tyres are also responsible for road noise, and the importance of tyre noise increases as adoption of hybrid, electric, and fuel-cell vehicles reduce powertrain noise.

1.1.1. Overview of tyre components

A tyre consists of the tread which contacts the road, a casing stiffened by body plies which supports the tread and includes the sidewalls and inner airtight liner, and a bead which forms the airtight attachment to the wheel. A tyre contains polymer fabrics and steel cords as well as a variety of natural and synthetic rubber polymer compounds. The tyre's tread slab comprises a tread base and the tread cap. While tyre size and shape affect performance and the tyre wall stiffness affects vehicle ride and handling, it is the tread that has the biggest influence on its grip, noise, rolling resistance, and wear rate. Abrasion of the tyre's tread cap on the road surface emits particles, including both tyre particles and resuspended road dust, some of which may become airborne while others settle on the road or surroundings where they can enter soil and waterways.

Tyre wear rate will depend on driving style but also vehicle and even road characteristics, as well as the tyre properties. Tyre labelling regulations in the UK and Europe rate wet grip, noise, and rolling resistance (economy) performance at present (discussed in more detail in Section 2.4.1); wear rate is also under consideration for Europe. European Commission (EC) Euro 7 [1] proposals imply tyre wear rates (by mass) will be limited, although values are not yet specified. Tyres are also rated for treadwear and traction in the US [2].

1.1.2. Overview of brake components

Vehicle brakes comprise a friction pad bearing on a rotating disc or drum. When brakes are engaged, the rotor slides against the friction materials, decelerating the vehicle. The disc or drum design, pad size and shape, and actuation mechanism are developed according to the required braking forces and resulting heat generation, within the envelope of the wheel. A disc brake system consists of callipers equipped with one or more pistons, a rotor (disc), and two brake pads which are pressed against either side of the rotor by the piston(s). In a drum brake two convex shoes are pushed against the inside of the rotor (drum) by one or more cylinders. The friction pads (or in the case of a drum, shoe linings) comprise a binder (typically an organic polymer resin), structural materials such as metals or glass fibres, friction additives to achieve required friction and wear attributes, and mineral fillers. X-ray fluorescence spectroscopy of a brake pad from a typical medium sized European passenger car identified 12 elements [3]. The rotors (discs or drums) are generally grey cast iron with high thermal conductivity, although other materials are used. Discs may be vented to increase heat dissipation and improve performance. The abrasion of the pad against the disc or drum causes wear of both, resulting in particles being emitted.

When not braking there should be no contact of the friction pads against the rotor, and so no impact on vehicle drag force, although in practice the pads are not actively retracted from the rotor and so a minimal residual drag may be present. Brakes are not normally considered to be noisy although poor fitment or wear can cause brake squeal under braking, and rotor rust or dirt ingress can cause scraping noises, usually short lived. Brake pads incorporate a metal wear indicator that emits a high-pitch noise under braking when the pads reach minimum thickness, indicating a change is required. While brake components need to meet minimum standards for braking force, there are currently no standard assessments of emissions, wear rate, performance, or any other attribute. However, standards for measuring brake emissions through brake dynamometer testing are being developed in a United Nations Economic Commission for Europe (UN ECE) working group, and the EC Euro 7 proposals include limits for brake emissions using the UN ECE standard, although so far limits are only proposed for light duty vehicles.

1.2. Key objectives

The objective of this study is to increase understanding of the environmental impacts of the manufacture, use, and disposal of tyres and brakes used commonly in the UK[2]. This objective results from a wider aim to reduce particulate, carbon, and noise emissions along the Strategic Road Network (SRN) through improvements to tyre and brake technologies. This study aims to determine the optimal environmental characteristics of tyres and brakes, in terms of noise emissions, particulate emissions to air and water, and rolling resistance which affects fuel efficiency and greenhouse gas emissions from conventionally fuelled vehicles. The study also considers how vehicle type and driver choices influence those emissions.

This study is intended to establish the current situation and baseline as Phase 1 of a wider piece of work to also develop (Phase 2) and then implement (Phase 3) mechanisms to drive improvements in the future. The study is delivered by Ricardo in partnership with and supported by AECOM, drawing on relevant experts from within both organisations, and research took place between August 2023 and February 2024. The study includes the following key elements:

- Determine the characteristics required of environmentally optimised tyres and brakes in terms of noise emissions, particulate emissions to air and water, and rolling resistance.
    - This aspect is considered in Section 3, with literature reviewed in Section 2.1.
- Determine potential trade-offs and conflicts between optimising performance in one area to the detriment of other areas.
    - This aspect is considered in Section 5, with literature reviewed in Section 2.3.
- Investigate the performance of tyres and brakes currently on sale and in use on the vehicle fleet.
    - This aspect is considered in Section 6, with literature reviewed in Section 2.4.
- Develop a method to understand consumers’ awareness of the environmental impact of tyre and brake choice and identify mechanisms to increase the demand for environmentally optimised tyres and brakes.
    - This aspect is considered in Section 7, with literature reviewed in Section 2.5
- Identify aspects of driver behaviour that may influence the environmental performance of their tyres and brakes.
    - This aspect is considered in Section 8, with literature reviewed in Section 2.6.

[2] Studded, winter, and other special tyres are excluded from the scope of this study.

As the study drew to a close it became clear that it would provide a more complete foundation for Phase 2 if two additional elements were added. The understanding of the current environmental performance of tyres and brakes as well as the development of new mechanisms could be supported by a review of relevant existing and developing standards and regulations in the UK and overseas. Also, both literature and experts indicated that the environmental performance of tyres was closely related to the attributes of the road surface. Therefore, the following tasks were added:

- Identify and review legislation, policies, and standards that align to objectives for environmentally optimum tyres and brakes.
    - This aspect is considered in Section 4, with literature reviewed in Section 2.2.
- Investigate the impact of road surface on the environmental impacts of tyres in use.
    - This aspect is considered in Section 9, with literature reviewed in Section 2.7

1.3. Methodology

The approach taken in this study included both primary and secondary research. With a desk-based literature review being carried out, alongside a review of products currently available on the market, and a small number of industry interviews. This was supplemented by inputs from experts in the field to analyse and interpret the key findings from the research and lead to the development of a series of recommendations that can be taken forward in Phase 2 of the overall project.

A summary of the sub-tasks and key research methods that formed the core of the project is provided in Figure 1-2 below.

Figure 1-2: Breakdown of tasks and research methods used in the study

Characteristics of environmentally optimised tyres and brakes	Performance optimisation, trade-offs and conflicts	Performance of tyres and brakes currently on sale and in use	Consumer research	Influence of driver behaviour on environmental practices
Life-cycle thinking applied to consider all impacts of tyres and brakes – including of manufacture & disposal, and to consider air, water, soil, noise, and CO_2 impacts. • ***Literature review*** • ***Life Cycle thinking and expert input***	Establish current status of and potential for optimising tyre & brake environmental characteristics, as identified in task 2. Identify trade-offs and conflicts. • ***Literature review*** • ***Industry engagement*** • ***Expert input***	Understand the key attributes of tyre and brake products on the market. As attributes may not be clear, use specifications, claims, 3rd party reviews. • ***Literature review*** • ***Industry engagement*** • ***Market research*** • ***Expert input***	Develop a method to understand consumer awareness Experienced survey team will use literature of past surveys and a workshop to develop an approach • ***Literature review*** • ***Expert input*** • ***Stakeholder workshop***	Identify and evaluate significance of direct (driving style) and indirect (vehicle state, route) driver behaviour factors that affect tyre & brake environmental performance • ***Literature review*** • ***Expert input***

The additional tasks were delivered through a review of literature, legislation, and standards, supported by expert input, with the scope:

- Explore current and proposed regulations and standards: Review legislation, policies, and standards in UK and overseas, current and proposed, that promote environmentally optimum tyres and brakes, and identify gaps in UK legislation and opportunities for standards development.
- Investigate the impact of road surface on tyre emissions: Explore literature on the tyre interaction with road surface and impact to its noise, abrasion/emissions, and rolling resistance, and understand how road surfaces could be optimised to minimise these impacts.

1.3.1. Literature review

The literature review formed a core element of this study. A Rapid Evidence Assessment (REA) three step approach was applied:

Step 1: Key search terms were selected to identify relevant material for review. As well as general web search tools, Ricardo utilised accessible databases such as Science Direct, and Ricardo's own knowledge portal, RiCK (Ricardo's Centre of Knowledge) database that has over 320,000 abstracted references from trusted sources. For each successful search, the key words used, and the sources identified were recorded.

The sources reviewed included peer-reviewed journal articles, patents, scientific papers, industrial publications, government and industry reports, outputs from projects, and manufacturer websites.

Step 2: An initial screening process was applied to the list of references to determine which were to be included in the review. Screening used appropriate review parameters established at the start of the review process to identify sources that closely align with the objectives and deliverables of this study.

An index (spreadsheet) has been used to document the results from the screening including information about the subject matter coverage and ratings for quality and relevance.

Step 3: Evidence relevant to the scope described above was extracted from the material to support the delivery of the objectives and questions outlined above.

More details of the specific approaches applicable to the areas of research in sections 2.1 and 2.5 are described in sections 2.1.1 and 2.5.1.

1.3.2. Stakeholder engagement

Another key research method used in this study was the engagement of key industry stakeholders in a small number of interviews. The purpose of this was to collect relevant evidence to supplement and/or cross-check the evidence gathered through the desk research. A total of 15 stakeholders were contacted, including trade and market associations, manufacturers of tyres and brakes and academic and research institutions. Of those contacted, six participated in an interview, and two further stakeholders provided a response to interview questions via email. A summary table is provided below.

Table 1-1: List of organisations engaged in consultation

Type of Stakeholder	Organisation
Manufacturer trade associations	• Society of Motor Manufacturers and Traders (SMMT) • British Tyre Manufacturer Association (BTMA) • Federation of European Manufacturers of Friction Materials[3] (FEMFM) • Tyre Industry Project (TIP) – via email
Brake manufacturers	• TMD Friction • Mat/Roulunds Braking ApS
Tyre manufacturers	• Michelin
Tyre repair kit manufacturers	• Active Tools Europe GmbH – via email
Academic /research	• Anon. (research expert)

The key topics explored in the interviews were:

- The environmental impacts of tyres and brakes.
- The different strategies for reducing environmental impacts during different life cycle stages, and their associated trade-offs and conflicts.

[3] The stakeholder interviewed for Mat/Roulunds Braking ApS was also the President for FEMFM.

- The key drivers for improving environmental performance and the expected impact from regulations.
- The different specifications of products supplied to the after-market compared to original equipment manufacturers (OEMs).
- The different specifications and considerations for tyres and brakes used for electric vehicles.

The list of interview questions used is provided in Appendix 1. Interviews took place in Autumn 2023. References to information provided by stakeholders within this report have been reviewed with the relevant stakeholder to ensure accuracy.

1.3.3. Market research

Our methodology for the Market Research section comprised of a targeted review of the literature, market analysis including OEM and customer level aggregated data and expert reviews.

We gathered data from tyre and brake manufacturers including information obtained through a literature review of journals, industry reports and regulatory documents. This initial phase was crucial in establishing a foundation of knowledge about the landscape of tyre and brake technology specifically focusing on their aspects due to limited manufacturer provided data on this subject.

Subsequently a market analysis was performed to complement the insights gained from the literature review. This involved examining sales data, consumer preferences and prevailing trends in tyre and brake selection. To ensure an understanding of the market dynamics we consulted specialised websites, industry reports and commercial databases. Engaging with industry experts was a part of our methodology. We sought input from experts at Ricardo who specialise in legislation and related vehicle systems pertaining to tyres and brakes for their review and comments.

In addition to expert insights, understanding the perspective of consumers was also essential. As part of our secondary research efforts, we analysed surveys targeting vehicle owners to gain insights, into their awareness levels and preferences regarding tyres and brakes. The collected responses provided insights, into how consumers think and act, which is crucial, for evaluating if the market is prepared for alternatives.

2. Review of the literature

2.1. Characteristics of environmentally optimal tyres and brakes

2.1.1. Approach

To assess the environmental impacts and evaluate the characteristics of “environmentally optimised tyres and brakes”, this exercise aims to apply a life cycle assessment (LCA) approach, as opposed to considering “in-use” impacts only. Life cycle thinking employs a holistic view of the components’ supply chains which include raw material extraction, pre-processing of those raw materials, transport of goods across facilities, main component production, their use, reuse or recycling and disposal of end-of-life products. These different life cycle stages constitute a product’s system (Figure 2-1). Life Cycle Assessment is a methodology that can be applied to quantify the environmental impacts of a product or service, from a life cycle perspective. Depending on the scope of study that the LCA practitioner chosen, an LCA can be “cradle-to-grave”, “cradle-to-gate” or “gate-to-grave” studies.

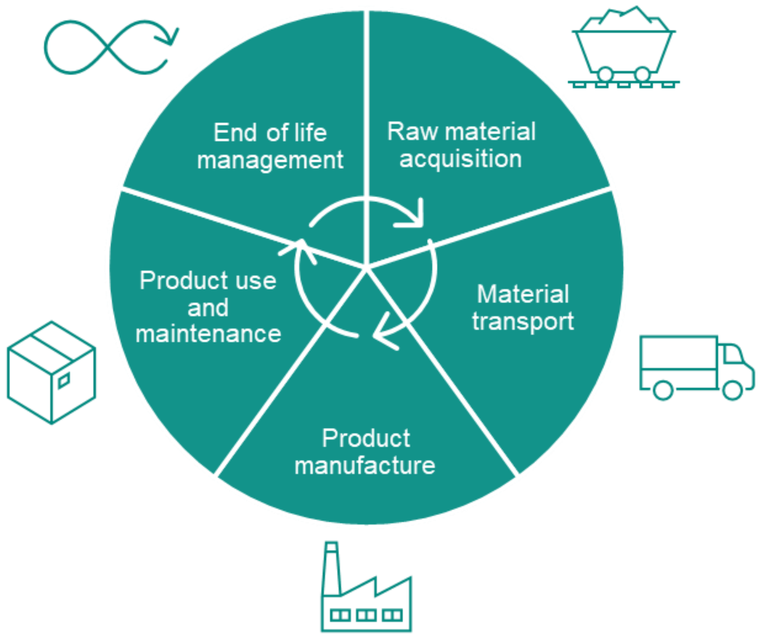


Figure 2-1: An illustration of a product's “cradle-to-grave” life cycle stages – an example

Inclusion of a broader picture, looking beyond “product-use”, is crucial to draw out information on the overall environmental impacts, considering resource and energy hotspots and potential trade-offs across the component’s life cycle (for example, from the use of recycled material vs part replacement frequencies over the maintenance phase). As mentioned, the intensity of the environmental burdens is mostly influenced by specific flows, for example, materials or energy resources flowing into the system and products, co-products and wastes flowing out of the system, over the product’s life cycle (Figure 2-2). These flows are conventionally captured by modelling and assessing the life cycle inventory of those products following their “bill of materials or BOM”. Any environmental burdens resulting from the use of resources over the relevant life cycle processes are characterised, quantified and reported through the "impact assessment" phase and interpreted into the most relevant set of impact indicators such as Global Warming Potential (GWP), Particulate Matter Formation (PMF), freshwater Ecotoxicity (ET), and Eutrophication potential (EP).

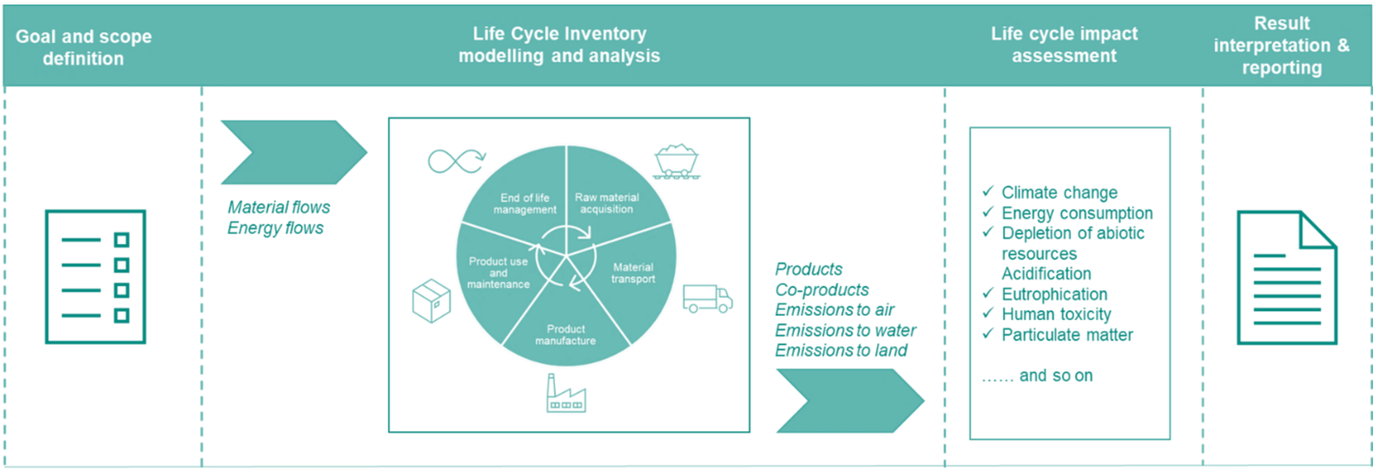


Figure 2-2: Illustration of the four key stages of Life Cycle Assessment

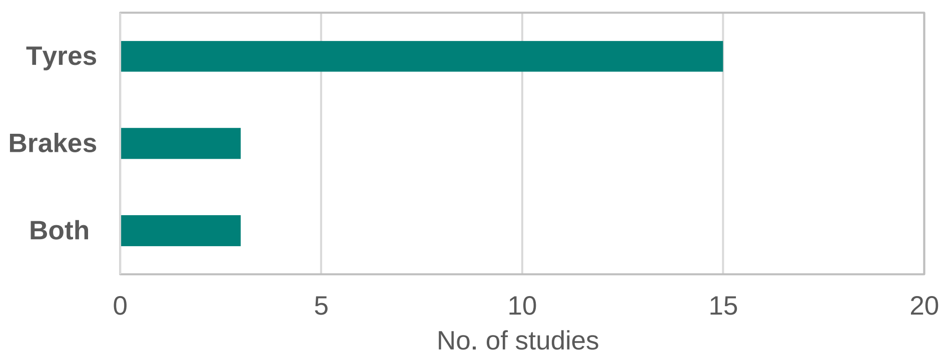
2.1.1.1. Goal of the task

The life cycle impacts of tyres and brakes (production, use and end-of-life) vary by tyre compositions, designs, road types on which the tyres are used, regulatory requirements, driver behaviour, local weather conditions and many other variables that are often outside the influence of relevant supply chain stakeholders for each of these vehicle components in the market. The choice of the most appropriate factors is also rather subjective and driven by the detailed goal and scope of study. Acknowledging these factors, this study undertakes an exhaustive review of the published literature. From the review, this study aims to identify some of the most relevant and crucial factors influencing the life cycle environmental performance of tyres and brakes. The literature review is, therefore, targeted at published LCA studies that emphasise ideally the “cradle-to-grave” (manufacture, use and disposal) environmental performance of tyres and brakes.

2.1.1.2. Literature collection and review methodology

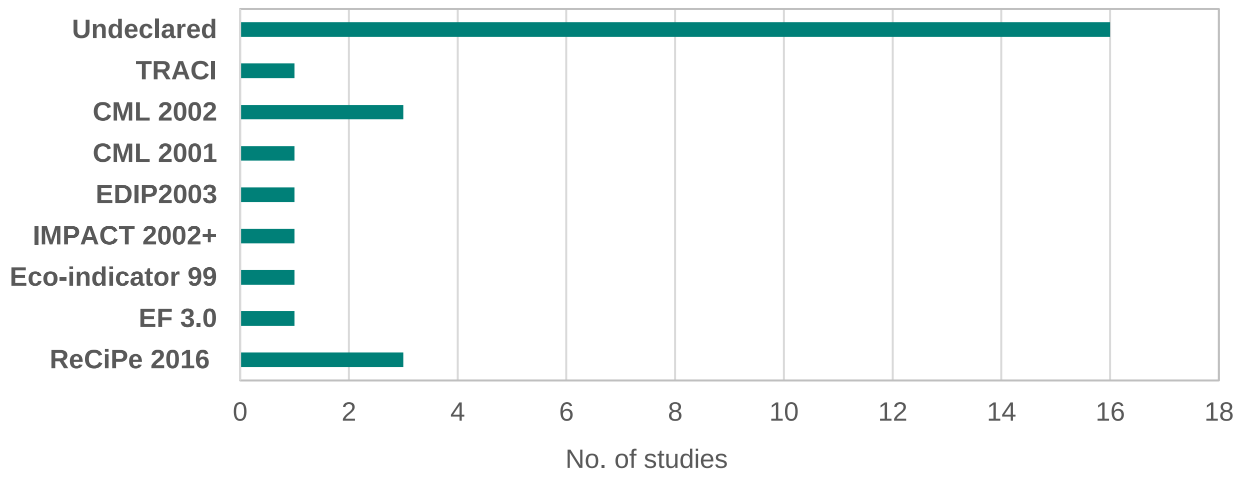
An exhaustive literature search and retrieval was undertaken to create an evidence base for establishing what “environmentally optimal tyres and brakes” entail and potential data gaps. Among the literature identified, a total of only 22 studies were found to focus on LCA of tyres and brakes, of which 19 focussed on the tyres and just three focussed on brakes. Literature numbers split by the type of component studied is presented in Figure 2-3. This shows a striking limitation in the number of studies emphasising the life cycle impacts of brakes and brake-related components.

Figure 2-3: LCA literature identified for review, split by components covered.



Life cycle assessment and non-exhaust emissions from tyres and brakes is a new topic of interest that is fast gaining momentum in the research and policy sectors. In 2017, Product Category Rules (PCR) were introduced for tyres [4]. PCRs are globally harmonised and validated LCA methodologies that are developed for specific products, aligned with the product’s manufacture and technical specifications. PCRs are primarily used for producing Environmental Product Declarations (EPD) by interested parties, which in most cases would be OEMs, to declare the environmental credentials of their product at a global level. PCRs tend to include a clear set of guidance or rules for boundary setting[4], cut-off criteria, choice of impact assessment methods, scenarios for modelling, data requirements in terms of source/ quality, verification needs and how to bridge data gaps, if any. Yet, no studies from the industry and research sector, besides tyre related EPD developers, have been identified via the literature review to follow PCR for methodological guidance. This deviation could have been due to factors including the prevalence of existing industrial practices, regionally relevant impact assessment and modelling scenarios (see Figure 2-4 below) and/or lack of relevant data, to name a few.

Figure 2-4: Variations in the life cycle impact assessment (LCIA) methods adopted by the Tyre and Brake LCA studies adopted for literature review



Note: TRACI: Tool for Reduction and Assessment of Chemicals and other environmental Impacts; CML: Centrum voor Milieukunde Leiden (University of Leiden developed LCIA methodology); EDIP: Environmental Design of Industrial Products (Danish LCIA methodology); IMPACT 2002+: Swiss Federal Institute of Technology developed LCIA methodology; Ecoindicator 99: an LCIA methodology developed by PRé Consultants (notable life cycle inventory development and research organisation; EF: Environmental Footprint method developed by the European Commission; ReCiPe 2016: an LCIA method developed jointly by RIVM and Radboud University, CML, and PRé Consultants

Attempting to arrive at significantly sound conclusions from the review of literature adopting variations of assessment methodologies and scenario assumption could lead to reporting of results that are inconsistent with each other and may prove to be unsuitable for direct interpretation for this particular task. Recognising this, we have attempted to thoroughly interpret those findings by normalising the results to a set of assumptions may require some level of modelling which may be time consuming yet leading to unreliable results. We have, therefore, attempted to improve the quality of our findings from this limited pool of literature by applying our pre-existing knowledge in undertaking product LCA and to some extent normalising some of those results to the technological scope of this review task. For example, the results reported in the reviewed literature have been normalised to a passenger car tyre weighing 12 kg that has been used to travel 40,000 km before needing replacement (in line with the recommended functional unit from the PCR for tyres).

2.1.1.3. Interpretation of Life Cycle Environmental Impacts

Universally, LCA is undertaken in accordance with the guidance in the ISO14040/44 standards[5]. An LCA can either be a comprehensive as recommended in the standard or “simplified” based on the goal and scope of study. For this study, we mainly review results and report key findings from the identified published literature. However, we aim to analyse and interpret those findings, identifying key pointers for the definitions of “environmentally optimal tyres and brakes” in the final report for this project. Contemporarily, the environmental burden over the life cycle of tyres and brakes is characterised using specific characterisation factors, which are then consolidated and presented into quantified impacts under specific impact indicators as those presented below in Table 2-1.

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[4] processes and life cycle stages to include and exclude.

[5] ISO14040:2006: Environmental management- Life Cycle Assessment: Principles and Framework []

Table 2-1: Different life cycle impact indicators reported by the reviewed literature, with a definition addressing the various impacts covered

Life Cycle Impact indicators	Scope of the indicator
Global Warming Potential (GWP)	GWP is an assessment of the gases emitted into the atmosphere that are liable to cause global warming. Key sources of this emissions include the material and energy flows into the production of relevant materials
Cumulative Energy Demand (CED)	This represents the efficiency of total primary energy use; it may be further split into non-renewable (fossil and nuclear) energy, and renewable primary energy. Applicable to most metals and minerals owing to the high energy intensity associated with the production of intermediate products feeding into the vehicle assembly
Ozone Depletion Potential (ODP)	This considers the degradation of stratospheric ozone due to emissions of ozone depleting substances, for example long-lived chlorine and bromine containing gases (e.g., CFCs, HCFCs, Halons
Acidification potential (AP)	This takes into the account acidic gases that react with water in the atmosphere to form “acid rain”, which can cause ecosystem degradation. This includes gases such as sulphur dioxide (SO_2) and ammonia (NH_3)
Eutrophication potential (EP)	This covers emissions which have the potential to cause over fertilisation of water, which disrupts aquatic ecosystems, in this case, terrestrial ecosystems. This includes ammonia and phosphorous containing emissions
Abiotic Resource Depletion_Metals and Minerals (ARD_MM)	This concerns the extraction of all minerals and metals. Conventionally, impacts are calculated using characterisation factors based on its remaining reserves and rate of extraction of these metals. While this indicator does not highlight the criticality of metals and minerals, it summarises and highlights impacts related to these non-renewable resources, on the overall.
Abiotic Resource Depletion_Fossil Energy (ARD_FE)	This concerns the extraction of fossil fuels. Values are determined by the lower heating value because fossil fuels are considered to be fully substitutable
Human Toxicity Potential (HTP)	This accounts for the adverse health effects on humans caused by intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin, in as far as they are related to cancer and non-cancer effects that are not caused by particulate matter/ respiratory inorganics or ionising radiation. It may be further split into cancer and non-cancer effects
Particulate Matter Formation (PMF)	This accounts for pollutant emissions which have the potential to impact on human health;
Ecotoxicity (freshwater) (ET)	This accounts for toxic impacts on freshwater ecosystems, damaging individual species, changing the structure and function of the ecosystem

2.1.2. Tyres

2.1.2.1. Production stage impacts

During production, chemicals (such as fossil rubber, carbon black, fabrics, bead wire and other chemicals are combined to form high-endurance rubber, which is then cast into a tyre form [5] [6] [7] [8] [9]. A breakdown of components typically used in contemporary tyre production is provided in Figure 2-5.

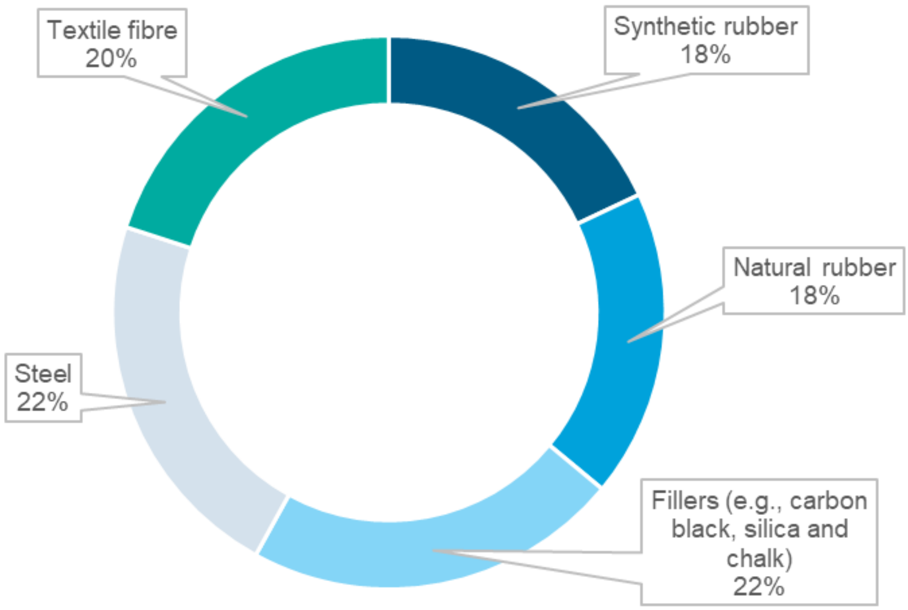

Figure 2-5: Chemical composition of a conventional tyre used in passenger cars; Source: [10]

All of the reviewed LCA literature, relating to tyres, report their production- to be the second largest environmental contributor with components such as synthetic rubber and fillers causing significant impacts which are captured by global warming potential (as CO_2 emissions), abiotic resource depletion _FE (as fossil fuel demanding) and abiotic resource depletion _MM (causing metal and mineral scarcity) and human toxicity potential (releasing harmful gaseous emission with human health implications). Figure 2-6 shows the number of studies that consider each of the impact indicators, all consider GWP and most cover particulate emissions although only around half consider human toxicity and ecotoxicity (impact on freshwater systems).

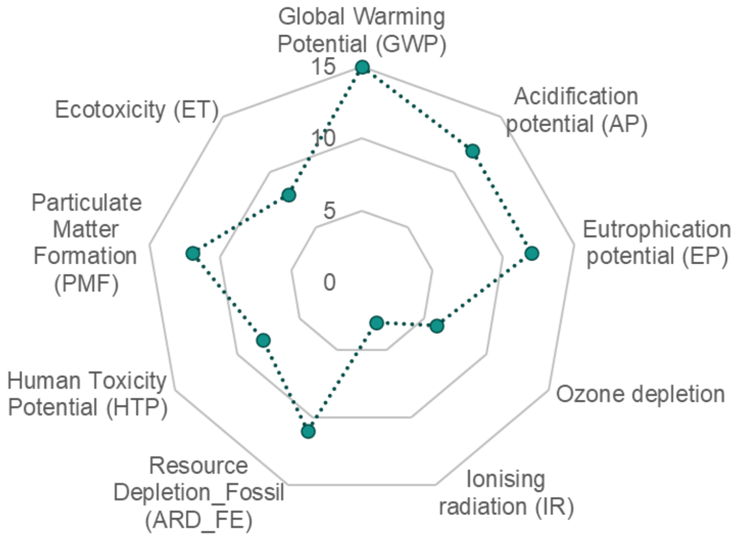

Figure 2-6: Number of studies considering each impact indicator for tyres

Production stage emissions are mainly dominated by climate change impacts, (captured by global warming potential (GWP)) which stems from crude oil extraction for synthetic rubber. Harmful aerosols and carcinogens released from the extracted and crude oil processing were also captured by other key impact categories including human toxicity and ozone depletion. Key chemical components used in tyre manufacture are also significant sources of harmful substances such as polyaromatic hydrocarbons (PAHs), benzothiazoles, isoprene, potential NOx and SOx emissions from the melting and tyre moulding phases, as well as heavy metals such as zinc and lead (Imperial Zero Pollution) [6] [7] [9]. These outputs of the tyre production processes could lead to hazardous respiratory organics and inorganics, affecting air quality in the manufacturing plant. Other dominant impacts reported in tyre manufacture include Abiotic Resource depletion (ARD) and Cumulative Energy Demand[6] due to the use of crude oil to produce synthetic rubber. Following key findings from this review, key environmental contributions from the life cycle of tyres will be analysed and discussed in detail in section 3.2.

Sustainable alternatives to conventional tyre materials

Guayule (bio-based) rubber has been explored by a few studies and found to demonstrate relatively lowered CO_2 emissions by an average of 50% over its product life cycle. However, these studies do not capture crucial impacts such as land use, biomass management or supply needed for commercial scale production [6] [7]. Any bio-derived products will require significant quantity of fertilisers, pesticides fuel/ electricity and freshwater. Conventionally, rubber is reported to only be produced in tropical areas with relatively high soil carbon content [11] [12] [13] such as South East Asia and South American regions, which also experience episodes of water-stress due to climate change.

A study by Wang et al, 2023, investigated the impact of cash crop expansion on natural forests, with particular emphasis on rubber, soy and other economically significant feedstocks, employing direct remote-sensing approach. This study reported rubber-related forest loss by about 4 million hectares, through deforestation in these regions, in addition to some areas in West and Central Africa, in addition to quantifying subsequent biodiversity losses [14].

A study by OECD in 2015 also discusses an alternative to carbon black that promotes resource efficient tyre production by reducing overall synthetic rubber requirement and eliminating the need for carbon black. This nanomaterial is called HD-HS (High-dispersion- high surface area) silica, as opposed to the conventionally used HD silica. This unique nanoclay mix was found to provide overall life cycle GHG savings of about 25%, compared to conventional tyres (using carbon black and carbon black with HD silica). However, the HS silica use in tyre compounding processes has been noted to release relatively higher amounts of VOCs during the tyre production phase [15]. A number of studies also explored the possibilities of producing green HD silica from rice husk ash, a bio-based, waste-derived alternative to carbon back and synthetic HD silica [16] [17] [15]. This bio-based alternative has

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[6]CED represents the efficiency of total primary energy use; it may be further split into non-renewable (fossil and nuclear) energy, and renewable primary energy. Applicable to most metals and minerals owing to the high energy intensity associated with the production of intermediate products feeding into the component assembly.

been credited with both life cycle GHG savings of tyres (-50%), as opposed to synthetic silica and being able to reduce the overall cost of production of green rubber due to it being 17% lighter. Nevertheless, the resulting tyres' performance and safety characteristics, over their service life and relevant shifts in environmental burdens across impact indicators (if any) must be critically assessed to be thoroughly conclusive.

2.1.2.2. Use-stage impacts

Studies unanimously establish that tyre use accounts almost 80% of the overall life cycle impacts [5] [6] [11] [7] [9]. Most studies show consensus in demonstrating the key sources of emissions in the tyre use-phase to be tyre-wear emissions, while poor tyre designs, that are not compatible with the vehicle characteristics, could indirectly contribute to increased fuel consumption in ICEVs (Internal Combustion Engine vehicles). Similar energy loss has been reported in electric vehicles but were reported to be proportionally lower in scale, due to the improved efficiency of electric vehicles (EVs) compared to the ICEVs [18] and increasingly renewable electricity share reduces the impact on CO_2 emissions. With developments in material technology and battery chemistry, future electric vehicles are expected to be reduced in weight compared to current EVs, utilising batteries with improved energy densities for extended range and body “lightweighting” strategies. An RAC foundation study into the dynamics of vehicle traction design and its impact on front and rear tyre wear suggests, assuming typical use of vehicles for taxi services between EVs and diesel ICEV, the age and deterioration of an EV-taxi is more or less similar to that of diesel taxis, except the front tyres of diesel taxis to get an extra 5000-10,000 miles service life. This is due to the lack of burden from the weight of the batteries on the front tyres (particularly under braking) and the increased torque of the electric motor that might be experienced by an EV-taxi. Therefore, a contemporary case of a more leisurely use of EVs, compared to use as a ‘taxi’, is likely to provide improved lifetime activity (km covered) and reduced wear emissions over a vehicle's service life [19].

Poorly designed conventional tyres have been found to lead to increased rolling resistance, thus increasing a vehicle's overall fuel consumption [5] [6] [11] [7] [9]. This impact has been captured via cumulative energy demand (CED) accounting for the increased fuel demand over the vehicle use phase and further CO_2 emissions captured by the GWP indicator. While vehicle use is outside the scope of the LCA of tyres, such tyre designs and the vehicle's characteristics such as age, segment/size and mass have been shown to increase wear and tear of tyres, deteriorating tyre grip over its service life, increasing particulate emissions (PMF) [6] [9]

Impact of interactions between tyre and road surface

Interaction between tyre and a road wearing course can be quite complex with a multitude of factors influencing the resulting rolling resistance, skid resistance and noise characteristics. To understand the complex interactions, a number of studies also emphasise on the key parameters that are independent of tyres or their design characteristics (including tread pattern, tread depth, rubber characteristics, age, tyre pressure etc) [20] [21] [22] [23]. These parameters strongly influence a tyre's performance, affecting its rolling resistance, and in in the presence of other environmental factors, tyre friction[7] and its skid resistance[8]. Efforts have been made to quantify these “hard to model” factors [20]. However, for the purpose of brevity, these factors are grouped into two other categories

- Road surface course - including the micro and macro texture of the surface, construction practices (pavement design, drainage characteristics, method and compaction approaches) and materials (aggregates, bitumen spec, fillers etc)
- Environmental effects - local temperatures, water film thickness etc.

While understanding the interactions between the three factors (tyre, road surface and environment) is crucial, most studies have only mainly emphasised on road surface characteristics and tyre design characteristics [22] [21] [23].

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[7] Friction describes the grip exercised by the tyre on a particular road type at a particular ambient setting.
[8] Skid resistance describes the road's influence/ impact on the tyre/ road friction, particularly under wet condition. Skid resistance therefore decreases when the coefficient of friction is lowered due to wetter conditions.

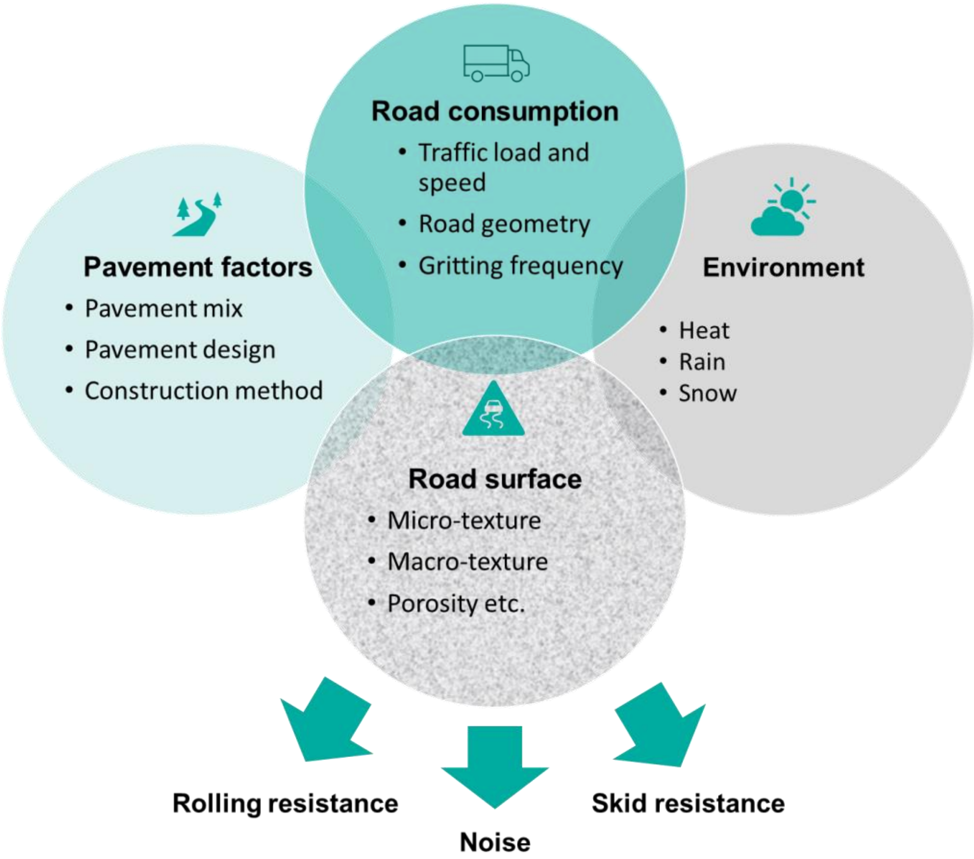

Figure 2-7: Impact of multiple parameters on road surface characteristics and subsequently a tyre's performance

Wearing course of roads are contemporarily constructed to the specifications of established standards on material selection and construction designs by road type [24]. Such standards define that the surface course must provide resistance to chipping or deformation when exposed to the elements and constant load from traffic, abrasion wear to name a few. Design of road surface course and its characteristics such as its porosity, road roughness, which is often represented as micro-texture[9] and macro-texture[10] is found to play a greater role, not only affecting the rolling resistance of tyres but also in particulate matter generation and skid resistance under wet driving condition. Micro or macro texture of the road heavily influence 'friction' at the contact point, and subsequently the skid resistance [25]. Key road surface components that influence the micro and macro texture, and thus the skid resistance, include the pavement type (asphalt or concrete, including its composition), method of their pavement and pavement design.

Non-optimal composition (blend of pavement materials) of pavements, in the long-term have been found to lead to unevenness of pavements by encouraging spikes in local temperature at the tyre-road contact point and causing rolling tyres to deflect and deform. This could lead to an increase in rolling resistance and subsequently, fuel consumption [25] [26]. A detailed study by Reeves et al, 2010 also suggests that an uneven road surface contributes directly to double the energy losses through macro and micro-deformation of tyre sidewalls and the slipping friction in the contact areas between the tyre and road surface [26].

When considering the impacts of the environment, a number of studies suggest that relative humidity or water films formed from raining or dampness on the surface coarse lead to an increased generation of finer particulates [22] [25] [26]. This is where "wet grip" characteristics of the tyre come under focus and this characteristic is influenced by the tread pattern and tread depth of the tyres. The tread pattern, supported by tread depth, mainly provides channels for water to escape to create a localised 'dry' contact point between the road surface and tyre, under wet conditions.

[9] Micro- texture could refer to the microscopic roughness of the road surface at the tyre contact area and is influenced by the type of aggregates used, deposited fine dust (from wearing of the road) and other elemental fine grains.
[10] Macro-texture corresponds to significant gaps or grooves between the aggregate particles.

Nevertheless, the macro and micro-texture of the roads need to be aligned with tyre treads to enable the 'draining' mechanism. It is to be noted that irrespective of these factors, increase in water height and high vehicle speed could lower the chances for maintaining a safe co-efficient of friction, subsequently leading to the skidding and the formation of ultrafine particles. It is important to note that there are only a handful of studies that integrate the investigation of the technical tyre-road surface- environment interactions [20] [25] [26] and even lower number of studies that provide findings that are relevant to the scope of this work [25]. The reason for this gap in literature and in industrial research is due to the lack of a dedicated testing method to measure the complex interactions between rolling resistance, skid resistance and noise in real road surfaces and the lack of relevant methods to measure abrasion wear and the generation of resuspended fine dusts as a part of the tyre and road wear particles. Only a brief and indicative account of the complex interactions between a multitude of parameters between the tyre-road surface- environment have been provided here. This study has arrived at some preliminary observations and recommendations for consideration, which will be covered in Section 8.4.1.

Impact of tyre and road wear particles on ecosystem and human health

Tyre wear is commonly cited as one of the largest sources of microplastic pollution to the environment [10]. Characterisation and investigation of the effects of microplastics on aquatic and terrestrial organisms is an area of significant ongoing research activity. Tyre wear particles are not only the source of microplastics most prevalent in the environment but also act as sources of numerous organic micropollutants. The nature of additives used in tyre production could vary according to the manufacturer and use of the tyre. A tyre can include as many as 200 additives. These chemicals are used in the manufacture of tyres for a range of purposes but can remain within the final product. They may subsequently be released into the environment through leaching from TRWPs. It can be expected that tyre and road wear particles (TRWP) are released into different environmental compartments. A small fraction is emitted into the atmosphere while much larger proportions will reach soils close to roads and aquatic compartments, respectively. Baensch-Baltruschat et al. [10] have investigated the transport and toxicity of tyre and road wear particles on human health, ecosystems and their fate in the environment. This study has shown how the particulate emission factors are influenced by the aforementioned characteristics in addition to road type and driver behaviour [10]

A 2017 study by Kole et al. [27] released figures on the sources of microplastics in the UK and globally, where an estimated 0.6-1.3 kg/ capita. annum of tyre wear particles is being released into the environment from tyre wear loss of about 10-20% by weight, over a tyre’s service life. It is unclear whether the particulate emissions, being referred to in this study, are coarse or finer particles. In the case of coarse particles, from both the tyres and the wearing course of the roads, several studies also report their transport to the soil immediately around the road banks. During rainfall events TRWP will be washed off road surfaces. The chemicals embedded in these particles, particularly heavy metals and other volatile and inorganic compounds of synthetic nature, lead to contamination of the soil and subsequent ecotoxicity [10]. However, another experimental study by Aatmeeyata et al. [28] on the release of PM_{10} (fine particulate) emissions, compared to the total weight of the run-off of (coarse) particles, were found to be less than 0.1% by weight. Run-offs often captured by the wastewater treatment plant are subjected to a significant level of fine particulate filtration. However, on average 19.8% of microplastics[11] (made of TRWP) were found to pass through the treatment plant processes.

There are a wide range of studies looking at ecotoxicological effects of tyre and brake particles on aquatic organisms. A useful review of published studies was prepared by Baensh-Baltruschat et al. [10] which provides further detail. Variable effects across a range of TRWP concentrations are reported. The large variability observed between different studies is likely to be a consequence of the high variability in terms of what is being tested, reflecting differences in the rubber recipes in tyres, in test designs and species sensitivity [10]. Experimental design may not always reflect environmental conditions and thus care should be taken in extrapolating laboratory-based effects data to likely effects in the field.

Acute toxicity to TRWP leachate has been demonstrated for a range of species including fish, daphnids and copepods [10]. Prominent and recently well studied tyre additives include the antioxidant N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6-PPD). The oxidation product (6-PPD quinone) has been identified as the cause of acute mortality in coho salmon, resulting in mass mortality events during seasonal migration in the USA [29]. Toxic effects of leachates from TRWP have also been associated with Zinc (Zn), other metals and organic compounds, e.g., benzothiazoles, phthalates and resin acids [30].

Several studies have aimed to model the transport of microplastics in the environment, particularly to water bodies including underground sewers, estuaries and other surface waters have been modelled and reviewed. While there has

[11] Tyre particulates are often referred to as microplastics due to the release of polymeric hydrocarbons as particulates and dust from tyre wear [].

been some methodological maturity in the estimation of the transport of these particles, there is little information from the LCA perspective, in terms of measurable and quantified impacts on ecosystem and human health. This requires a much more evolved analytical methodology, precise modelling studies to estimate transport, degradation, and retention of particulate emission in soil and water and dedicated ecotoxicological studies targeting impact on freshwater and marine species.

Impacts of tyres on noise

Noise is considered the second largest environmental cause of health problems, after air pollution, and vehicle noise plays a leading role in this as over four times as many people in Europe are estimated to be affected by high levels of road traffic noise than by rail, aircraft and industrial noise put together [31]. The World Health Organisation (WHO) recommends that road traffic noise levels be kept below 53 dB L_{den} [32] but it can be seen from national noise mapping that this level is exceeded for many people close to busy roads [33]. At traffic speeds encountered on the Strategic Road Network (SRN) the dominant source of this road traffic noise is from the tyre / road interaction and therefore it is important that optimised tyres help to address this source of pollution (see section 2.3.1.2).

The mechanisms of tyre road noise generation are generally considered to consist of impacts and shocks, aerodynamic processes and adhesion effects [34]. Impacts and shocks describe the forces between the tyre tread and the road surface and generate noise below 1 kHz. Aerodynamic processes describe the compression and decompression of air trapped between tyre tread blocks and this generates noise above 1 kHz. Adhesion effects describe vibrations in the tyre caused by friction between the tyre and the road surface and this also generates noise above 1 kHz.

The precise amount of tyre road noise that is generated is a factor of several complex interactions between tyre rubber and tread pattern and the road surface texture. As such, changes in tyre road noise measured on an ISO test (ISO10844) surface [35] are not the same as those measured on other surfaces that are laid on typical roads [36] [37]. It is therefore challenging to consider factors within tyre design which can be said to definitively influence tyre road noise generation in one direction or another. Nevertheless, there are some conclusions that may be drawn. It is well understood and accepted that wider tyres lead to greater noise generation, and this is reflected in type approval noise limits for tyres which are categorised by tyre width [38]. Studies have also found that, in general, transverse tread patterns lead to noisier tyres than circumferential patterns and tyre wear, and the associated impact on tread depth, can lead to an increase in tyre road noise [39].

Tyre labelling includes an indication of noise emissions, and this is discussed in section 2.4.1.

Alternative sustainable options: The environmental performance of tyres are predominantly reviewed from fuel-use perspective in a number of LCA studies [8] [9] [11] [40], whereas the emphasis on improving/optimising tyre wear resistance as a part of its overall performance is rarely found. This has been confirmed by the findings reported by Dong et al. 2021 [6], in their comprehensive review of tyre LCAs and relevant literature. Nevertheless, the PCR for tyres published in 2017 by the EPD system [4] provides detailed guidance and a dedicated methodology for the calculation of tyre and road wear particulate emissions as a part of the estimating use-stage emission for their tyre EPDs. Adoption of such standardised methodologies for estimating the life cycle environmental impact of tyres could improve the completeness of the environmental impact assessment, consistency of the approaches employed in future studies and the reliability of reported results.

2.1.2.3. End-of-life (EoL) stage impacts

In the UK, there is clear guidance on the storage and mechanical treatment of end-of-life tyres (ELT) for recovery [41]. While this regulation requires adherence to the Waste Framework Directive, there are no clear guidance on how the resulting environmental impacts are to be monitored and mitigated. According to the guidance in the PCR for tyres, the most commonly modelled end-of life scenarios for ELT include landfill, recycling, and waste-to-energy (in cement kilns and power plants, for example) [4]. However, more innovative material recovery strategies such as:

- Re-treading
- Production of recycled tyre crumb (RTC) (through ambient or cryogenic pulverisation) and reclaimed rubber tyres
- Pyrolysis (for the production of waste-based fuels)

are all being explored by a number of studies [6] [8] [11] [42] [43]. Within the PCR for tyres, the mass of ELTs is considered, in addition to the guidance on ELT treatment split by region, to support the estimation of EoL impacts. This provides an LCA practitioner the needed set of preliminary data for relevant parameters and appropriate scenarios to be able to model the EoL impacts of a tyre. Nevertheless, none of the reviewed studies have adhered to this global guidance and all have undertaken independent studies on EoL impacts. Most of these studies were found to quantitatively evaluate the environmental performance of some of the currently practiced end of life routes including innovative material and energy recovery approaches [7] [5] [9] [11] [40], while the remaining studies were majorly qualitative discussions of the future evolution for these innovations [44] [42] [43]. Depending on the choice of EoL processing pathway, there will be environmental impacts pertaining to both materials (for example water and chemicals such as polyesters, textiles, binders) and energy consumed in the process. Tyres entering EoL routes other than disposal onto a landfill have been generally found to deliver GHG savings, as opposed to tyre production and use stage. The emission savings from this phase mainly stem from the minimisation of disposal of ELTs onto landfills through either incineration with energy recovery or more productively through their recycling and application in other sectors and products such as in civil construction, use of shredded and recycled tyres in modified asphalt and synthetic flooring [8] [42] [45].

Alternative EoL treatment routes: Retreading can be assessed a potential EoL route to enable more efficient material recovery, however, some studies report higher environmental impact due to the demand for original components such as synthetic rubber, natural rubber and carbon black, in addition to the associated energy demand. While this can be justified with the displacement of production impacts from virgin tyres, this strategy has been found more useful for application to HGV tyres, as opposed to that of LGVs [46]. Among the list of other alternative EoL treatment routes, incineration with energy recovery (as alternatives to coal in cement kilns, for example), and pulverisation to produce powdered rubber, for use in secondary applications such as production of wires, and manufacture of synthetic floors, were found to provide greater environmental benefits from a GHG and air emissions perspective [42] [45], only if the baseline scenario consisted of landfilling tyres. Since disposal of tyres on a landfill is illegal in the UK, according to the regulation on Waste Framework Directive, this study will eliminate landfill from a potential EoL scenario. Recycled tyre crumb (RTC) is commercially produced for recycled applications, such as rubber granules used in artificial turf, basketball courts and recreation areas, at smaller necessary sizes through mechanical grinding or cryogenic freezing from chipped or shredded whole tyres [47].

On the other hand, environmental impacts were found to be worse-off, compared to other alternative routes discussed, for production of modified asphalt pathways. Another product that benefits from recovered ELT crumb rubber, modified asphalt, can be a highly energy intense process with significant impacts reported across a range of impact indicators [45]. Pyrolysis of ELTs generates pyrolysis oils and other components such as gas and carbon black. While carbon black can be recycled, the more desirable venue for pyrolysis oil is the production of alternative fuels for industrial use and other relevant applications [7] [42] [46].

2.1.2.4. Overall Life Cycle Environmental Performance of Tyres

Following the review of the collected literature, the key highlights on the overall life cycle impacts of tyres have been summarised, including any gaps and specific areas of high relevance which must be further explored and analysed.

- The manufacturing or production of tyres, as indicted by literature, was determined to be the second most polluting life cycle phase; Key sources of pollution in the production phase include processing of crude oil during the production of synthetic rubber, which also contributes to the increased non-renewable resource depletion and emission of respiratory inorganics that are harmful to human health; The second most dominant impact from tyre production process is the CO_2 emission (captured by GWP) attributed to the overall material and energy consumptions across the production phase.
- A bio-based alternative, Guayule rubber has been explored by a few studies and found to lower life cycle CO_2 emissions by about 50%, over its life cycle. However, the reporting studies do not capture crucial impacts such as land use, biomass management or supply needed for commercial scale production.
- An alternative to carbon black (a conventional filler component used in tyre manufacture), called HD-HS silica, that promotes resource efficient tyre production by reducing overall of synthetic rubber requirement and eliminating the need for carbon black. This option was found to provide 25% GHG savings and 10% overall reduction in synthetic rubber requirement, against that of baseline scenarios (carbon black and carbon black with HD silica)
- Tyre use was found to contribute to the highest environmental impact, over a tyre's life cycle; Key impact contributors from this stage are CO_2 emissions from fuel use resulting from influence of rolling resistance of poorly designed tyres, followed by tyre wear emissions resulting from abrasion with the road surface. Within a tyre's LCA, CO_2 emissions from fuel use is conventionally captured by GWP indicator, while the allied additional fuel demand is quantified and reported via the cumulative energy demand (CED) and abiotic resource depletion_ fossil fuels.

- End-of-life phase was generally found to contribute the lowest overall impacts across a tyre's life cycle. Key environmental impacts from disposal onto a landfill would include release of CO_2 and other aromatic compounds if incinerated (which will be captured and negatively reflected by a range of GWP, AP, EP, ODP and PMF).
- Tyres, in general, have been found to provide EoL credit by eliminating the disposal of ELTs onto landfills via incineration without energy recovery (ER) or by being used for more productive applications such as in civil construction, use of shredded and recycled tyres in modified asphalt and synthetic flooring.
- Pyrolysis of ELTs generates pyrolysis oils and other components such as gas and carbon black. While carbon black can be recycled, the more desirable venue for pyrolysis oil is the production of alternative fuels for industrial use and other relevant applications.

2.1.3. Brakes

Brake systems are mainly made of brake discs and brake pads. Brake discs are predominantly made from cast iron (>95%), silica (2-3%) and either carbon-carbon or ceramic matrix composites (<3%) depending on the tyre and regional preference for the type of brake systems [48]. Brake pads typically consist of a coated metallic backplate onto which the friction material formulation is bonded. The formulations may vary depending on the type of brake pads and varies between semi-metallic, non-metallic and ceramic components. Low-metallic formulations are the most common in Europe and have been found to have the most complex formulation with a bill of material comprising of a number of reinforcing fibres, fillers, binders and friction additives [49]. However, semi-metallic brake pads generate the most brake dust among the brake pad candidates, with ceramic pads generating the least amount of brake dust due to efficient diffusion of local temperatures and relatively high wear resistance. Friction developed during brake application wears the discs and pads resulting in the requirement for periodic replacement [50]. A study by Gradin et al. 2019 [51], shows that sixteen brake pads and four brake discs are required over the life cycle of a vehicle[12].

Some of the key emissions from brake wear identified in a number of studies include copper, chromium and iron, the more elaborate emission profile of which is dependent on the friction material formulation and process used for coating on the brake discs and pads in more recent vehicles [52] [53] A study by the Air Quality Expert Group (AQEG) in 2019 [53] has identified that increase in friction-generated local temperature by about 15°C when above 170°C was found to result in 5000 times more fine and ultrafine particle number emissions. Another study also observed particulate emissions increased by several magnitudes as the temperature passed a critical temperature at around 170-190°C [115] (see 2.3.2.1). Such findings have resulted in a significant innovation focus towards, high-resistance, local thermal diffusing, low-environmental impact friction materials for brake systems [53] [54]. With the importance of innovative brake materials gaining momentum, particularly towards an overall objective of improving air quality, only a small selection of studies have been found to quantitatively evaluate the life cycle environmental impact of brake discs and pads.

From the review of published literature, only one study by Gradin and colleagues, employs full LCA to analyse the comparative life cycle impacts of contemporary and new formulation brake discs and pads, with a selection of other studies, covering impacts related to brake use and wear in a fragmented faction and are not necessarily LCA studies. Gradin et al. [51] have reported production related impacts via a variety of impact indicators which are as follows:

- Global warming potential, $kgCO_2$ eq
- Ozone Depletion potential, kgCFC-11 eq
- Ozone formation potential, $kgNO_x$ eq
- Particulate matter formation, kg $PM_{2.5}$ eq
- Acidification potential (terrestrial), $kgSO_2$eq
- Eutrophication potential (Freshwater), kg P eq
- Terrestrial, freshwater and marine Ecotoxicity, kg 1.4-DCB e
- Human toxicity_ carcinogenic and non-carcinogenic, kg 1.4-DCB e
- Land use, m^2a crop eq

[12] Over the assumed service life of the vehicle (240,000km), four brake pads are required per brake disc in a passenger car. This assumption is discussed further in the section 2.1.3.2

- Mineral resource scarcity, kg Cu eq
- Fossil resource scarcity, kg oil eq
- Water consumption, m^3

Other studies that apply principles closest to the selection of sustainable materials for brake system design are those by Eddy and colleagues in 2014 and 2015 [54] [55]. Eddy 2015 and Eddy 2014 introduce a predictive modelling-based approach that uses surrogate models to efficiently select materials based on sustainability considerations. They address the challenges of material selection by consolidating contributing factors into categorised groups and streamlining the process to avoid the need for full LCA in early stages. Another master's thesis by Andersson and Dettman in 2013 [56], on the life cycle assessment of brake systems, was also found, however, the impacts have been reported only for the production stage, covering only three impact categories (Global Warming, Acidification and Eutrophication). This study was also restricted by the technology and time representativeness of the products analysed to contribute to any meaningful conclusions for this study. Owing to the limited pool of existing evidence on the LCA of brakes, it is suggested that the findings reported in this section to be treated with caution and that further exploration of the future publications as a means of updating the reported outcomes is recommended.

2.1.3.1. Production stage impacts

A detailed inventory of contemporary disc brakes by Gradin et al. 2019 [51], shows the use of reinforcing fibres such as polyacrylonitrile compounds and heavy metals such as zinc, copper and chromium in the production of the friction formulation. They also investigate the environmental impacts of an innovative disc brake, the material formulation of which is designed to reduce the release of brake wear particulate matter.

The overall process of production includes the manufacture of brake discs which are cast in a sand mould, machined and finished to desired dimensions and refined for balance. This is followed by the adding a protective corrosion-resistant coating over the contemporary brake disc. Often, thermal spraying is used or coating brake discs with friction material which is disclosed as one of the most energy intense process by Gradin and colleagues in their analysis.

Among the reported impacts over the life cycle of brake disc production, use and disposal, Gradin and colleagues have highlighted the production phase for both conventional and innovative brake discs to be the most polluting. The key emission contributor from production phase was reported as energy consumption from moulding and finishing, Nevertheless, for innovative brake discs, the more energy-intense thermal spraying employed to coat brake discs with friction material was reported to carry the most environmental burden. Thermal spraying, as well as utilising electricity, also uses liquid oxygen, which in-turn can be even more energy demanding. Due to the increased electricity consumption at this phase, the impacts from electricity generation, also considering the generation technologies used (mainly nuclear energy), was observed to contribute higher environmental impacts under the 'ionising radiation' indicator. These emissions were quite significant for the innovative brake discs that the component’s environmental footprint struggled to break-even, even over their extended use under a sensitivity study that evaluated “longer vehicle’s lifetime”. Gradin et al. also reported relatively higher metal consumption, captured by the mineral resource scarcity indicator (+50% compared to conventional brake disc production), attributed to the use of tungsten carbide and cobalt in the innovative brake discs [51]. Use of metals and minerals such as cast iron, steel, brass and copper were also found to exacerbate impacts under the resource scarcity indicator. However, the use of recycled components and the current industrial practice of recycling brake discs by 90% by mass, has led to a neutralising some of the key environmental burden from this phase.

2.1.3.2. Use-stage impacts

Use-stage emissions were mainly focussed on evaluating and quantifying both exhaust (from fuel consumption) and non-exhaust emissions (brake wear emissions) [51] [57]. These emissions were quantified over an assumed baseline vehicle service life of 240,000km. Due to the lack of standardised approach or guidance in terms of the most appropriate drive cycles, the authors of this study adopted an emission factor for brake wear particulate release of 7.6mg/vkm[13] [51]. The brake discs, usually made of material with high-wear resistance, are expected to last longer than brake pads over a vehicle’s lifetime. In the comparative LCA between conventional brake discs and the innovative brake discs designed for longer life and lower particulates generation, Gradin and colleagues accounted for the differences in the number of replacement brake components needed in the brake system use-stage modelling [51]. This study accounted for the need for 1.5 times more conventional brake discs, relative to the one innovative brake disc for one vehicle lifetime service. Owing to the high wear rate of the brake pads during use phase, four

[13] Vehicle kilometre

additional brake pads were assumed required [49] [51]. Gradin and colleagues (2019) study also undertook additional sensitivity analysis focussed on the impacts from varied rate of brake wear and the need for additional brake pads to keep up with a vehicle's potentially extended service life at 330,000km. Their investigation identified that the innovative material formulation improved the service life and reduced the overall amount of brake wear particles released. Over longer vehicle lifetimes, the new disc brakes were also able to reduce the rate of particulate formation significantly (by 42%), compared to the conventional brake discs.

No clear distinctions are made on the destination of particulates originating from the brake discs or pads, in the environment, from sampling study undertaken by the reviewed articles [10] [27] [58]. Kole et al (2017) have found predominantly a heterogenous mix of water and soil contaminants which include synthetic polymers, rubber, zinc, road wear, in addition to brake and tyre wear. However, similar to the tyre wear, brake wear materials are found in higher concentrations immediately by the road banks, whereas some are found to be transported by run-offs into nearby water bodies [27] [56].

In a baseline scenario, $PM_{2.5}$ and PM_{10} are some of the most commonly reported brake wear emissions metrics which are anticipated to have direct air quality impacts leading to affecting respiratory issues and leaching into harmful chemical in lung tissues [18] [52] [27]. Iron dust has been found to create reactive oxygen species in the respiratory lining tract affecting the performance of antioxidants and metal binding proteins in humans. Moreover, accumulation of these metals in varying particle sizes, particularly the fine and ultrafine fractions, have been found to penetrate through tissues into blood streams and deposit in other organs [58]. Particularly, copper, iron, lead and nickel from brake wear have been documented to toxic effects on green alga *Raphidocelis subcapitata* and altered germination and growth patterns on barley (*Hordeum vulgare*) and white mustard (*Sinapis alba*). [59] [60].

2.1.3.3. End-of-life stage impacts

Worn out brake pads from the maintenance phase and EoL, made of 90% by mass of the steel in the backplate, is subject to metallurgical extraction in EAF (electric arc furnace) steel plants, while the toxic residue from the friction materials remains.

Lyu and colleagues have reported an analysis dedicated to evaluating the feasibility of material recovery as a more sustainable option from two viewpoints [49]. First, this study quantifies the environmental impact of recycled brake pads through an LCA, however, only in terms of two indicators: CO_2 footprint and energy consumption. Secondly, the authors evaluate the tribological (friction and wear performance) properties of the recycled brake pads in terms of coefficient of friction (CoF), wear and particulate emissions rate, compared to that of the virgin pad's performance. This study reported roughly 36% of CO_2 savings and 34% savings in energy consumption, compared to virgin brake pads, stemming from some level of virgin material displacement. In terms of tribological (friction) performance, the recycled brake pads were observed to demonstrate very similar wear and particulate emission rate compared to that of the virgin pads. It is crucial to note that these results are based on experimental tests and may not be adapted for industry practice yet. In contrast, Gradin and colleagues captured the end-of-life management of worn-out brake discs and pads via 14 different impact categories [51].

2.1.3.4. Overall Life Cycle Environmental Performance of Brakes

Review of the identified literature provides the following highlights and key areas for further exploration:

- Manufacturing or production phase of brake discs and brake pads is observed to be the most polluting life cycle phase over a brake systems' life cycle; Innovative material formulations used in designing brake discs and pads and processes/ activities involved in component production influence the production phase environmental footprint of these components.
- In the limited LCA studies reviewed, key impacts associated with the production, use and end of life routes of brake discs and pads were captured by a range of LCA impact indicators. However, the dominant contributors of environmental burdens were captured by: Global warming potential (GWP), acidification and cumulative energy demand (accounting for high energy demand in the production of brake discs) and mineral scarcity (accounting for production of iron, brass, tungsten and cobalt required for brake pad production).
- Use phase was the second most polluting life cycle stage across the life cycle of brake systems. This has however, been investigated only for semi-metallic brake pads. Similar investigations need to be undertaken for all types of brake pads to be conclusive in terms of lifetime environmental performance.
- Iron, brass and synthetic silica are some of the most commonly found components in the composition of brake wear dusts. The composition of brake wear emissions is highly influenced by the material formulation of brake

pads and discs. Accumulation of these metals in varying particle sizes have been reported with, particularly, the fine and ultrafine fractions being found to penetrate through tissues into blood streams and deposit in other organs.

- Increase in local temperatures of just +15°C over a critical temperature (typically between 150-250°C) has been found to exacerbate brake wear particle number emissions by about 5,000 times, these temperatures can be reached in high speed or repeated braking conditions even in normal driving. Therefore, formulations and design considerations that aid local temperature dissipation/ diffusion when brakes are engaged is crucial for brake wear reduction and dust control.
- None of the studies provide a comprehensive coverage of EoL routes for brake discs and pads, despite including this life cycle stage as a part of the analysis. Review of the identified but limited literature provided no compelling evidence of significant environmental impact from this stage, despite the current global practice of disposal of used and worn-out brake pads in landfill. Some studies have evaluated the feasibility of their recovery for the production of recycled brake pads and incineration of a fraction of the collected brake pads with energy recovery. These investigations seem to retrieve no substantial evidence on the environmental significance of either of these resource efficiency strategies.

2.2. Current and proposed regulations and standards

2.2.1. Approach

A review of legislation, policies, and standards that align to the goal of achieving environmentally optimum tyres and brakes was carried out, covering:

- Regulations in or affecting the UK, both current and future proposals
- EU regulation (where different from UK) and future proposals
- International standards, current and in development
- Notable regulation or policies from the US or Japan
- Non-regulatory voluntary standards, certification, labelling, or consumer information schemes

The review identified legislation, policies and standards that have relevance to the environmental impacts of tyres and brakes, and a selection of literature sources that explain or comment on them. In addition to the standard literature review methodology described in Section 1.3.1, Ricardo experts were consulted to identify an initial list of relevant regulations and standards, which was then expanded on through desk research.

Index tables were developed listing each of the identified legislation, policies and standards relevant to the UK and other regions (see Appendix 2 – Regulations and standards index) .The tables provide a high-level summary and include details and attributes of each mechanism including the regional scope, life cycle stage affected, and overall relevance to the environmental impacts of tyres and brakes. This index provides the key output for this section.

2.2.2. Summary of regulations and standards identified

The index tables (see Appendix 2 – Regulations and standards index) provide a full list of all 50 regulations and standards identified as part of this review. Of the 50 measures, 34 apply to the UK, 45 are published/current, while five are in the proposed/draft stage. In terms of breakdown by life cycle stage[14], 13 apply to production, 35 apply to use, and 14 apply to end-of-life. Table 2-2 below summarises the breakdown of the number of measures that apply to each of the life cycle stages and their relevance to tyres and brakes.

[14] Note that some measures apply to multiple life cycle stages.

Table 2-2: Breakdown of the number of identified standards and regulations between life cycle stages and relevance to tyres and brakes

Life cycle stage	Production	Use	End-of-life
Tyres only	5	17	7
Brakes only	-	7	-
Both Tyres & Brakes	8	11	7
Total	***13***	***35***	***14***

A review of the legislation, policies and standards that were identified as most significant and relevant to this study from the index is provided in Section 4.

2.2.3. Literature sources reviewing regulation and standards for tyres and brakes

Several key sources of literature provided useful overviews and assessments of legislation, policies and standards related to tyres and brakes. These were drawn upon for this review and used to identify some of the measures captured in the regulations and standards index. This section provides a brief overview of this key literature. Insights from these literature sources are used further for the assessment in Section 4.

A paper by Trudsø et al. (2022) on 'the need for environmental regulation of tires' [61] maps the EU regulations that apply along the life cycle of tyres and discussed various advantages and disadvantages of each from a technical perspective. The list of relevant EU regulations provided span from 1996 until 2022, and includes regulations related to raw materials, tyre production, tyre use, and end-of-life tyres (ELTs). The authors of the study note that tyre wear particle sustainability needs to shift focus from recycling and material sourcing to abrasion and chemical constituents, since these particles and the leaching of their chemicals should warrant environmental regulation.

A document produced in collaboration between the UK government and industry associations, "Used Tyre Recovery: An introduction to applicable regulations in England and Wales" [62], sets out the practical implications of regulations applying to end-of-life tyres to give businesses a clear understanding of their responsibilities. Eleven regulations are referenced spanning from 1989 to 2011. They particularly apply to retailers for part-worn or re-treaded tyres, vehicle dismantlers, tyre waste collection, waste storage and processing and importer/exporters of waste. Most regulations are from an environmental and general waste management perspective. There are also two sets of safety regulations and two sets of regulations applying specifically to vehicle tyres.

A paper by Grigoratos (2018) on "the regulation on brake/tyre composition" [63] summarises the situation regarding the existing regulations around the world on tyre and brake composition. Key pieces of legislation mentioned include asbestos-related regulations which mainly affects brake pad composition, REACH and REACH-like regulations which affect tyre composition, the European regulation on classification, labelling and packaging of chemical substances and mixtures; and other regional regulations restricting the use of trace elements and heavy metals.

A paper by the OECD (2022) on the "policy responses to tackle particulate matter from non-exhaust emissions" [64] contains several sections that review existing measures aimed at reducing non-exhaust emissions. They highlight the issue of non-exhaust emissions and the lack of public policy addressing PM from non-exhaust emissions compared to traditional exhaust emissions. The list of regulations cited within this review span both European policy and others worldwide that consider both tyre and brake manufacturing and restrictions on the level of trace and heavy metal content. The authors also note that the insights from the findings of their report stands at odds with prevailing policy stances regarding electric vehicles and note that EV's are generally exempt from policies that discouraging the use of conventional vehicles, but since they emit similar levels of non-exhaust PM emissions to conventional vehicles, policymakers must exercise caution regarding policy approaches that provide blanket support for electric vehicles.

The Japanese Automobile Tyre Manufacturer's Association (JATMA) in their 2023 report [65] on the tyre industry in Japan reviewed several of Japan's regulations and standards relating to the safety and the environmental impact of tyres. JATMA produces its own tyre standards that promote the standardisation, simplification and unification of tyre use. They also work in collaboration with the Ministry of Land, Infrastructure, Transport and Tourism on safety standards, including the "Safety Regulations for Road Vehicles and their detailed items". Additionally, there are legal limits on tread wear highlighted in the "Safety Regulations for Road Vehicles", for passenger car and light truck tyres, the minimum groove depth limit is 1.6 mm. Environmental considerations are also mentioned in the report. A system in operation since 2010 was established as an industry voluntary standard to classify rolling resistance performance and wet grip performance based on a grading system, this is labelled on tyres for the purpose of providing consumers with easy-to understand and relevant information. JATMA have also developed a third version of their "Tyre $LCCO_2$ Calculation Guidelines" in 2021 which complies with international standards and explains how to calculate GHG emission throughout the entire lifecycle. It aims to use these standards to publicise the benefits of resource usage saving and CO_2 emissions reduction.

In December 2023, the European Tyre and Rubber Manufacturers' Association (ETRMA) produced a document commenting on the European Commission's proposal on circularity requirements for vehicle design and on management of end-of-life vehicles [66]. They viewed the revision of the End-of-Life vehicles directive (ELV) as a good opportunity to address concerns that have been observed such as a conflict in the interaction between the ELV and the Extended Producer Responsibility (EPR) systems: this conflict has led to a portion of the tyres from the ELV being introduced to the replacement market without paying a recycling fee. They stress the importance of the synchronisation of the legislations to avoid double regulation. For example, the European Commission's intention is for tyres to be considered under the eco-design for sustainable products regulation (ESPR), as opposed to the ELV, due to it providing a better framework for addressing all the aspects of tyre eco-design comprehensively.

2.3. Performance optimisation, trade-offs and conflicts

2.3.1. Tyres

2.3.1.1. The demands and constraints of tyre design

The performance of tyres is essential to road mobility since tyres are the only contact point between the vehicle and the ground [67]. Tyre attributes affect the tyre and vehicle performance, such as manoeuvrability, ride comfort, noise, durability, rolling resistance (and so vehicle fuel/energy consumption), wear rate, and traction, cornering, and braking performance [67]. These attributes are shaped by tyre design features, construction methods, and materials, and are optimised through research and development by manufacturers according to their objectives.

The key components of tyres and their impact on performance include:

- **Tread:** Provides traction, braking and cornering grip (essential for safety) and has a considerable impact on rolling resistance.
- **Inner liner:** Designed to keep air inside the tyre it is important to ensure safety, to optimise fuel consumption, and prevent oxidation of the internal tyre components.
- **Body plies:** Provide the tyre with strength and flexibility and ensure the tread is kept flat on the road.
- **Beads:** Ensure the tyre is seated properly on the wheel rim and helps maintain an airtight fit.
- **Side walls:** Protects the casing from external damage and atmospheric conditions and connects the tread to the bead. The tyre wall stiffness affects vehicle ride and handling.
- **Belt:** Provides stiffness to the tread and protects the tyre carcass.

In the UK, as in Europe, tyres are assessed according to standards and labelled for consumer information according to three attributes [68] (further details provided in Section 2.4.1):

- **Fuel consumption:** Rated from A (highest performing/lowest consumption) to G (lowest performing/highest consumption). For internal combustion engine vehicles using fossil fuels, higher fuel consumption translates into higher GHG emissions. A 10% reduction in the rolling resistance of tyres can lead to an average fuel savings of 1.5% to 2% [69], although this is dependent on the vehicle baseline fuel economy, the original tyre's rolling resistance, and the distance driven [70].
- **Wet Grip:** Rated from A (highest performing) to G (lowest performing). Better performing wet grip improves safety in wet conditions, although it should be noted that performance in wet and dry conditions may not be correlated – a tyre optimised for dry performance may not be optimum in the wet.

- **Noise:** A measure of the noise from outside the vehicle (of the vehicle passing), that is, the contribution to environmental noise levels. This is provided as a decibel level (higher = more noise)[15].

Tyre **wear or abrasion rate** is not currently subject to standard assessment in the UK (or Europe). However, there is a well-established “treadwear” rating in use in the USA which assesses the life of a tyre compared to a standard baseline [71], and a UN ECE task force is looking at establishing a standardised measurement method for tyre abrasion performance[16] which could enable labelling and/or limits to be introduced in Europe. The European Commission Euro 7 proposals[17] include reference to tyre abrasion limits, although the limits and measurement standards are not yet defined. A tyre abrasion test is being developed under the auspices of the UN ECE[18]

Several studies describe what is referred to as the ‘magic triangle’ of tyre properties (Figure 2-8), which refers to the relationship between the three main tyre performance parameters: rolling resistance (fuel efficiency), wet grip (safety), and abrasion/wear resistance (tyre life) [25] [72] [73] [53] [74]. These performance parameters are described as being connected so that improving one parameter will generally worsen at least one of the other two, leading to trade-offs when optimising these parameters [25].

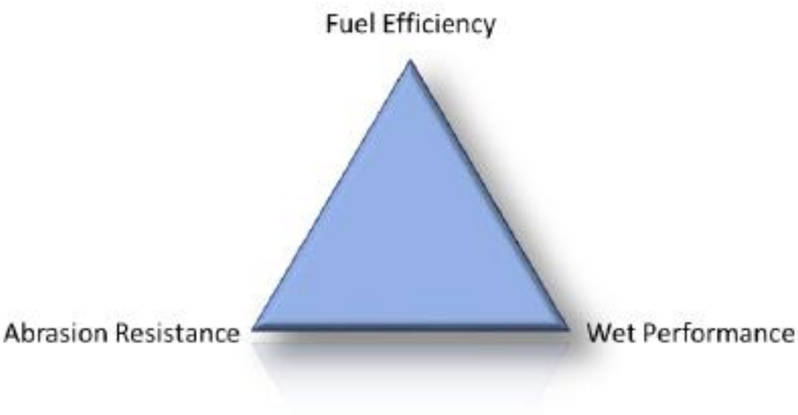

Figure 2-8: The tyre performance 'Magic Triangle'; Source: [74]

A study by ADAC investigated the correlation between tyre abrasion and tyre performance of existing tyre models [75]. When comparing summer tyre test results of the same brand between 2019 and 2022, the study found that tyre safety improved for most tyre manufacturers, seemingly at the expense of tyre wear which also mostly increased. In some cases, the study also found that certain tyre models demonstrated a decrease in their abrasion, while safety characteristics became weaker. For example, the Continental EcoContact 6 showed a 52% reduction in wear, but its ratings for dry and wet road surfaces both worsened slightly.

A study that reviewed mitigation measures to reduce tyre and road wear particles noted that “the only way” of overcoming the compromises between two or three of the ‘magic triangle’ parameters at the same time is through the development and use of innovative materials, such as silica (see Section 2.3.1.2) [25].

Noise is seen as an additional parameter to be considered, which may have an impact on the other three parameters [74]. A review of studies by the STEER (Strengthening the Effect of quieter tyres on European Roads) project found that some studies have determined a conflicting relationship between noise and wet grip, while others have found no significant correlation between these parameters.

2.3.1.2. Technologies to reduce the use-phase environmental impacts of tyres

Nanomaterials: Silica and nanoclay as filler materials

The replacement of carbon black, which was the main reinforcing agent for tyres, with silica was found to be the most frequently mentioned measure in literature to improve tyre performance [69]. Compared to carbon black, silica shows

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[15] In Northern Ireland as in Europe, the label also classifies the noise rating from A (the highest performing) to C (the lowest performing).

[16] See https://wiki.unece.org/display/trans/TF+TA+Terms+of+Reference

[17] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0586

[18] See GRBP-78-17e.pdf (unece.org)

a greater increase in abrasion resistance performance when used as an additive in tyres [76] [77]. The addition of silica made it possible to improve rolling resistance compared to tyres that only contained carbon black, without compromises on grip and safety [69]. Silica reinforced rubber has lower hysteresis at lower frequencies and higher hysteresis at higher frequencies compared to carbon black, which leads to tyres that use this material having lower rolling resistance and higher traction [69]. While standard silica was used in the early stages of the technology's development [25], Highly Dispersible (HD) silica is currently used as it shows superior wear resistance and improvements in wet grip and rolling resistance [69].

Another nanomaterial that has been shown to improve tyre performance is nanoclay, which can be dispersed in the rubber of the tyre's inner liner [25]. The loss of tyre inflation pressure can greatly increase rolling resistance [25]. Nanoclay can minimise the loss of inflation pressure since it reduces the permeability and air loss through the tyre's inner liner, thereby inhibiting an increase in rolling resistance [69] [25]. A conservative estimate for the reduction in air permeability for nanoclay inner liners was stated to be 30% when compared to conventional liners [69].

An OECD report on nanotechnology and tyres conducted a case study and analysed a new generation silica technology, known as HD-HS silica, and nanoclays for tyres in terms of their rolling resistance, wear resistance and wet grip [69]. The results are summarised in Table 2-3 below, indexed against carbon black [69].

Table 2-3: Summary of OECD case study on nanomaterials in tyres; Source: [69]

Nanomaterial	Tyre performance benefits		
	Rolling resistance (fuel use)	**Wear resistance (tyre life)**	**Wet grip (safety)**
Carbon black (mature market stage)	Index	Index	Index
Conventional HD Silica (mature market stage)	✓✓ (up to 25% improvement)	✓✓ (up to 20% improvement)	✓ (up to 10% improvement)
New generation HD-HS Silica (market entry)	✓✓ (up to 30% improvement)	✓✓ (up to 20% improvement)	✓ (up to 10% improvement)
Nanoclay (market entry)	✓ (a few per cent improvement)	✓ (a few per cent improvement)	-

Key:
- : indicates negligible improvement relative to carbon black
✓ : indicates some improvement (<10%)
✓✓: indicates significant improvement (>10%)

As shown in the table, the use of conventional HD silica and new generation HD-HS silica both showed improvements in all tyre performance parameters, with HD-HS silica being superior in terms of rolling resistance [69]. However, key barriers noted with these materials were that HD silica and nanoclays have higher costs, while HD-HS silica had significantly higher costs. These costs may decrease in the longer term as production capacities increase and processes improve [69].

The OECD study also conducted a cost benefit analysis of the new nanotechnologies compared to incumbent nanotechnologies (carbon black and conventional HD silica) in tyres between 2015 and 2035. While the tyre purchase costs for OEMs and replacements by vehicle owners would increase with these new technologies, the study found that consumers would experience a net benefit due to longer tyre lifetime and fuel savings [69].

A study by Kocher [78] also confirms that silica reduces abrasion rates for tyres. However, the author notes that there is generally a correlation between abrasion rate and the size of the emitted particles, which means lower abrasion rates predominantly cause smaller particles (i.e., fine fraction). This correlation is specific to mass contributing particles and to loss related to abrasion and not other mechanisms. The study notes that this relationship could lead to silica-containing tyres increasing finer particulate matter emissions [78].

Tread design

Tread design and patterns have a key influence on the noise and wet grip of tyres [72] [74] [79]. The wet grip of tyres is influenced by the ability of the tread's design to channel out water from the footprint area of the tyre, such as through sipes (thin slits across the tyre surface) and grooves to reduce aquaplaning [72]. A report by ADAC noted that aquaplaning features are linked entirely to tread design and depth and not on the rubber compound used for the tyre [75].

A study by STEER [74] developed three prototype tyres to optimise noise through a two-step approach. First, a tread pattern that was favourable to reducing noise was selected, followed by two additional improvements that related to increasing the amount of damping material in either the tread or sidewall of the tyre. The experiment found that the best compromise to improving noise performance was the redesigned tread pattern. However, this was found to have a negative effect on wet performance. The study noted that while tread pattern design modification was found to be the most effective improvement, it is also the most complicated due to the process of making tyre moulds [74]. The report also notes that changes to tyre moulds after production are “hardly possible”, which may limit the implementation of small changes to tread design which would be required for these potential improvements [74].

Another study investigated the optimisation of noise (airborne and structure-borne), vibration and harshness of tyres for future mobility through a full factorial Design of Experiment approach, and focused on tyre pattern, structure and tread compound [79]. As the study notes, airborne noise is caused by two primary mechanisms, impact noise and aero-acoustic noise (also described in Section 2.1.2.2). Impact noise mechanisms include pitch impact noise, scrubbing noise, stick-slip noise, stick snap noise [79]. The aero-acoustics noise in tyres is due to pipe resonance of various ‘pipes’ that exist in tyre’s tread pattern. The study found that circumferential groove width (Figure 2-9) was a key factor affecting pipe resonance noise, with noise decreasing with narrower grooves [79]. This conflicts with the requirements of larger grooves needed to avoid aquaplaning. The study noted that an optimisation approach would be required to improve airborne noise and the approach could use a database of different tread patterns and sizes [79]. The study also found that the lateral groove angle is critical to pitch impact noise while lateral groove width was key to scrubbing noise.

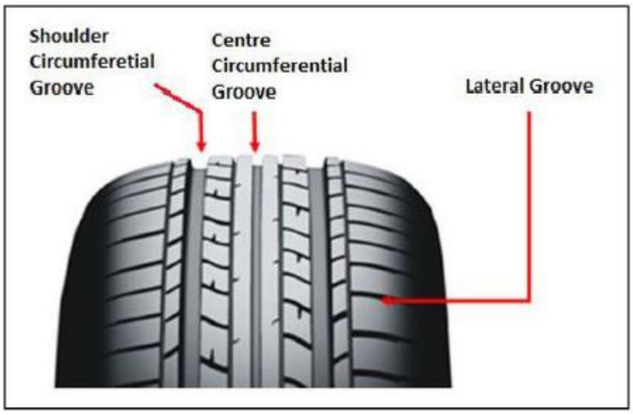

Figure 2-9: Schematic of circumferential and lateral grooves in tyre tread; Source: [79]

Manufacturing methods to improve environmental properties

Elimination of vent spews

The report by ADAC on tyre wear particles in the environment provides an overview of production residues that may be found on some new tyres [75]. The thin rubber threads (see Figure 2-10 [75]), known as vent spews, are a result of the production process, and lead to an increased loss of material through wear during the initial kilometres driven with the new tyres. Since these production residues have no technical benefit to tyre performance, they are an unnecessary environmental emission. The report states that these threads could be removed easily through an additional production step or manufacturing procedure. A study that reviewed different mitigation measures for tyre and road wear particles noted that information on the mass of these residues and the proportion of tyres that contain them were not found in their review of literature [25]. The authors of the study stated that the removal of these residues could be a cost-effective measure to reduce rubber particle emissions from tyres.

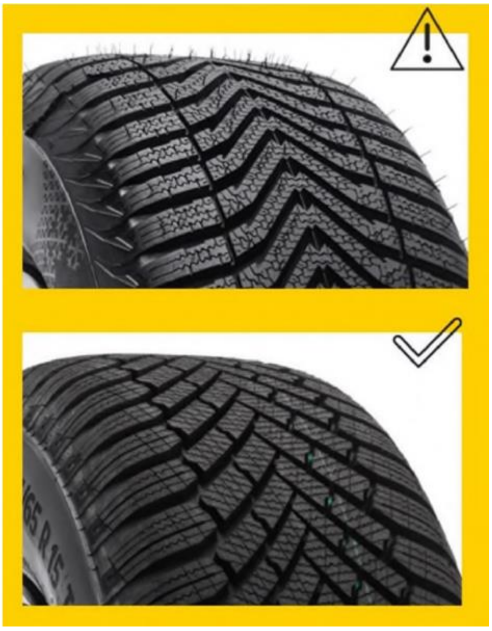

Figure 2-10: Tyre shown with (top) and without (bottom) vent spew threads; Source: [75]

Porous tread tyres

A report by FEHRL (Forum of European National Highway Research Laboratories) [80] provided an overview of a project led by VTI (Swedish National Road and Transport Research Institute) that examined the possibility of replacing a conventional patterned tyre tread with a porous tread to reduce tyre noise [81]. The FEHRL report stated that speculations and earlier testing indicated porous tread tyres might have excellent wet friction and rolling resistance properties but may have poorer wear. The first prototypes produced in 2014 are shown in Figure 2-11 [80].

Figure 2-11: Two porous tread tyre prototypes (right) alongside regular tyres (left) used as carcasses for the porous tread; Source: [80]

Testing of the porous tread tyres showed that noise emissions were very low on surface textures typical of Swedish highways with a noise reduction of around 7 dB(A) compared to two commercial reference tyres [82]. Rolling resistance was also found to be 10% lower than the best performing tyre (Michelin Energy 3A) that had been measured at the time of the study in 2005 [82]. However, wet friction was found to be poorer than the reference tyres. The study mentions that there was potential to improve wet friction performance if high-quality rubber compounds were used instead of the low-quality recycled rubber that was used to produce the first prototypes.

Non-pneumatic (airless) tyres

Alternative tyre technologies such as non-pneumatic tyres (NPT) have been proposed as an alternative to traditional tyres to address their shortcomings. Various performance and environmental advantages have been identified with one of the most acclaimed potential benefits of NPTs being their low rolling resistance. This is caused from an increased tyre stiffness which reduces energy loss from hysteresis [83]. However, there remains limited knowledge in the development of NPTs in literature. Substantial amounts of NPTs currently are still restricted to low-speed applications. In addition, lateral and longitudinal stiffness have hardly been studied and ongoing research is taking place as they could be related to fundamental breakthroughs for optimising tyre performance.

The reduced energy consumption from optimised rolling resistance is not the only sustainable aspect of NPTs of note, benefits can come from reduced energy and material consumption during production, maintenance and an increased recycling potential. In terms of manufacturing, the vulcanisation process used to obtain the rubber material that is present in traditional tyres imposes a permanent change in the molecular structure of the material, making them economically difficult and complex to recycle. Many NPT proposals are based on plastic polymers; in which a generally simple and low energy-demand process is employed to produce the tyre. However, this presents an issue from the perspective of plastic waste and the biodegradability of materials. Meanwhile, when considering the end-of-life, contrary to traditional tyres, many NPTs that have been proposed are often composed of a single and easily recyclable material such as thermoplastic polyurethane (TPU), which could solve the recyclability issue of rubber tyres, while addressing the environmental impact of tyre production and contributing to more sustainable and efficient use of resources. Furthermore, as NPTs can reduce the number of punctures and wear from inadequate air pressure, the number of tyres that are scrapped before reaching their life expectancy will be diminished.

Various large tyre manufacturers have recently produced and tested the concept of non-pneumatic tyres. Michelin developed an airless integrated tyre (called Tweel), which used strip spokes instead of air pressure. The performance of a Tweel tyre is similar to that of a traditional tyre [84]. More recently, they have developed a new generation of prototype airless tyres that is able to reduce the risk of flat tyres and other air loss failures [85]. It can replace traditional pneumatic tyres in certain scenarios from the perspective of comprehensive performance. Bridgestone announced in 2022 the development of prototype non-pneumatic tyres for the passenger vehicle market [86]. Their design simplifies the structure the tyre and thus minimises the energy loss and the corresponding rolling resistance.

2.3.1.3. Technologies to reduce the manufacture and end-of-life environmental impacts of tyres

Sustainable sourcing of materials

Alternative rubber matrix materials

Several different sustainable rubber matrix materials have been explored as an alternative to the existing source of natural rubber, *Hevea Brasiliensis* (rubber tree), used in commercial mass production of tyres [72]. Similar species include dandelions and guayule [72]. For instance, Russian Dandelion roots contribute approximately 15% of the latex as that of rubber trees and shows improved performance in wet grip of tyres [72]. Guayule has similar constituents to natural rubber, and has an added advantage of requiring less time to harvest than Hevea Brasiliensis trees [72].

Green silica

Shoul et al. [16] provide a comprehensive overview of literature investigating the potential use of green silica in the tyre industry. Green silica is proposed as an eco-friendlier alternative to standard silica, and is produced using plant materials, such as rice husk ash, sugarcane bagasse, bamboo leaf, and corn stalks. The main advantages of green silica include its availability, the low cost of agricultural waste, the decrease in energy consumption, and the elimination of chemical substances [87]. Green silica production has been reported to reduce associated CO_2 emissions between 20-50% compared to the production of conventional silica [88] [89]. The production of green silica also has the advantage of recycling a large amount of agricultural waste that contains silica, therefore enabling a more circular economy [16]. An assessment by Should et al. found that shifting from commercial silica to bio-waste green silica could reduce the consumer price of tyres by more than 1 USD [16].

Other natural reinforcing fillers

The partial replacement of carbon black with natural fillers can reduce the eco-toxicological effects of tyre rubber associated with carbon black [72]. Different properties of tyres, such as low rolling resistance, weight, durability, ease of fabrication and energy conservation have also been altered and improved through the use of natural fillers [72] [90]. These bio-derived fillers included cellulose, lignin, cellulose nanocrystals, cellulose nanofibres, starch, eggshell, and pistachio shell. [90]

Reduced waste

Materials to improve ageing resistance

Over the lifetime of tyres, increasing abrasion resistance can also improve ageing resistance (increasing tyre life), normally through the addition of additives to the rubber compound used in tyres [57]. As summarised in a review study [25], additives can slow down or prevent different ageing processes such as those due to biological degradation [91], UV light, moisture, oxidation by ambient oxygen [92] and ozone [93]. The review study notes that conflicts may be found when preventing tyre rubber from ageing from biological degradation, since biodegradability of tyres may be key to their end-of-life sustainability. Stevenson et al. [94] noted that it may be favourable to improve the biodegradability of rubber material for this reason, however, it might not be possible to reduce levels of some microbial-inhibiting additives without compromising tyre performance and safety.

Self-healing materials

Several studies have looked at the use of self-healing materials for tyres which can increase the life of tyres by sealing damage due to punctures or cracks that could otherwise render the tyre unsafe or require early replacement [25]. The process involves adding substances to modify the tyre rubber and allow it to compensate for the damage and ageing processes [95]. One approach involved transforming conventional bromobutyl rubber (BIIR) into a highly elastic material that could also regain its original properties through the self-healing process, as proved with a cut sample [96]. Another study showed that self-healing could be achieved by modifying BIIR with butyl imidazole [97]. Adding ground tyre rubber to styrene-butadiene rubber (SBR) was found to enable self-healing while also reducing rolling resistance and maintaining wet grip [98]. A review paper that provided an overview of these studies noted that detailed information on the impact of self-healing tyres on tyre wear could not be found [25].

Reuse, recyclability, and use of recycled content

Retreaded tyres

According to the authors of a study looking at trends for green tyres, customers can save up to 40% when buying retreaded tyres compared to new [72], although new ranges of budget tyres are very cost competitive which has led to re-treading becoming less relevant. Additionally, since only the tread of the tyres is replaced during the re-treading process, damage to the chord area (including sidewalls) of the original tyres can affect the retreaded tyres' lifetime.

The STEER (Strengthening the Effect of quieter tyres on European Roads) project final report discussed some of the complications related to retreaded tyres compared to new tyres [74]. Since retreaded tyres involve new tread being fitted to different tyre carcasses, it can cause uncertainty in the labelling of these tyres. The report states that the performance will primarily depend on the new tread, and the carcass will have negligible effect on noise and wet grip but may have a more significant effect on rolling resistance. The authors suggested that reasonable limits may need to be introduced for the carcasses to limit the effect they may have on rolling resistance [74].

Recyclability and use of recycled content

As mentioned in Section 2.1.2.3, pyrolysis of ELT rubber can produce tyre pyrolytic oil (TPO), which can then be distilled into sustainable pyrolytic carbon black (CBp) [99]. The European Horizon 2020 funded project, BlackCycle[19], aims to design processes to develop new tyres from ELT, and aims to use CBp in new Michelin tyres as a more sustainable raw material [100]. While assessment of sustainable tyre performance is part of the project's scope [101], no results had been published at the time of writing this report. A study by Wu et al [99] noted that pyrolytic products may have some drawbacks, for example, CBp has high ash and sulphur content, poor micropore structure, and carbonaceous residues on the surface, which can hinder its use.

Rubber granules from shredded scrap tyres can be devulcanised and used in the production of new tyres [102]. A review by Asaro et al. [102] provides an overview of the different devulcanisation processes that can be used to process tyre rubber, including chemical, ultrasound, microwave, mechanical, and thermomechanical processes. For industrial scale processing of tyres, the study notes that thermomechanical devulcanisation based on extrusion seems to be the most suitable [102]. According to the study, devulcanised rubber can be mixed with virgin rubber or other kinds of matrices without causing any major reduction in material properties.

Another EU funded consortium, WhiteCycle[20], aims to recycle polyethylene terephthalate (PET) from complex waste, including that from tyres, and could be used in producing new tyres.

[19] See https://blackcycle-project.eu/about-the-project/
[20] See https://www.whitecycle-project.eu/project

2.3.2. Brakes

2.3.2.1. The demands and constraints of brake design

Brake system design

Two brake system configurations have been widely used in modern passenger vehicles: disc brakes, in which flat brake pads are forced against a rotating metal disc, and drum brakes, in which curved brake shoes are forced against the inner surface of a rotating cylinder [103]. Modern passenger vehicles are usually equipped with disc front and rear brakes, while in the past, drum brakes were usually employed as rear brakes. It is estimated that front brakes have to provide approximately 70% of total braking power and therefore have to be replaced more frequently than rear ones.

Brake friction pads/linings typically consist of five primary components: binders, fibres, fillers, frictional additives or lubricants, and abrasives [104]:

- Binders are responsible for holding the brake pad components together, ensuring structural integrity under mechanical and thermal stress. They make up around 20-40% of the lining material and are typically composed of modified phenol-formaldehyde resins.
- Reinforcing fibres provide mechanical strength and structure to the brake lining, accounting for 6-35% of the material's mass. These fibres can be metallic, mineral, ceramic, or organic, including materials like copper, steel, brass, potassium titanate, glass, and organic substances such as Kevlar.
- Fillers are used to enhance thermal and noise properties while reducing manufacturing costs. They typically include inorganic compounds like barium and antimony sulphate, magnesium and chromium oxides, silicates, ground slag, stone, and metal powders, constituting 15-70% of the lining material by mass.
- Lubricants impact the wear characteristics of the lining and can be inorganic, metallic, or organic. Common materials include graphite, ground rubber, metallic particles, carbon black, cashew nut dust, and antimony trisulfide, making up 5-29% of the brake lining material by mass.
- Abrasives are used to increase friction, maintain cleanliness between contact surfaces, and prevent the build-up of transfer films. They typically account for up to 10% of the lining material by mass and include substances like aluminium oxide, iron oxides, quartz, and zircon.

The proportions of these components vary depending on the type of lining and the manufacturer. In passenger vehicles, three main types of brake linings are commonly found [104]:

- Non-asbestos organic (NAO), semi metallic, and low metallic. NAO pads are relatively soft and produce less brake noise but exhibit reduced braking capacity at high temperatures and tend to create more dust. Asbestos-free materials are used due to health concerns arising from asbestos[21].
- Low-metallic pads combine organic compounds with small amounts of metals (10-30% by mass), offering high friction and good braking capacity at high temperatures. Semi metallic brake pads contain a higher metallic content (up to 65% by mass), providing durability and excellent heat transfer but potentially causing higher rotor wear and noise issues.
- Semi-metallic linings are used in high-performance or demanding braking conditions due to their heat resistance and as such may be preferred in performance and premium vehicles. Steel and copper fibres are common materials employed.

Rotor/disc material

The most common brake rotor (disc) material is grey cast iron (GCI). It has excellent thermal characteristics, wear resistance and mechanical strength and is also cheap to manufacture [105]. GCI guarantees a good dry sliding wear resistance due to the combination of high hardness and self-lubricating capability from its graphite lamellae structure. Alternative disc materials such as aluminium-based metal matrix composites, titanium-based materials and ceramic matrix composites based on carbon fibres have been proposed and their performance characteristics have been investigated in various literature. The main drawbacks of GCI relate to its tendency to corrode and its relatively high wear rate during operation, thus contributing to the emission of fine particulate matter PM [106]. The oxide particles generated during braking, due to tribo-oxidation, usually represent more than 50% of the total emitted PM [107].

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[21] The use of asbestos in brake components has been banned since 1999 in the UK. https://www.hse.gov.uk/mvr/mechanical-repair/asbestos.htm

Binder

The binder resin serves as a key influencer in brake performance due to its role in keeping components together as a matrix in a composite. Thus, the kind of binder and its proportion in the brake pad material composition are crucial to meeting the standard requirements for friction materials. Currently, one of the most used materials in brake pads are phenolic resins. This is due to their low thermal conductivity, low density (thus weight-efficient), outstanding fatigue and impact properties and inexpensive manufacturing costs [104] [108]. However, recent advances in brake performance expectations have driven the need for improved friction stability and wear resistance, especially at elevated temperatures. To achieve shorter stopping distances and reduce pad wear in high-temperature brake applications, several chemical modifications to the binder resin have been made. These modifications enhance the thermal stability of brake pad friction materials, resulting in safer braking performance and increased resistance to thermal decay. The improved thermal stability allows the brake pads to withstand compressive forces during braking, maintaining a stable friction coefficient. Consequently, this leads to reduced weight loss and slower wear rates on the brake pads. Generally, brake pads exhibiting a high coefficient of friction offer superior braking efficiency with minimal effort on the brake pedal.

Temperature constraints

The effect of temperature has been a focus and has been demonstrated in previous research studies [109] [110] [110] [111] [111] [111] [112] [113]. Sensitivity to temperature mainly depends on the brake system, pad material, for temperature-sensitive materials, high temperatures may cause it to become unstable and thus altering the frictional state and contact interface of the brake pad and disc [114]. Higher temperatures associated with brake components will typically promote the generation of ultrafine particles and increase particle concentration. Above a certain critical braking temperature, the emission will increase of several magnitude orders in the range 150-250°C (Figure 2-12) [115]. Above this threshold, it is suspected that the emitted particles originate from the degradation and combustion of resin material and of the organic material in the pad binder [116]. An additional consequence of the temperature increase is a progressive shift in the number size distribution towards the ultrafine fraction.

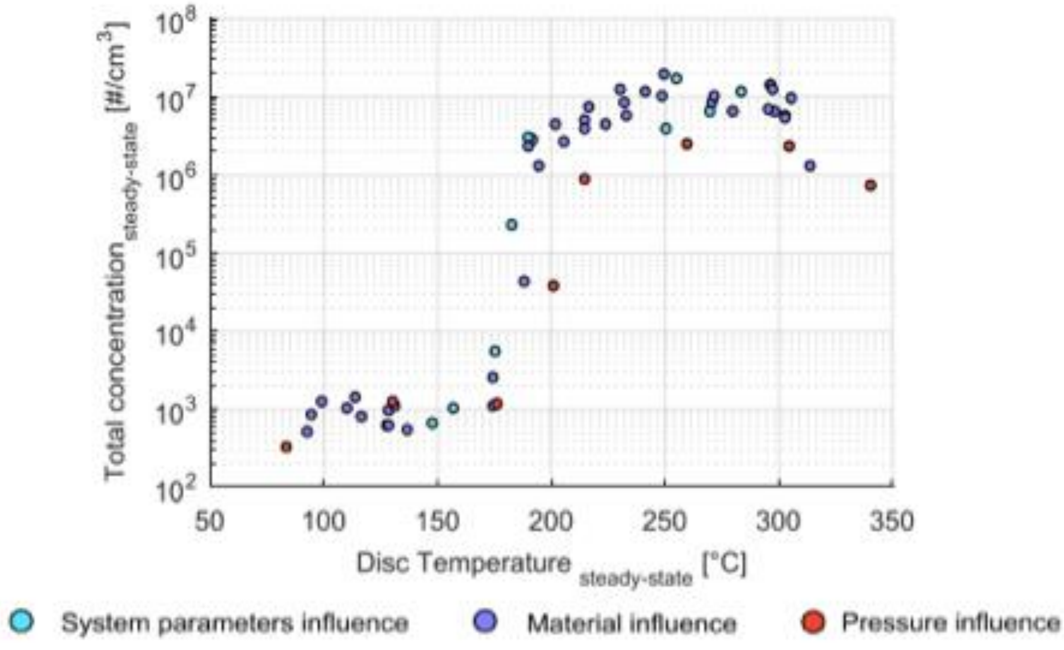


Figure 2-12: Transition temperature for different testing conditions. An emissions increase of several magnitudes occurs in the 150-250°C. Source: Alemani (2017) [114].

To reduce emissions the system temperature should therefore be kept as low as possible, although this is not easily controlled since the ambient temperature and the driving style are the two main influencing factors [114]. Hence, brake system cooling effectiveness is a significant design factor for emissions.

Results also show that the higher brake power results in higher emissions, both in terms of particle number and particle mass. Nominal contact pressure, sliding speed and coefficient of friction do not play a major role when considered alone, but it is when they are combined, giving the developed frictional power, that counts. Reducing the coefficient of friction would not provide any advantage since the driver will increase the nominal contact pressure to provide the same braking power, aiming to brake in a given stopping distance.

2.3.2.2. Technologies to reduce the use-phase environmental impacts of brakes

The application of natural materials in brake pads is increasingly being researched to avoid harmful environmental impacts, although it is important that the use of such material does not negatively affect braking performance. Thus, the following literature researched the application of alternative brake materials and their performance characteristics and its effect on emissions during the use-phase.

A significant project under this scope was the EU's LOWBRASYS project, it was designed with the aim of demonstrating a novel and low environmental impact brake system that would reduce PM and PN emission by at least 50% during the use phase [117]. It considered a series of different technologies, the most important being the introduction of novel material formulations for brake pads and discs. The project concluded that no single technology was able to reduce PM emissions by the 50% target. Rather, a multitude of different technologies would be required to achieve this reduction. A conclusion of the project is that further development is required to advance the proposed solutions from prototype-level technologies to market ready applications.

Coated discs

A promising solution for reducing brake wear and particle emissions is the application of a hard coating on the rubbing surface of the brake disc, the coating improves the mechanical and tribological properties of the disc surface in contact with the pads [118]. Recent advancements in coating materials design emphasise trends towards sustainability due to concerns towards energy and cost savings. With several coating technologies available, there have been a number of studies in literature by various brake system developers and researchers on their performance.

Shi et al. (2021) investigated the use of laser cladding technology as a fast and eco-friendly process to avoid brake disc failure caused by wear [119]. The surface of the brake disc was coated with a Ni-based alloy powder to improve its wear resistance following the use of laser cladding. With a change of the solidification rate and temperature gradient and by comparing the wear rate of the coating and substrate it was found that the coating has improved wear resistance of about 1.5 times that of the substrate, and also shows good oxidation resistance. The oxidation film formed during the wear process of the coating is beneficial to inhibit the regeneration of oxide. Thus, the test results were found to show the laser cladding Ni-based coating is an effective means to improve the tribological properties of the brake disc.

Rajaei et al. (2022) also studied the use of laser cladded brake discs using a Fe-based coating material with manganese sulfide (MnS) added as a solid lubricant [120]. Microstructural and tribological characteristics of the coated discs (with and without MnS) were studied comparatively. Three different friction materials typically used in commercial brake pads were adopted to evaluate the performance of the coatings. The results indicated that, with the addition of MnS, both friction coefficient and wear rate have been reduced to levels comparable with those obtained in case of uncoated GCI discs.

Federici et al. (2017) investigated the tribological behaviour of a commercial semi-metallic friction material dry sliding against an uncoated cast iron disc and a High Velocity Oxygen Fuel (HVOF) coated disc at room temperature and at 300 °C [121]. The HVOF process where fuel gas and oxygen are ignited and used as a thermal spray coating. Two types of disc coatings were investigated, based on chromium carbide (Cr_3C_2-NiCr) and tungsten carbide (WC-CoCr) systems. The results show that the wear rates of the coated discs are always negligible since the contact temperature is not sufficiently high to induce a softening or an oxidative damage of the coatings. In contrast, the wear rates of the commercial friction materials were as expected; mild at room temperature and close to severe at 300°C. The conclusions are that although testing conditions were rather simplified, the results obtained provide useful indications on the possibility of using HVOF coatings in braking systems to reduce not only their wear, but also the release of particulate matter in the environment.

While HVOF is a well-established processing route for depositing metallic binder based coatings [122], coatings processed using relatively new thermal spray technologies such as High Velocity Air Fuel (HVAF) and Suspension Plasma Spray (SPS) have shown promising results under laboratory test conditions [123]. HVAF processed coatings possess excellent bond strength and minimal oxidation due to their relatively lower operating temperatures compared to HVOF coated brakes [124]. These characteristics enable the HVAF sprayed coatings to exhibit superior wear and corrosion performance compared to HVOF sprayed coatings.

The understanding of how the friction coefficient is affected with increasing temperature during a wear test is one of the important characteristics considered in evaluating brake efficiency of coated disc-brakes and was studied by

Altuncu et al. (2020) [125]. Wear and braking performance of a standard, uncoated friction material, a stainless-steel coated disc with laser cladding and a ferritic nitrocarburising (FNC) applied disc were compared. It was observed that the 2 coated discs stayed more stable compared to the friction coefficient trend of the uncoated disc in the wear test (Figure 2-13). This is particularly evident at higher braking forces (and consequently temperature). Accordingly, in all wear performance tests, the friction coefficient trend has generally remained above this value the minimum friction coefficient limit of 0.25 and meets the general requirements, demonstrating the capability of coated discs from a safety perspective. It is concluded that both coating methods of laser cladding and FNC application are solutions that have industrialisation potential following further optimisations. Results from Reddy et al, (2021) also showed that FNC-treated cast iron brake discs have a higher coefficient of friction of 0.27 compared to the than the untreated GCI discs which has a coefficient of friction of 0.24 [126]. However, it was found that FNC-treated GCI brake discs shows higher wear rate than the untreated GCI brake disc.

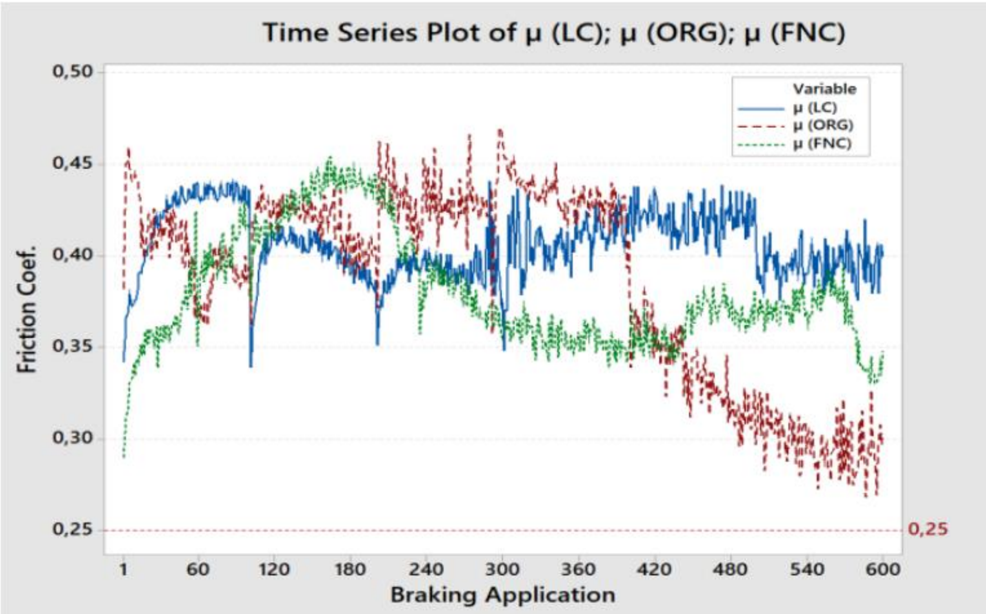


Figure 2-13: Trend of disc-pad friction coefficient for uncoated (ORG), coated (LC) and FNC treated (FNC) at different braking cycles. Source: Altuncu et al. (2020) [125]

Alternative disc and pad materials

Studies on brake wear emissions have so far primarily been carried out with conventional cast iron brake discs from both dynamometer and vehicle tests. However, there is currently a limited number of studies to identify the emission characteristics and emission reduction potential of alternative friction materials.

Below is a summary table of several studies into various brake pad materials and their effect on brake wear and performance.

Table 2-4: Summary of various materials used in brake pads and discs and their wear and braking performance against standard commercial materials.

Reference	Material	Pad or Disc	Wear rate vs conventional	Braking performance vs conventional
Yang et al. (2020) [127]	Addition of zinc (0, 2, 4, 6, 8) wt%	Pad	Wear rate decreases with increasing zinc wt%	Braking noise decreases with increasing zinc wt%
	Molybdenum disulphide	Pad		

Reference	Material	Pad or Disc	Wear rate vs conventional	Braking performance vs conventional
Antonyraj and Singaravelu (2020) [128]	Tungsten disulphide	Pad	Lower wear rate because of better lubrication characteristics	Greater coefficient of friction because of thermal stability
Zhang et al. (2019) [129]	Al_2O_3 fibre additive	Pad	Wear is reduced	Increase in coefficient of friction
Zhang et al. (2020) [130]	Addition of Zn Cu-carbon fibres	Pad	Wear is the smallest	Most stable characteristics
Jeganmohan et al. (2020) [131]	$CaSO_4$ whiskers	Pad		The inclusion of $CaSO_4$ whiskers enhanced the frictional performance during fade.
Perricone et al. (2018) [132]; Wahlström et al. (2010b) [133]	Non-asbestos organic (NAO)	Pad		Stable coefficient of friction
	Low metallic	Pad/disc	Greater and more aggressive wear rate than NAO with a greater mass loss in both pad and disc samples	Higher coefficient of friction
Ahmadijokani et al. (2020) [134]	Carbon fibre-aramid fibre	Pad	Improved wear rate and fade behaviour	Improved coefficient of friction, thermal conductivity and impact strength

As mentioned above, although grey cast iron brake rotors have many advantages, other base materials have gained attention for automotive applications in the last 20 years. Changes to brake pad composition have a large potential for brake wear reduction. Given the wide range of materials available and the possible trade-offs entailed by different compositions (e.g., with respect to friction performance, noise, vibration, etc.), brake pad options including their materials deserve careful consideration on a case-by-case basis. Composition changes should be evaluated carefully since they may involve trade-offs in terms of the types and relative toxicity of particles generated: for example, one modification may reduce the mass of particles emitted but increase their number, or may reduce the metallic particulates but increase the organic content of PM.

The trade-off between brake performance and brake wear particle emissions can only be resolved to a limited extent with the pad mixtures known to date [135]. Brake wear particle emissions can be reduced by using low-wear brake pad mixtures, such as NAO–friction materials. While significantly higher reduction potentials can be expected by using wear-resistant brake discs such as tungsten carbide-coated discs (HMC) or carbon–ceramic discs (CC), the market penetration of these disc concepts is currently limited to use in high-performance sports cars and luxury class vehicles due to the continuing high costs.

The use of aluminium as a base material for brake discs has been proposed due to its lightness (up to 60% weight saving vs GCI), stable friction level, and corrosion resistance. Agbeleye et al. (2020) found that the use of composites including aluminium and a certain percentage of clay in the brake disc can reduce brake wear, because clay particles can act as a solid lubricant [136]. However, Rettig et al. (2020) highlighted concerns over the use of aluminium in brakes are due to its relatively low maximum operating temperature when compared to other materials [137]. At around 400ºC this presents a safety concern during hard or continuous braking applications. Surface modification of the aluminium alloy has been proposed using processes such as thermal spraying and anodising to not only for protection against high temperatures but also improve wear resistance. Aluminium alloy reinforced with ceramic (SiC) particles to form a metal matrix composite (MMC) has also been used to increase the surface resistance and strength of the alloy but again has been found limited to a maximum surface temperature of around 450°C. Another type of surface treatment is plasma electrolytic oxidation (PEO) which provides a good thermal barrier of aluminium oxide because of its low thermal conductivity and good wear resistance. The proposed material must be able to withstand thousands of cycles of reaching temperatures up to 400ºC.

Other research has shown that titanium also has advantageous properties as a brake rotor material. Muthukannan, et al. (2014) discusses the use of titanium brake rotors and compares the performance of commercial grey cast iron with untreated titanium alloy [138]. They find that untreated titanium alloy exhibits significantly higher wear rates and volume losses, presumably due to poor resistance to abrasion processes and severe plastic deformations. Laser treated titanium material, in contrast, shows a much better wear performance in all operating conditions and its frictional behaviour is comparable to that of GCI. No adapted lining material was used in this test, suggesting that wear-reducing potential may be even greater than that measured in the study. However, similarly to HMC discs and CC brake discs, the use of titanium material remains limited, mostly appropriate for niche applications because of the high material and manufacturing costs.

Alternative binders

There are several papers reporting on the use of green and eco-friendly binders, however due to the difficulty of finding suitable alternatives to phenolic resins which is the predominantly utilised form of friction material matrix, few have been found suitable [139].

Lignin has been proposed as an alternative to phenol resins due to their similarities in structure and a more stable friction coefficient. Park et al. (2020) studied three different types of lignin including soda lignin (SL), sulphuric acid lignin (SAL) and heat-treated SAL were studied, using cashew nutshell liquid as a filler [140]. Lignin was also used as a filler in association with phenol–formaldehyde resin as a binder. When lignin was applied as a binder, only soda lignin showed a moderate advantage in terms of enhancing impact strength and regulating the friction coefficient. Instead, when lignin was used as a filler, heat-treated SAL lignin showed the best properties. The most suitable composition was with 10% lignin in the friction materials. From the Figure 2-14 below, it can be seen that the three types of lignin investigated performed well against the commercial pad.

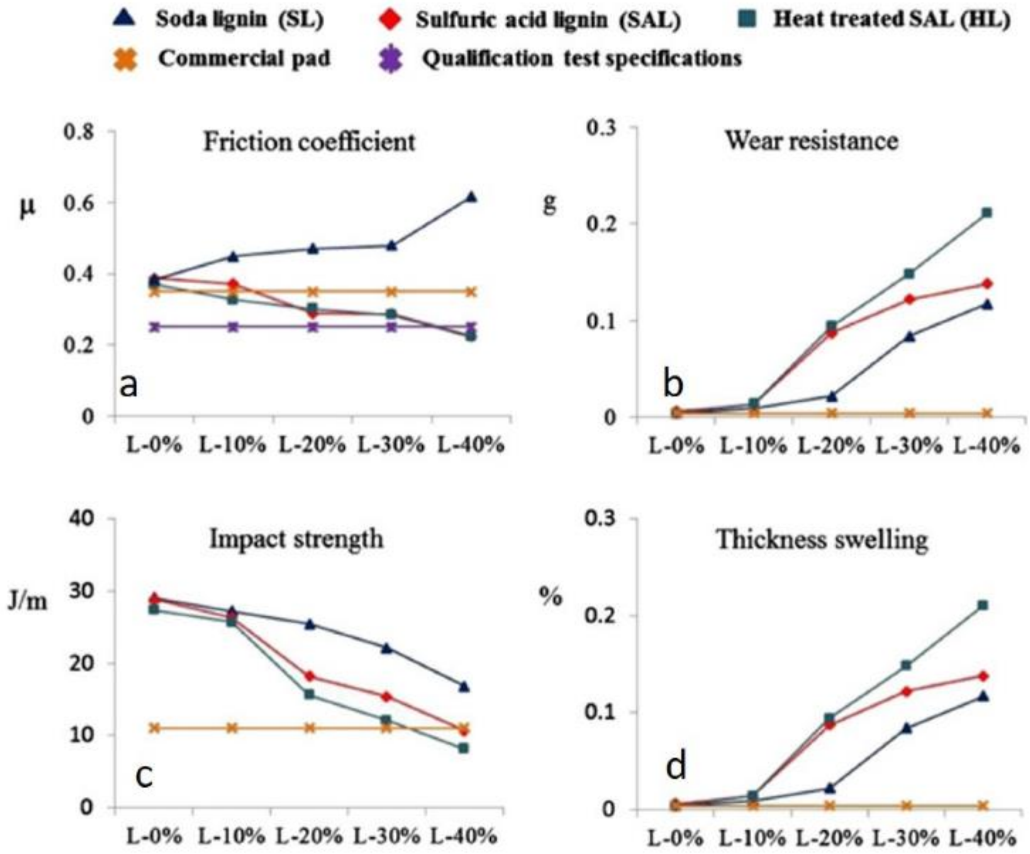


Figure 2-14: Effect of friction materials containing different amounts of lignin as a binder on different brake performance characteristics. Source: Park et al, (2020) [140]

Another proposed class of materials are geopolymers, which have similar mechanical properties to cements and organic resins whilst having a higher heat resistance than organic binders [141]. Lee et al. (2013) studied the wear and friction performance of a composite consisting of an environmentally friendly geopolymer and natural hemp fibres as a replacement of phenolic resin and synthetic Kevlar fibres, respectively, with the goal of substituting the traditional materials of copper and antimony. The phase-out of copper, antimony and other heavy metal compounds in brakes has been promoted in various legislations including a memorandum of understanding between the US EPA and various vehicle manufacturers in the United States [142]. The study's dyno analyses revealed a higher friction level of the copper-free samples compared to the baseline material (formed with 9.5 wt% phenolic resin, 3.4 wt% Kevlar fibre, 8.0 wt% of copper and 3.6 wt% of antimony trisulfide). A higher wear resistance for the modified samples was also observed.

The use of bio-based resin matrix composed of condensed tannins and furfuryl alcohol was tested for use in automotive brake pads by Lagel et al. (2016) [143]. The automotive brake pads based on this bio-based resin showed excellent braking properties and wear resistance when used under real car, full scale test conditions. Their mechanical resistance was found to be comparable to that of commercial automotive brake pads bonded with synthetic phenolic resins. From a safety perspective, all bio-based resin brake pads in the study were shown to exhibit reduced braking distances compared to commercial pads, including during an emergency braking scenario. However, the tested hardness of these new bio-based brake pads is lower than that of the commercial brake pad, this is not necessarily a negative characteristic, rather indicating its lower brittleness. Furthermore, by producing and industrially developing these new bio-based brake pads under the same industrial conditions which are used for commercial brake pads (at a temperature of 200°C and higher pressure), it was concluded that bio-derived materials can be competitive with oil-derived materials for the same application. Using a Chase-type friction tester, Saffar & Shojaei (2012) also found resin-based materials better than rubber-based composites in brake pads due to greater wear resistance [144]. This increased wear resistance is due to the resin-based material serving a protective role to the underlying surface.

Natural fibres

The intrinsic properties of natural fibres limit their use to certain friction material applications. They are less regular and uniform than man-made synthetic fibres and present poor wettability and incompatibility with certain polymeric matrices. Nonetheless, non-toxic natural fibres (also known as lignocellulosic biomass) are considered a prospective alternative to synthetic fibres due to their low costs, low environmental impact (biodegradable), low density, abundance and availability [145] [146]. Their benign nature also does not present an increased risk of the health hazards linked to exposure towards inorganic fibres. The performance characteristics of various natural fibres have been evaluated including palm kernel, flax, agave and aloe, most of the studies demonstrating that environmentally benign materials had the potential to replace conventional fibres in friction material manufacturing.

The use of palm kernel fibres was investigated by Ikpambese et al. (2016) [147]. The fibres treated with a caustic soda solution and incorporated in an epoxy resin binder exhibited encouraging results and were considered a viable alternative in friction material manufacturing. The creation of a composite material by combining palm kernel shell fibres with epoxy resin via compression moulding, and incorporating aluminium oxide, calcium carbonate, and carbon, revealed notable trends as the fibre content varied. As the fibre content increased, both hardness and compression strength decreased, likely attributed to the weaker bonding between the fibres and the resin. Simultaneously, the flame resistance of the composite diminished with the higher proportion of palm kernel shell fibres. However, a notable enhancement in wear resistance was observed as the fibre content was increased.

Bowei (2009) discusses a non-metallic ceramic brake pad for automotive applications, recommending the use of a ceramic binder (10-20 wt%) with a modified aluminium sodium silicate to improve heat resistance and wear in high temperature operating conditions [148]. Zhao (2013) proposes a brake pad composed of composite ceramic fibres that are designed to be soluble, decomposable, and can be used as reinforcing fibres [149]. The authors emphasise that the fibres do not affect human health and generate low environmental impacts. They also state that the use of a soft ceramic fibre protects the rotor disc from excessive wear. As with conventional brake pad designs, the composite ceramic brake pad consists of a lining matrix and a backing plate made of steel.

In conclusion, while the potential of natural fibres as green constituents of friction materials is high given their physical properties and wear behaviours, in order to promote their wide diffusion, some issues still need to be addressed. For example, the bonding strength between the fibres and the matrix in absence of chemical treatments with high environmental impact should be improved.

Fillers

Rice husk, ground nutshell, periwinkle shell and maize husk have been proposed as valid alternative to conventional fillers. Not only is chemical treatment not necessary, but they can also induce higher wear resistance in friction materials. For example, Primaningtyas et al. (2019) found that rice husk which is an agro-industrial waste product induced better wear resistance compared to asbestos friction materials [150]. Embedding 80 and 100 rice husk dust mesh in a friction material and evaluating hardness and impact resistance properties indicated that composites with smaller particle size and higher filler percentages resulted in better properties.

Regenerative braking systems

The reduction in environmental impacts from brakes can also be addressed through considering the entire braking system and reducing the use of friction brakes. With the rise of electric and hybrid powertrains in the vehicle market, there will be an increase in the use of regenerative braking systems (RBS) [151]. As opposed to the hydraulic friction based braking systems in ICEVs, RBS utilises the magnetic resistance in the electric motor to generate the braking force allowing some of the excess energy to be recovered and stored in a high voltage battery. Since regenerative braking does not rely on frictional wear of brake materials to slow the vehicle, the need to use conventional friction brake systems is greatly reduced and thus particulate emissions are reduced as well. Due to legislative and safety requirements, friction brakes are still present in vehicles and must be considered as the primary braking system even where regenerative braking would be utilised for most deceleration events [152]. Friction braking is still required during rapid deceleration, during a quick change from acceleration to braking, at very low speeds and when the vehicle is stationary [153].

There have been several studies that investigated the brake wear emission reductions made possible using RBS. Hicks et al. (2023) found that vehicle mass, powertrain technology, driving style, and deceleration rates significantly impacts braking power requirements and therefore brake wear emissions [153]. RBS substantially reduces brake power requirements and so brake wear emissions, with the greatest reductions occurring during urban driving conditions. The average PM emissions reductions of transitioning to electric and hybrid vehicle fleets were found to be 88% under the WLTP drive cycle and 68% under the TfL drive cycle. However, the extent of mitigation depends on driving style, vehicle speed, and vehicle mass. Hesse & Augsburg, (2018) in their study of three different types of regenerative braking observed a reduction in the particle number concentrations ranging from 66-99% [154]. Bondorf et al. (2023) found that driving with regenerative braking could lead to a significant reduction in the particle number concentration, with up to 89.9% of emissions potentially being saved in the fine/ultrafine range [115]. Further reductions in emissions of up to 78.9% were achieved in the fine/ultrafine bracket and 83% in the coarse bracket with the addition of hard-metal brake coating (see coated discs section above). However, it was also found that the extent of the reduction depended strongly on the driving cycle. However, some trade-offs of RBS have been found. Friction brake systems on vehicles with RBS can be slow to reach bedded conditions due to infrequent use leading to greater likelihood of the friction brake rotors being degraded and corroded which could result in increased brake wear emissions when they are used [155]. This can lead to less effective braking performance such as a decreased coefficient of friction and thus increased stopping distances, risk of skidding and noise [156] [157].

2.3.2.3. Technologies to reduce the manufacture and end-of-life environmental impact of brakes

Reducing the environmental impact of brakes does not only apply to technologies that reduce emissions during the use-phase but covers cleaner production technologies and waste recycling as well. Currently, recycling procedures in brakes are mostly adopted for brake callipers and discs since their typical manufacturing materials allows for use of traditional metal casting technologies at their EOL [158]. As for brake pads, since they are non-degradable, the disposal of the replaced brake pads is difficult. A common way for dealing with the replaced brake pads is landfill, however this method is prone to induce heavy metal pollution of soils. Another popular way is to combust the brake pads to extract the internal energy. Neither of these two methods is favourable due to the large amount of energy required and large CO_2 footprint [159]. From a sustainability perspective, recycling replaced brake pads is a promising method due to the conservation of resources and the environment.

Yang et al. (2012) explored the possibility of removing the residual friction material via a high temperature thermal decomposition of the adhesive layer between the pad top layer and the backplate itself [160]. Alternatively, the embrittlement of the brake lining can be induced by immersion of the used pad into a liquid nitrogen bath, helping the subsequent detachment by applying mechanical stresses [9].

Lyu at al. (2020) investigated the recycling of worn-out brake pads through crushing and ball milling of worn friction material and adding 8% of phenolic resin to the resulting batch [49]. The results of the wear tests indicated comparable coefficient of friction, wear and particle emissions as those of the virgin material. However, in this study, the management of the pad underlayer was not considered. It was also found that the energy consumption and CO_2 footprint of the recycled brake pads are 36% and 34% less than virgin brake pads respectively, indicating that recycling could be a promising method of handling replaced brake pads.

Friction material from industrial waste

Researchers have been prompted to explore new materials solutions utilising waste resources because of increasing environmental concern and the push for a circular economy [139]. Many by-products and wastes in the automotive and metallurgical industries have the potential to be used in the manufacturing of brake components, and these have been investigated by many researchers.

Singh et al. (2018) explored the use of waste tyre rubber particles as useful additives to NAO friction material compounds [161]. Limited tyre waste rubber led to a high and constant coefficient of friction, low fade, low frictional variability and the minimum variations during sliding, while, when employing a high content of tyre, the most recovery, the least wear and the lowest disc temperature rise were found.

Fly ash produced during the combustion of coal for energy production is an industrial by-product that is considered an environmental pollutant. Most fly ashes are made of silica, alumina, calcium sulphate and unburnt carbon [162]. Öztürk & Mutlu. (2016) investigated friction material composites containing various mixtures of zinc borate and fly ash. Decreased wear rates was obtained by increasing zinc borate and decreasing fly ash contents [163].

Laser metal melting

Technologies are being researched to supersede current end-of-life methods for treating replaced brake discs and rotors such as remelting and disposal in landfills. Laser metal melting deposition is an emerging tool for refurbishing or even repairing brake discs [164]. Coating discs is a process that is not restricted to new discs but can also be applied to exhausted discs near their end-of life as well. Rather than simply remelting GCI discs at the end of their lives, this approach allows for refurbishing the worn discs by replacing the lost material during braking and restoring the original disc thickness. Results from Olofsson et al. (2021) even show that the refurbished brake rotor yields a higher friction coefficient compared to the original GCI utilising the same pad material [164]. Additionally, the refurbishing of worn brake discs requires a lower energy input than remelting and casting with an estimated 80% and 90% reduction in energy and CO_2 footprint respectively.

2.4. Performance of tyres and brakes currently on sale and in use

There is a very large difference between the published literature on the performance of tyres compared to that for brakes currently on sale and in use. Principally this is driven by tyres having a standardised rating and labelling for key attributes (fuel economy, wet grip, and noise), whereas there is no equivalent for brake performance.

2.4.1. Tyres

Using the EU Tyre Labelling Regulation's information researchers can establish how manufacturer's product ranges reflect these attributes, where brands align to the attributes, and can identify which of the attributes are popular. In addition, the price of the tyres is another variable. The Tyre Labelling Regulation is the principal way these attributes are communicated with consumers and is illustrated in Figure 2-15.

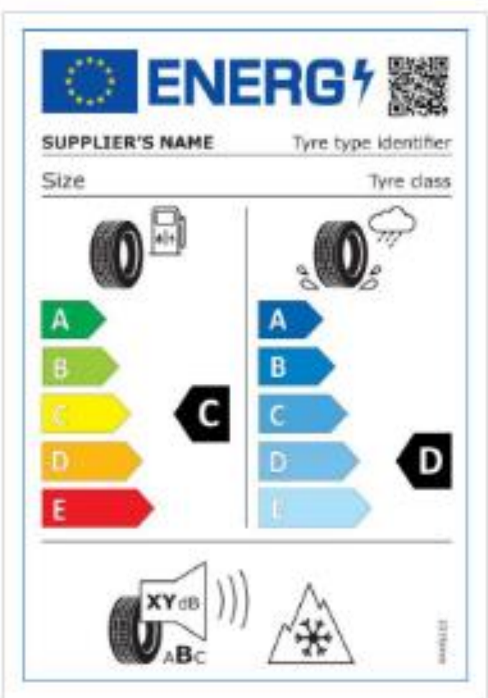


Figure 2-15: A generic EU tyre label

The upper left pictogram indicates the tyre's fuel economy, based on its rolling resistance, measured in units of N/kN (i.e. retarding force per 1,000 N load carried by the tyre. This is graded A – E, where for passenger car (C1) tyres a rolling resistance of $\leq$ 6.5 N/kN is designated "A" and a rolling resistance of $\geq$ 10.6 N/kN is designated "E" (i.e., the dynamic range of this scale is less than a factor of 2).

The upper right pictogram indicates the tyre's wet grip, based on its stopping distance as determined by a specified measurement procedure, (UN ECE Regulation No 117, Annex 5). Wet grip indices (G) are graded A – E, where for passenger car (C1) tyres if G > 1.55 the tyre is designated "A" and if G < 1.09 the tyre is designated "E" (i.e., the range of this scale is less than a factor of 1.5).

The lower portion of Figure 2-15 shows a generic noise label. Tyre noise is assessed using a defined measurement procedure (UNECE Regulation No 117, Annex 3). For passenger car (C1) tyres there are three tyre noise designations (A, B and C) where the measured noise is compared to a limit value (specified in the EC Regulation. For tyre noise above the limit value, tyres are designated "C", whereas for tyre noise less than 3 dB below the limit value, they are designated "A", and those between 3 dB below, and the limit value are designated "B". However, it should be noted there are limitations with the labelling procedure, meaning that the "A/B/C" label is not always a reliable indicator of the tyre noise level in practice. This is primarily due to only the loudest tyre in a range being tested with this value being attributed to the entire range, meaning that some tyres will be much quieter than indicated [165].

In addition to the tyre labelling regulation, in the US, the Uniform Tyre Quality Grading (UTQG) gives a system for **comparing tyres** to a baseline (control tyre) [71]**.** The tyre treadwear rating (TWR) provides information which is intended to inform the customer about the expected durability of the tyre and is printed on the sidewall of tyres. It is a comparative figure, with, for example a tyre having a TWR of 400 being expected to last twice the distance of a tyre with a TWR of 200. However, tyres for the UK and EU market do not carry the TWR.

A paper in Atmospheric Environment [166] by researchers at JRC (Ispra, Italy) and the Swedish National Road and Transport Research Institute (VTI), investigated the relationship between treadwear and particle emissions to the atmosphere from tyres with different treadwear markings. It explores the possible correlation between the TWR and tyre wear dust emitted in the form of PM_{10} and $PM_{2.5}$. Tyres of the same TWR but of different brands showed different behaviour in terms of material loss, PM, and PN emissions under the selected testing conditions. This means that it is not feasible to categorise tyres of different brands in terms of their emissions based on their TWR. An important additional conclusion reached was that in all cases approximately 50% (by mass) of emitted PM_{10} fall within the size range of fine particles, while PN size distribution is dominated by nanoparticles most often peaking at 20–30nm.

A large quantity of research is reported by the German Allgemeiner Deutscher Automobil-Club (ADAC)[22]. They undertook, and have reported, on an extensive testing of tyres [75]. An important finding reported by ADAC, from an

[22] See https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/reifen/reifentest/

analysis of the particles generated on a laboratory test rig for tyre abrasion as well as particles collected on the road from tyre and road abrasion, was their size distribution – see Figure 2-16.

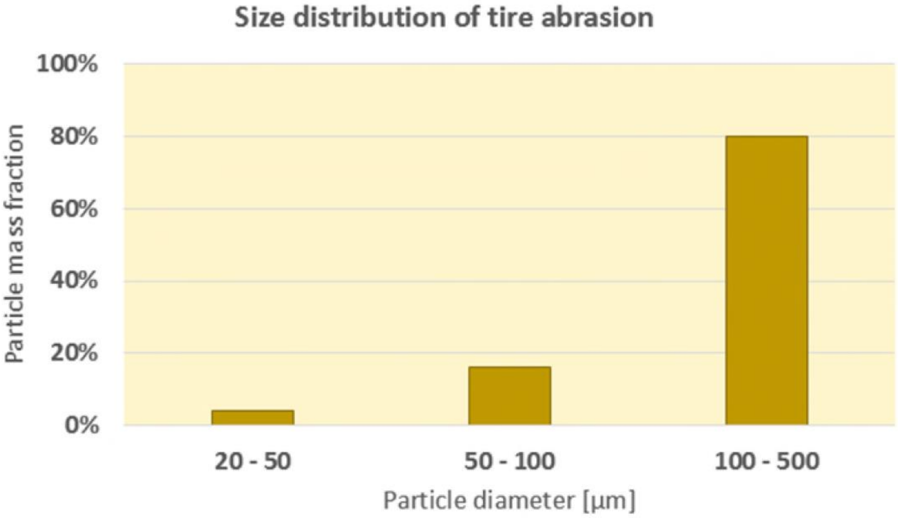


Figure 2-16: Particle size distribution of particles abraded from tyres; Source: [75]

It was explicitly noted "only a very small proportion of tyre abrasion has a diameter below 10µm". This is important because it emphasises that there may be a disconnection between tyre wear rates (i.e. the rate at which material is lost from the tyre) and non-exhaust (tyre) emission rates to the air, since it is the smaller particles which may become airborne and the proportion of abraded material that becomes airborne may not be constant. When evaluating the potential impact on health, measurements of particle number (the total number of particles emitted) may be more relevant than mass, since most of the abraded mass does not become airborne and large numbers of ultrafine particles may total a tiny fraction of mass lost.

ADAC tested a total of 90 winter and summer tyre types of different wheel sizes over 4 years, as summarised in Table 2-5 below, where 15 tyres were tested for each size.

Table 2-5: Tyres sizes tested by ADAC, in given years; Source: [75]

Year	Summer tyre size tested	Winter tyre size tested
2019		185/ 65 R15 winter tyres
2020	225/40 R18 summer tyres	205/55 R16 winter tyres
2021	205/55/R16 summer tyres	195/65 R15 winter tyres
2022	185/65 R15 summer tyres	

Tyre abrasion (g/1,000 km), and dry and wet road surface grip ratings were tabulated in the ADAC report [75]. This was measured by comparing the weight of the tyre when new and after 15,000 km. Different tyre models, from a range of manufacturers were each tested over real road distances of 15,000 km, (60% urban and country roads, 40% motorway) under controlled driving conditions, with tyres being exchanged across the front axle every day, 610 km.

The research tested a variety of different tyre models available, from a range of manufacturers. At the end of the research ADAC combined data for the different manufacturers, and published Figure 2-17, where the vertical axis is tyre wear (in units of g/1,000 km). It is emphasised, that this is the rate of abrasion of the tyre (mass lost), not the non-exhaust air emission rate for PM_{10}.

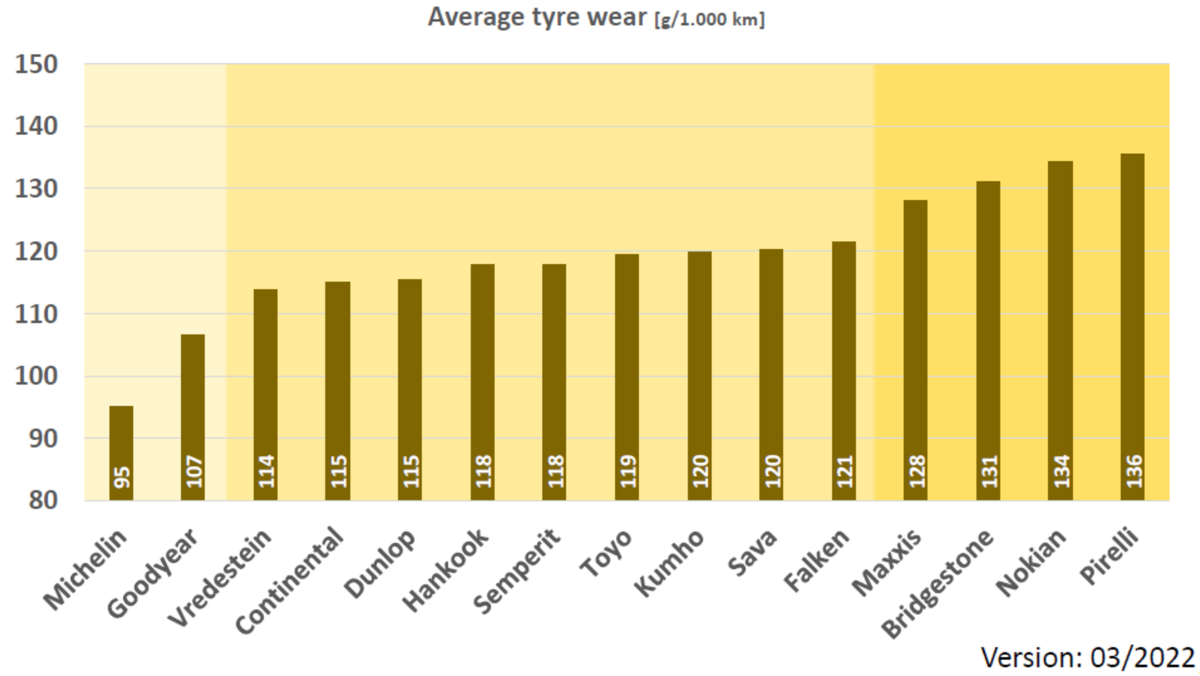


Figure 2-17: Average tyre wear characteristics (g/1,000 km) for different tyre manufacturers; Source: [75]

This extensive research by ADAC drew the following conclusions.

- There are tyre models in all sizes that have low abrasion combined with good driving safety.
- Tyres with low abrasion do not necessarily lead to an increased risk of aquaplaning, as the aquaplaning features depend entirely on the tread design and depth and not on the rubber compound.
- In the case of winter tyres, it is evident that tyres with low abrasion tend to provide poorer snow performance. However, there are tyres that reconcile this conflict of objectives most effectively and still provide an acceptable performance in snow with low abrasion.
- Especially in the case of racing tyres and so-called ultra-high-performance tyres, the focus often seems to be placed only on high performance stability on dry roads. The tyre abrasion that is associated with this is rarely the focus of many manufacturers. The above-average tyre performance on dry roads, however, provides hardly any additional safety advantages in normal road use. At best, these tyres are good for the racetrack.

Further analysis of these data will be undertaken and reported in this project's final report.

2.4.2. Brakes

There is no brake system equivalent to the Tyre Labelling Regulation, nor yet a standard procedure to evaluate environmental impacts of brakes for the UK market. A standard for measuring brake emissions has been recently developed at UN ECE level using a brake dynamometer test, and which will be used to test compliance with the proposed EC Euro 7 brake emissions limits. There is a lack of research and literature on the environmental impact of brakes, and limited details about the attributes of brakes on sale, and consequently a lack of public awareness of the issue. This reinforces the view that environmentally optimal attributes are very low on the public's priorities for brake product selection.

A special report entitled "Innovations in vehicle braking" has been published by Automotive World in 2017 [167]. Though this is somewhat dated, it lists eight trends in vehicle braking that are relevant to this study:

1. Use of electrification and brake-by-wire systems is increasing.
2. Automatic Emergency Braking is evolving to protect vulnerable road users.
3. The price of brake systems is expected to reduce, but not for all brake systems.
4. Split second stops will need rapid high-pressure build-ups.
5. Sales continue to climb worldwide, creating serious price pressure.
6. Braking pads will continue to become cleaner (environmentally).
7. Demand for high performance brakes is increasing.
8. Brake performance visibility will be essential for truck platooning.

Though not itemised in this list of eight trends, the article does note: “Every OEM is developing and introducing electric vehicles…”. This, of course, relates to the introduction of regenerative braking. There are an increasing number of articles describing various regenerative braking systems.

Vehicles that make use of regenerative braking rarely require the additional assistance from standard friction braking systems, except for the cases of instant/emergency braking. Some OEMs are reintroducing drum brake as rear brakes on EVs since the required braking force is reduced, the Volkswagen ID.3 is one example of this[23]. Drum brakes are a closed system meaning that they are less susceptible to corrosion through infrequent use. Additionally, PM emissions are reduced, as the particulates accumulate within the enclosed housing and are not emitted to the atmosphere. A reference to this was published by S&P Global [168]. They note that overall it is expected that the global demand for drum brakes will increase at a compound annual growth rate of 2.8%, from the present to 2029.

2.5. Understanding consumer awareness of the environmental impacts of tyre and brake choice

2.5.1. Approach

The approach was broadly as set out generally in Section 1.3, adapted for the topic of understanding consumer awareness of the environmental impacts of tyre and brake choice:

Step One: Source and review published reports, including journal articles, industrial publications, government and industry reports, outputs from projects, and manufacturer websites.

> Literature sources were selected for review based on their relevance to the research topics and the wider project scope. A spreadsheet was used to document the results from the screening, specifically, source type, authors, company, information about the subject matter, for example, tyres or brakes, life cycle stage and environmental impacts, attributes covered and ratings for quality and relevance.
>
> There were 68 articles sourced and reviewed prior to the in-depth review. The sources were found using relevant search terms and targeted a range of key players, including manufacturers, retailers, and environmental groups.

Step Two: In-depth screening of the sources to exclude materials without consumer research.

> Literature sources were selected for review based on their relevance to the research topics and the wider project scope. A spreadsheet was used to document the results from the screening, specifically, source type, authors, company, information about the subject matter, for example, tyres or brakes, life cycle stage and environmental impacts, attributes covered and ratings for quality and relevance.
>
> The literature review process found there was a very limited number of pieces of literature in the public domain which specifically reported consumer research for tyres and no primary consumer research was found about purchasing brakes.

Step Three: Gathering of evidence relevant to the scope from the material to support the delivery of the project.

> Each source was reviewed in detail, detailing the project objectives and methodology, the findings and limitations of either the research or the information provided in the literature.

Note that some literature sources are from the United States (US) and therefore the spelling of ‘tyre’ is Americanised (‘tyre’).

Statistics have been quoted in the report when these were provided in the literature. In some cases, headlines statistics were written in the literature report as a main finding, but other statistics were missing, in these cases only the headline statistic(s) has been provided.

[23] See https://www.volkswagen.ie/en/electric-and-hybrid/sustainability/id-brake-system.html

2.5.2. Tyres

2.5.2.1. What Factors Do Consumers Consider When Purchasing Tyres, YouGov (2022) [169]

The research was designed to explore how often consumers replace their tyres and the factors influencing their purchase decision. The research offers insights into how and why consumers make decisions when buying tyres, including how often they make these purchases.

Method

The research was conducted as part of an online Omnibus[24] survey, using YouGov Profiles (an audience intelligence tool), collecting data from participants based in both Great Britain (GB) and the United States (US). YouGov Omnibus surveys are nationally representative and weighted by age, gender, education, region, and ethnicity.

Findings

The survey found that 55% of GB respondents only change their tyres when absolutely necessary. 14% of GB participants stated they only changed their tyres once every three years, in comparison to 23% of US respondents. The survey revealed only 3% of consumers in both countries changed their tyres twice or more per year.

Participants were asked which factors they consider to be most important when purchasing tyres and had the option to select up to 13 factors, as shown below in Figure 2-18.

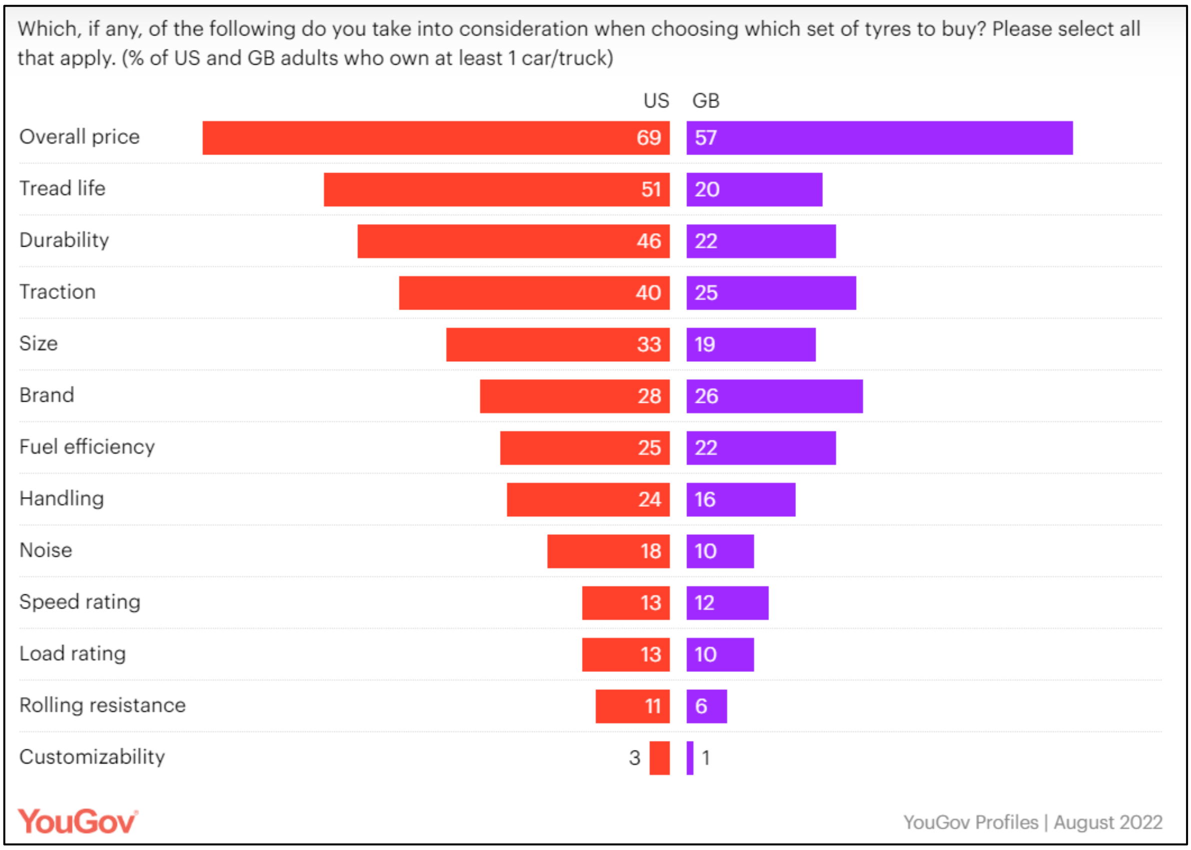


Figure 2-18: Most important factors when purchasing tyres; Source [143]

[24] An Omnibus survey is one which has questions on a variety of subjects, these questions are provided by multiple sponsors (companies). A sponsor can ask one or more questions. An Omnibus is often more cost effective than an ad-hoc customised survey. Omnibus surveys are completed by a nationally representative sample of the country. Omnibus surveys typically have a sample size of at least 1,000 respondents.

The survey found that the most important factor was price, with twice as many respondents selecting this than any other factor. The next five most important factors to GB consumers were brand, traction, fuel efficiency, durability, and tread life. However, US consumers had different priorities with tread life and durability scoring next highest.

Limitations

A sample size was not provided, however, Omnibus surveys typically have a sample size of at least 1,000 respondents. The sample was restricted to online panellists and therefore may not be fully representative of the whole population. Specifically, those on the lowest and highest income may be underrepresented in online panels. A further limitation is the sample represents the general population and not car owners.

The questionnaire length, other topics included in the Omnibus, and the position of these questions in the questionnaire are all unknown and there may be respondent fatigue at the time of answering questions.

2.5.2.2. Consumer Study: Buying Behaviours – Marketplace Insights, Tyre Review (2019) [170]

Study designed to understand how often consumers replaced their tyres and what factors drove their purchase decisions. The study, which took place in the United States, explored how consumers purchase tyres, including their actions prior to purchase and where they prefer to make a purchase. Like the YouGov survey referenced previously, the study explored the most important factors to consumers purchasing tyres.

Method

This national study was drawn from more than 10,000 interviews with recent tyre and service buyers in 26 metro markets across the United States. Demographic information was recorded, including age, income, and gender. Over half (55%) of participants were women and the age and income of respondents is shown in Table 2-6: Income of participants; Source: below.

Table 2-6: Income of participants; Source: [170]

Income level	Percentage of respondents
Less than $20,000	11%
$20,000 but less than $40,000	20%
$40,000 but less than $60,000	20%
$60,000 but less than $75,000	17%
$75,000 but less than $100,000	18%
$100,000 or more	13%
Preferred not to answer	1%

Age of participants:

- 18-29 - 40%
- 30-49 - 27%
- 50-64 - 22%
- 65 or older - 11%

Findings

Price was the main factor for purchasing the tyre (52%). All the main other reasons provided were about the dealer rather than the tyre, such as the dealer's location, the respondent's past experience of the dealer, brand selection and availability of tyres and speed of service.

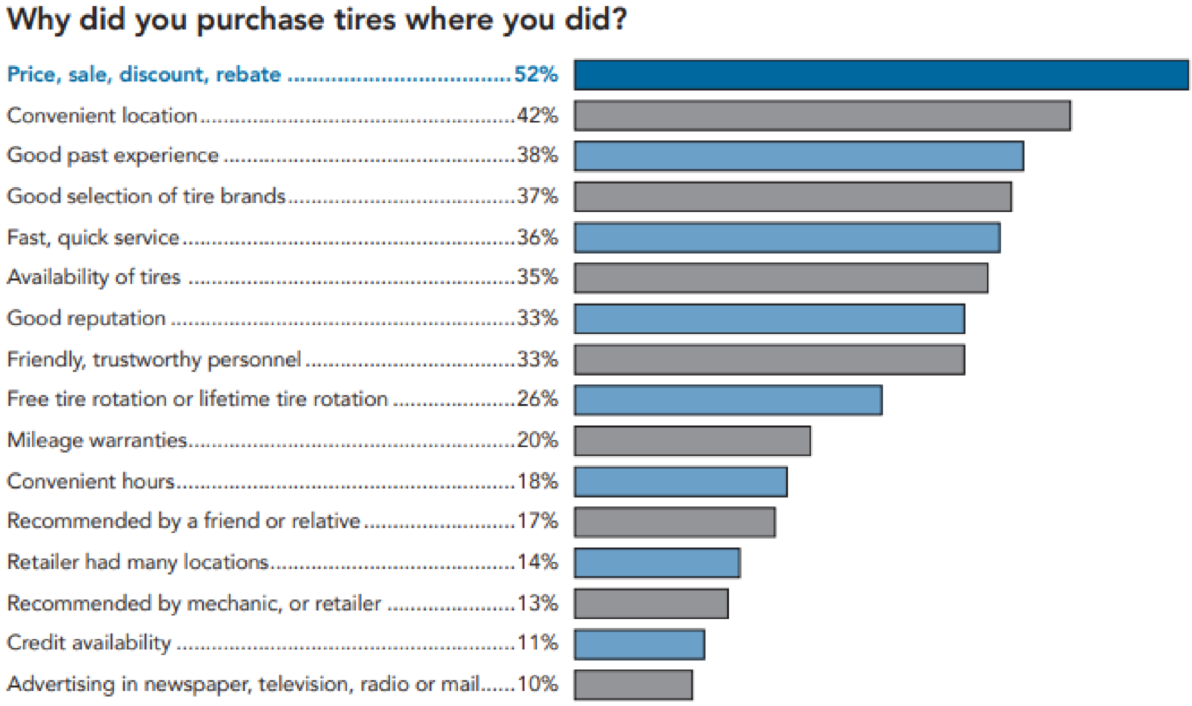


Figure 2-19: Reasons for choosing the tyres; Source: [170]

The study also investigated the actions consumers took before making a purchase, in which 55% of respondents stated they conducted online research prior to purchasing. 37% stated they talked to a car service professional and 31% talked to friends, relatives, or co-workers beforehand. On the other hand, 11% of participants stated they conducted no research prior to making a purchase.

Limitations

The sample was skewed to younger people, aged under 30, with 40% of responses provided by this age group, while 33% were provided by those aged 50 and over.

The methodology and sampling plan was not detailed, other than the owners were recent tyre buyers.

2.5.2.3. An Assessment of Tyre-Buying Among Millennial Consumers (2017) [171]

The aim of the study was to understand the preferences of millennial consumers when purchasing tyres. The scope of the study covers online tyre retailers as well as dealerships to assess how consumer choices differ between the two platforms. The study provides information on the purchasing behaviours of consumers and assesses what factors influence purchasing decisions. The study was conducted in the United States at the University of Akron, Ohio.

The study was prompted by an initial quote from tyre manufacturer Goodyear;

"Goodyear wants to understand how the tyre purchasing experience can be redesigned in order to diminish pain points in the purchasing journey and create an experience that is compelling and worthwhile to millennial customers."

Method

The report draws upon existing studies which surround the purchasing habits of millennial consumers, as well as additional primary research methods. The primary research methods were:

- Online surveys with Millennials (those born between 1981 and 1996) studying at the University of Akron;
- Face-to-face interviews with Millennials to understand attitudes to the sales process when buying tyres; and
- Site visits to five tyre retailers.

The topics of the survey were:

- The pain points in the buying experience;
- How Millennials researched products to buy, and how their purchase decision was influenced; and
- The importance of the environment in the decision-making process.

Findings

The study found that Millennials were not confident about their purchase decision making for new tyres, it found that Millennials were likely to seek advice from a range of sources prior to purchasing tyres, including:

- Parents (64%);
- Partners and family friends (% not provided); and
- Online reviews (% not provided).

62% of those surveyed stated they would be more likely to purchase eco-friendly tyres. The online survey found that one-third of respondents (32%) would be willing to pay $101+ more per environmentally friendly set of tyres and a further 43% would pay between $1-100 more per set of environmentally friendly tyres. Three-quarters (75%) of Millennials would pay more for environmentally friendly tyres.

Three quarters (74%) stated that they would prefer to purchase tyres in-store rather than online. Although in store purchases were the preferred option, 40% of Millennials felt tyre sales personnel were untrustworthy and "push the most expensive tyres".

Site visits were made by Millennials to tyre fitters to understand the sales process for tyres. Participants asked sales associates to check their tyres to gain information and gauge which factors were mentioned as important when buying tyres. Each researcher stated that their tyres were inspected and were given advice on choosing tyres in future and how to look for all weather certification and tread depth. These site visits investigated the process of receiving advice and therefore had limited detail about the purchase decision.

Learnings

The main learning is the importance Millennials put on:

1) Purchasing tyres from a brand with eco-friendly or environmentally friendly credentials;
2) The importance of seeking information from trusted advisors such as parents, friends, and tyre retailers;
3) Concerns about retailers being trustworthy; and
4) The reported willingness to pay more for tyres considered to be eco-friendly or environmentally friendly.

Limitations

The study conducted primary data collection using online surveys, interviews, and on-site visits. A significant limitation of the research was the lack of detail provided about the process, specifically, the sampling and the sample sizes achieved. Only university students were included in the research. Furthermore, the study focused on Millennials which limited data collection and excluded other consumer groups.

2.5.2.4. Getting the Green: Understanding the Market for Eco-Friendly Tyres (2016) [172]

The study was designed to investigate the public's motivations when purchasing eco-friendly products, using Goodyear sustainable tyres as a case study. The study provides information on the purchasing behaviours of consumers and assesses how consumers value environmental factors when purchasing tyres. The study was conducted in the United States at the University of Akron, Ohio.

Method

Two focus groups were held in March 2016. The first focus group hosted eight participants (six females, two males), while the second hosted six (five males, one female).

Following the focus groups, surveys were conducted to gain a further understanding into the research questions. A series of questions were developed, designed to gain insights into any influencers in the decision-making process, the most desirable tyre features, and initial reactions to potential terminology.

The survey questions were developed using the factors below:

- Attractiveness of different tyre names;
- The influencers in the tyre decision-making process;
- The importance of various tyre features;
- The potential willingness to pay a price premium;
- The intent to purchase eco-friendly products; and
- The loyalty that respondents might have toward eco-friendly companies.

In addition, respondents were profiled using demographics (age, gender, income).

Sample size and profile

A total of 204 respondents completed the survey, 56% were female and 44% were male. From this, 54% of participants were Millennials - those born between 1981 and 1996), 31% came from Generation X (those born between 1965 and 1980), and 15% were Baby Boomers (those born between 1946 and 1964).

Findings

The survey found that to warrant an eco-friendly purchase, products needed to have additional benefits, such as a better performance. Brand loyalty was considered more important than eco-friendly credentials for tyres.

Key influences in the decision-making process, in no particular order, were:

- Family members;
- Friends;
- Keeping the same brand as previously;
- Online reviews; and
- Tyre shop professionals (retailers).

The three top factors used when making the purchase decision, in ranked order, were:

1. Tyre tread life
2. Price; and
3. Brand;

Older participants (Baby Boomers) were less price sensitive than younger participants. Overall, 60% of respondents would be willing to pay a premium for an eco-friendly tyre of the same quality as a regular tyre (77% of Baby Boomers, 61% of Generation X and 54% of Millennials). Over half the participants would pay 10% more for a tyre with improved environmental performance. The study also found that females were significantly more likely to support eco-friendly efforts than males. Of the 60% of respondents who stated they would pay a price premium for an eco-friendly tyre, they felt they would pay an increased price between 5% and 10% compared to other tyres.

Overall, the study recommended that Goodyear pursue eco-friendliness on a companywide basis and concluded that it had the potential to attract customers by offering eco-friendly products. The study also highlighted that becoming known as an eco-friendly company would be as beneficial, if not more so, than offering a single product considered to be eco-friendly.

Limitations

The sample size was small (n=204) and the detail provided about the study methodology is shown at Table 2-7 and

Table 2-8 alongside the associated limitations. An overview of the type of respondent and sample size was provided but there was no detail about how the respondents were sourced and the questionnaire length was not stated.

Table 2-7: Focus group limitations. Source: [172]

Topic	Survey information	Limitations
Participants	Mix of ages Baby Boomers to Millennials Even split of gender (56% female; 44% male)	Good spread of ages but no further detail
Sample size	Two focus groups Group 1: majority female; Group 2: majority male	Low number of groups; Insufficient number to draw meaningful conclusions

Table 2-8: Online survey limitations. Source: [172]

Topic	Survey information	Limitations
Participants	Mix of ages: Baby Boomers to Millennials	Good spread of ages but not shown to be representative of either the population or drivers
Sample Size	204 interviews	Low base to draw meaningful conclusions.

Learnings

It was noted that terminology for being eco-friendly needed to be clearly defined and understood for respondents. Terms such as ‘green’ were treated with scepticism, as it was felt to be an overused term, while ‘eco-friendly’ was considered an acceptable term and ‘sustainable’ more appropriate. However, ‘sustainable’ needed to be a familiar term, and in this study more Millennials than Baby Boomers were familiar with this term.

2.5.2.5. Customer Preferences on Two Wheel Tyre Purchase- A Study on Brand Awareness (2018) [173]

The aim of the study was to explore customer preferences when purchasing a motorcycle tyre. It provides an overview on consumer preferences surrounding motorcycles, producing primary data using an Indian case study.

Method

An exploratory phase of primary data collection using focus groups and in-depth interviews with tyre customers (two-wheeler users, tyre dealers and distributors) was completed. Following the exploratory phase a questionnaire was designed and distributed as a Google Form, and therefore it is assumed it was a self-complete (online) survey. 158 responses were achieved. The questionnaire gathered demographic information of the respondent including factors such as age, gender, education, and occupation. 85% of respondents were male and 15% were female. The majority of respondents were aged from 20-to-30 years-old and described themselves as professionals.

The respondents were asked to rate the importance of different variables in influencing their decisions of buying tyres using a Likert scale of 1 to 5 (where 1 was lowest and 5 was highest).

Findings

The study found that 62% of respondents wanted to replace their tyres using the same manufacturer that the motorcycle was originally fitted with, 6% of respondents stated they would switch to any brand with a lower price, whereas one-third (32%) would switch to a brand of higher price.

Figure 2-20 displays the results of the questionnaire data in the form of factor analysis. The findings show performance was the most important factor to motorcycle respondents, followed by value for money and safety.

1.Brand Image	2.68	4. Driving comfort	3.4
Advertisements	2.5	Riding Comfort Provided	3.76
Sales Promotion	2.38	Ease of braking	3.82
Past Experience	3.2	5. Technological superiority	3.08
Auto Magazines and Brochures	2.66	Pattern of button/treads	3.3
Comparative Advertisements	2.68	Customer satisfaction surveys	2.84
2. Performance	3.98	Technical specifications	3.1
Durability	4.34	6. Safety 3.48	3.48
After Sales Service	3.62	Lower noise	3
3. Value for money	3.68	Ease of driving on wet road	3.96
Price	3.56	7. Opinion / Recommendation of Experts	3.03
Discount Received	3.38	Mechanic Recommendations	3.1
Warranty Offered	3.76	Driver Recommendations	2.94
Brand Name	3.9	Friends Recommendations	2.94
Value for Money	3.82	Dealer's Recommendations	3.12

Figure 2-20: Selection criteria obtained from factor analysis. Source: [147]

Limitations

The survey took place in India therefore cultural differences would be expected. The full methodology was not described in detail, a sample plan was not provided.

There was a low sample size to disaggregate responses any further than for all motorcyclists. The sample was mainly young professionals, and it is unclear whether this was representative of motorcycle owners. The questionnaire length was not provided.

2.5.2.6. TyreSafe tread depth at the point of replacement survey: 2016 vs 2023 [174]

A combination and comparison of two in-depth surveys at the point of tyre replacement conducted between October 2015 and April 2016 and the results from data complied between April 2022 and March 2023. The study compiled data on trends relating to the tread depth of vehicles at the point of replacement across the UK from TyreSafe's members and non-members across national franchises and independent tyre dealers.

Method

Retailers provided information about the tyre tread depth at point of replacement. The survey data was collected by vehicle type and National Highways region from 01 April 2022 to March 2023. The areas are shown in Figure 2-21.

Figure 2-21: National Highways geographical regions; Source: [174]

Data was collected using the number of tyres and the exact number of retailers who participated was not specified, other than it was at least ten retailers in each region.

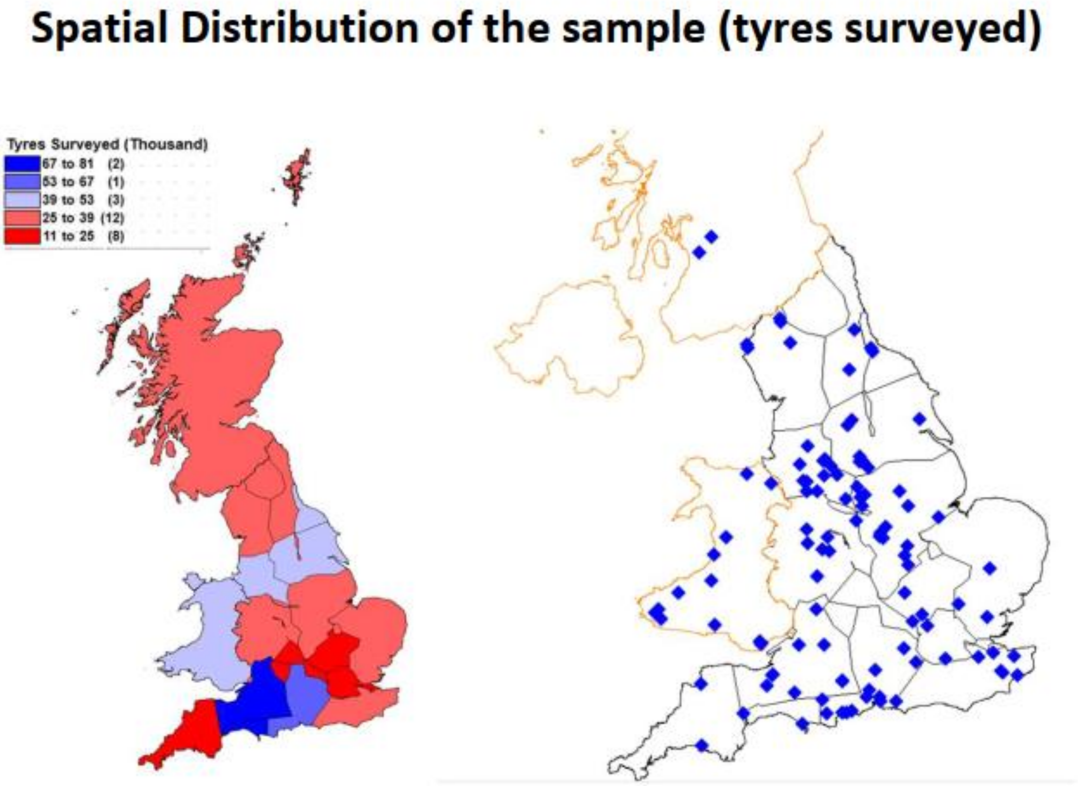


Figure 2-22: Distribution of tyre retailers in the sample; Source: [174]

Findings

The survey found an overall reduction in the number of illegal and borderline tyres at the point of replacement. The 2023 findings were put in context with 16.7% of tyres being below the legal limit of 1.6mm when replaced, remaining a concerningly high proportion. Across England, 16.6% of car tyres were found to be illegal, while 40% were between 1.6mm and 2mm. For LCV tyres,17.2% were found to be illegal, while 38.9% were between 1.6mm and 2mm.

Limitations

This study does not explore the reasoning for tyre replacement and the considerations customers made when choosing their replacement tyre. The survey does not specify how many retailers participated or the number of retailers approached in each region.

2.5.2.7. Bridgestone Survey Finds Lack of Tyre Safety Knowledge, tyrenews.co.uk (2023) [175]

This article covers a survey was commissioned by Bridgestone to investigate driver attitudes toward tyre safety and completed by Research Without Barriers. The study investigates the lack of knowledge surrounding the role of tyre maintenance in ensuring safety using survey data from UK drivers.

Method

2,000 UK car owners were surveyed online by Research Without Barriers in February 2023.

Findings

The survey found that 14% of the 2,000 participants described tyres as the most crucial safety feature on their cars.

The survey also found that:

- 54% don’t believe that driving on illegal tyres is an extremely dangerous act;

- 31% of motorists say they are ‘definitely’ well informed on road safety matters;
- 12% check their tyre treads once a fortnight (which is the recommended period); and
- 17% check their tyre pressures once a fortnight (which is the recommended period).

Limitations

The level of detail is limited as this was a press release. There is no information about whether the sample of 2,000 car owners was representative, either of car owners or of the general public. The questionnaire was not available; therefore, it is not clear how the questions were asked.

2.5.2.8. Consumers eye many factors when choosing tyres – Consumer Reports, Rubber News (2019) [176]

The survey in this US article was conducted with the aim of gathering responses from consumers who had purchased tyres in the last 12 months. It gathered primary data surrounding consumer purchasing behaviours, using information from consumer reports subscribers. This focused on what factors respondents considered to be important when purchasing tyres.

Method

Consumer Reports conducted the survey in 2018 among its subscriber base seeking experiences from those who had purchased tyres within the last 12 months. The survey received more than 33,477 responses.

Findings

The study found that respondents typically owned vehicles between three and six years old and 83% bought a full set of tyres at once. Notably, it found that the price of tyres was the most important factor, with 62% of respondents changing brands due to the price, followed by good tread life and brand trust. It also stated that consumers change tyres for two primary reasons: wear and tear or to improve their tyres for winter weather and grip.

Limitations

The study was conducted with Consumer Reports subscribers only, who are likely to already be engaged in these types of survey and possibly more concerned with car maintenance than other people. The questionnaire was not available for scrutiny, nor was any detail of the respondent profile.

2.5.2.9. Survey reveals tyred tyres could be missing out on TLC as drivers urged to check vehicles this Bank Holiday, National Highways (2022) [177]

National Highways commissioned ICM to conduct an online Omnibus survey about what drivers considered to be a priority before setting off on trips over the August bank holiday. The information was provided as a press release with no more detail provided.

Method

An online Omnibus with 2,000 respondents, aged 18 and above took place in June 2022. As the study is an Omnibus, it is assumed it was a representative sample using age, gender, and region as a minimum, but this is not stated. It is not stated how many of the respondents were drivers, or drivers intending to travel by car on the bank holiday.

Findings

The objective of the study was driver preparations for bank holiday travel - it found that 6% would check tyre pressures and 3% would check oil levels.

Limitations

The survey took place in June, two months before the August bank holiday and therefore may not have been top of mind for some drivers. There was no detail provided about respondents’ attitudes to tyre choice. The limitations of the

Omnibus sample are the same as the YouGov Omnibus, such as the number of other questions asked to respondents and the position of these questions in the Omnibus questionnaire (respondent fatigue).

2.5.3. Brakes

There were no consumer research publications, press releases or articles found about consumer research for brakes or the decision-making process when brakes are purchased.

2.6. Influence of driver behaviour on environmental performance

The intricate relationship between driver behaviour and the environmental impact of tyre and brake wear is drawing increasing attention in environmental research. It is evident that actions taken by drivers, and the indirect consequences of those actions, play a pivotal role in determining tyre and brake wear, with subsequent emissions of pollutants as discussed in Section 2.1. The OECD (2020) [178] and Liu et al. (2022) [179] suggest that driving behaviour and conditions can significantly influence tyre wear; driver behaviours even accounting for as much as 30% of tyre wear. In the case of brakes, driving behaviour also influences drastically in its lifespan. According to the Royal Automobile Club (RAC) (2022) [180] brake pads can last anywhere between 30,000 and 70,000 miles, and even more, depending on the way the vehicle is driven. Most of the actions and behaviours that lead to increased tyre and brake wear are associated with an “aggressive” driving style. In the paper Xia et al. (2023) [181] aggressive driving behaviour is characterised as that where drivers follow closely the vehicle in front while accelerating and braking harder, as presented graphically in Figure 2-23 where braking and acceleration periods are shorter than when driving calm or neutral, representing abrupt changes in speed.

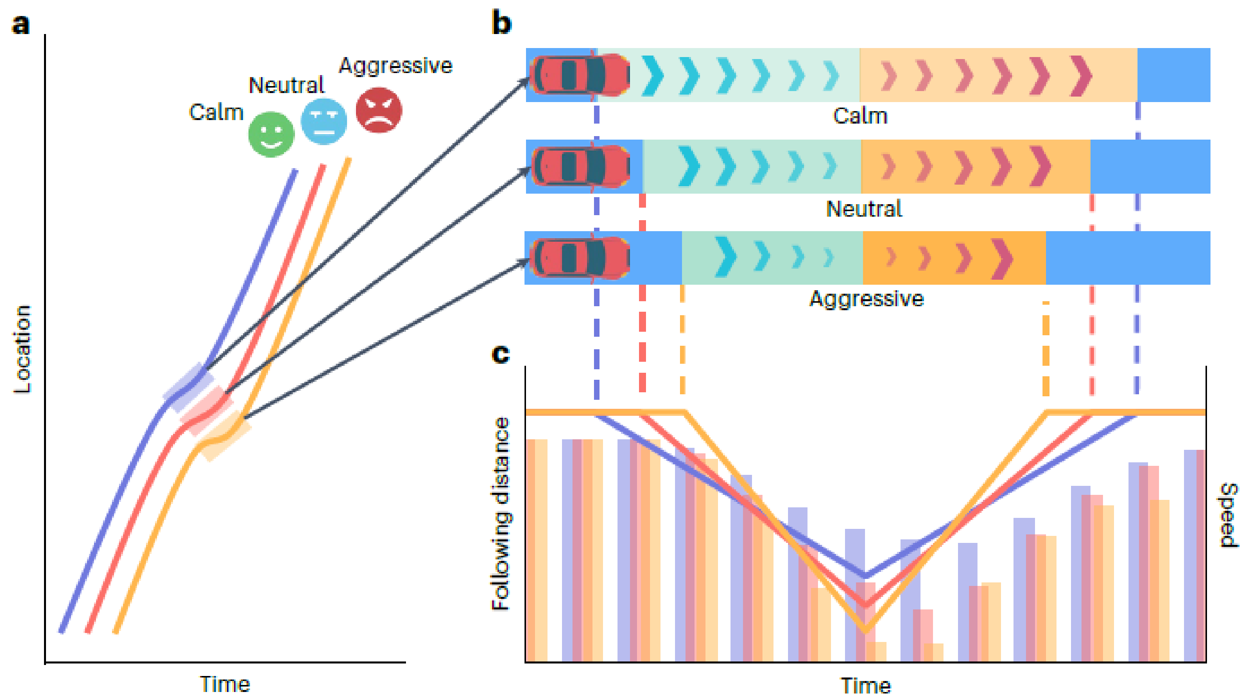


Figure 2-23: Driver aggressiveness and corresponding driving behaviours; Source: [181]

In this section, the term aggressive driving refers to this definition of driving at higher speeds with shorter more abrupt acceleration and braking times.

This section explores the different actions and driver behaviours that influence the environmental performance of tyres and brakes according to the literature reviewed.

2.6.1. Tyres

Regarding tyre wear and degradation, Liu et al. (2022) [182] establishes braking and accelerating aggressively, have the most significant influence on tyre degradation among driver behaviour actions. After braking and acceleration actions, cornering and driving speed also influence tyre wear and degradation.

Grigoratos & Martini (2014) [183] and Liu et al. (2022) [182] indicate that aggressive driving can increase tyre wear by up to 50% compared to smoother driving styles, due to the higher friction and shearing forces experienced by the tyre during rapid acceleration and deceleration. Rapid acceleration and high-speed cornering strain the tyre surface, causing them to wear out more quickly. Adopting smooth driving habits like slowing down when approaching speed bumps, refraining from quick accelerations, and minimising stop-and-start patterns, especially in traffic, can reduce tyre wear.

Liu et al. (2022) [182] developed a methodology to measure tyre wear under different conditions and driver behaviours where longitudinal accelerations correspond to the vehicle accelerating (positive) and braking (negative), and lateral accelerations represent cornering right (positive) and left (negative), respectively. Figure 2-24 (below) presents the frequency of acceleration levels between an aggressive driving behaviour (left) and a moderate driving behaviour (right). Acceleration levels in each direction can be interpreted as related to tyre wear. As the graphs below show, a more aggressive driving behaviour has higher acceleration levels, and thus higher tyre wear rates, when accelerating and braking (longitudinal acceleration) and cornering as well (lateral acceleration). The aggressive driving behaviour (left plot) has a higher tyre wear rate as the frequency of 0 g on longitudinal and lateral accelerations accounts for only 36% of the measurements. For moderate driving behaviour (right plot) the longitudinal and lateral acceleration of 0 g accounts for 50%. Kreider et al., (2010) [184], Mathissen et al., (2011) [185], and Piscitello et al., (2021) [186] corroborate that both shearing force and friction heat between the tyre tread and the road pavement increase tyre wear. When the shear force is increased when harsh braking or acceleration occurs, the tyre's mechanical wear increases and thus generates coarser and larger particles. Additionally, Mathissen el al. (2011) [185] and Farwick zum Hagen et al. (2019) [187] found that the number of ultrafine particles may also increase due to the increased number of organic compounds, found in tyre treads, being volatilised due to the friction heat caused when harsh braking and acceleration occurs. These ultrafine particles are generated from the evaporation of volatile materials that undergo a thermo-mechanical process in local hot spots on the tyre tread reaching high temperatures.

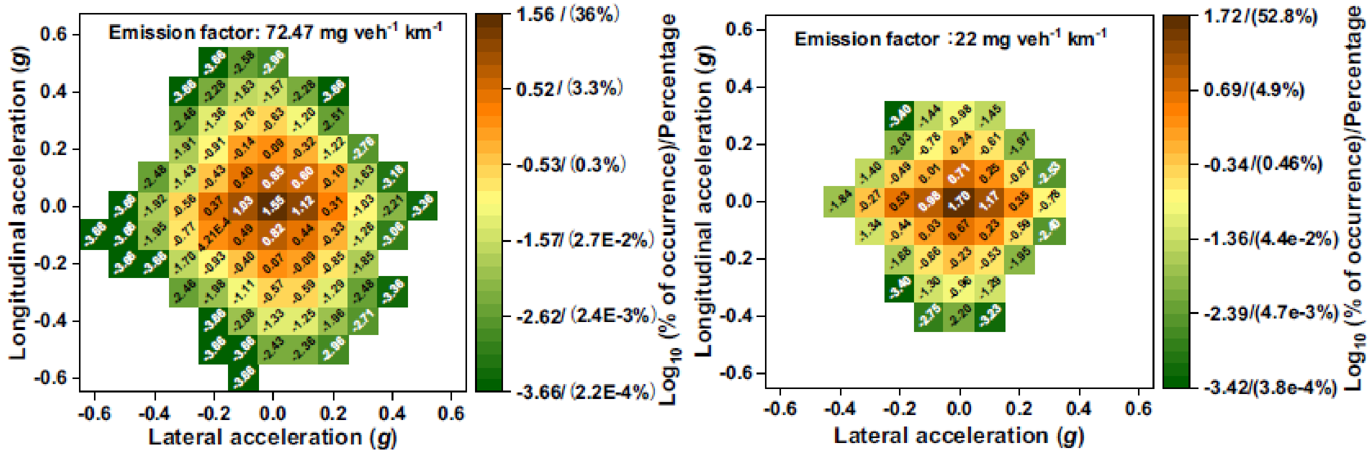


Figure 2-24: Comparative of tyre wear for a Skoda Octavia with summer tyres under typical aggressive (left) and moderate (right) driving behaviours. Source: [182]

Aggressive braking, just like aggressive acceleration, has an influence in tyre wear and particulate material emissions. Oroumiyeh and Zhu (2021) [188] measured $PM_{2.5}$ and PM_{10} concentrations from different vehicle types tested under different braking behaviours. In Figure 2-25 below, Low, Moderate and High deceleration rates produce different levels of PM concentrations. The higher the deceleration rate (i.e., more aggressive braking behaviour), the higher the concentrations of $PM_{2.5}$ and PM_{10} measured for each of the vehicle types. The resistance on the road surface during skidding or hard stops causes more tread material to volatilise.

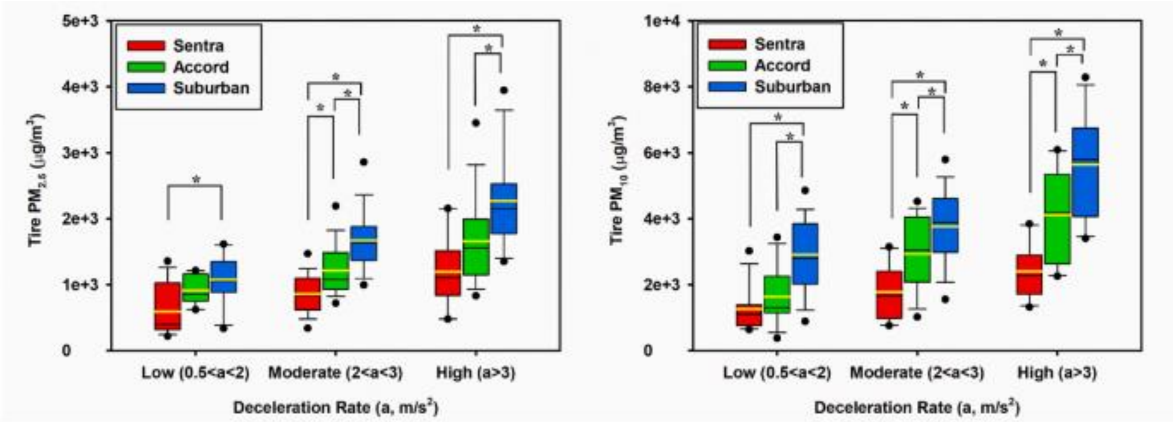


Fig. 4. Peak values in PM concentrations for the test vehicles at three deceleration rate (i.e., braking intensity) levels (a) brake PM2.5, (b) brake PM10, (c) tire PM2.5, (d) tire PM10.

Figure 2-25: Peak values of PM concentrations for text vehicles at three deceleration rate levels (i.e., braking intensity); Source [188]

Xia et al. (2023) [181] highlight that, compared to emission baselines, aggressive driving can result in an additional 1.8 million tonnes of $PM_{2.5}$ and 2.4 million tonnes of PM_{10} from exacerbated tyre wear, leading to increased emissions of particulate matter and microplastic pollution.

Cornering and travelling speed also influence tyre wear rates and its subsequent non-exhaust emissions. Liu et al. (2022) [182] found that cornering manoeuvres, particularly aggressive or high-speed cornering, can exert additional stress and strain on tyres. Aggressive cornering can amplify tyre wear by up to 40% on the outer edges. This increased stress can lead to enhanced tyre wear, releasing more particulate matter and microplastics into the environment. This study supports previous studies, such as Pohrt (2019) [189] and Veith (1992) [190], which reported that increased lateral forces on tyres lead to a sharp increase in tyre wear. Li et al. (2011) [191] also found that more tyre wear is generated during the cornering sections of roads. The same study also found that driving at speeds 20% above the average (e.g., consistently driving at 120km/h rather than at 100km/h) can lead to a 25% increase in tyre wear due to the amplified rotational forces and temperatures. Farwick zum Hagen et al. (2019) [187] associates higher tyre surface temperatures, caused by braking at higher speeds, to a higher production of finer particles (i.e., particulate matter). As seen in the figure below, Mathissen et al. (2011) [185] also confirmed the influence of driving speed and braking in particle size. The size distribution of particles during a full stop from 30km/h was unimodal with a mean particle size between 70nm and 90nm. In contrast, braking to a complete full stop from 100 km/h showed a bimodal distribution with a small node near 10nm and another mode between 30nm and 60nm (see heat map graph in Figure 2-26: Particle size distribution, total concentration and CO_2 mixing ratio of full-stop braking from 30 km/h (left) and 100 km/h (right); Source: Figure 2-26 below).

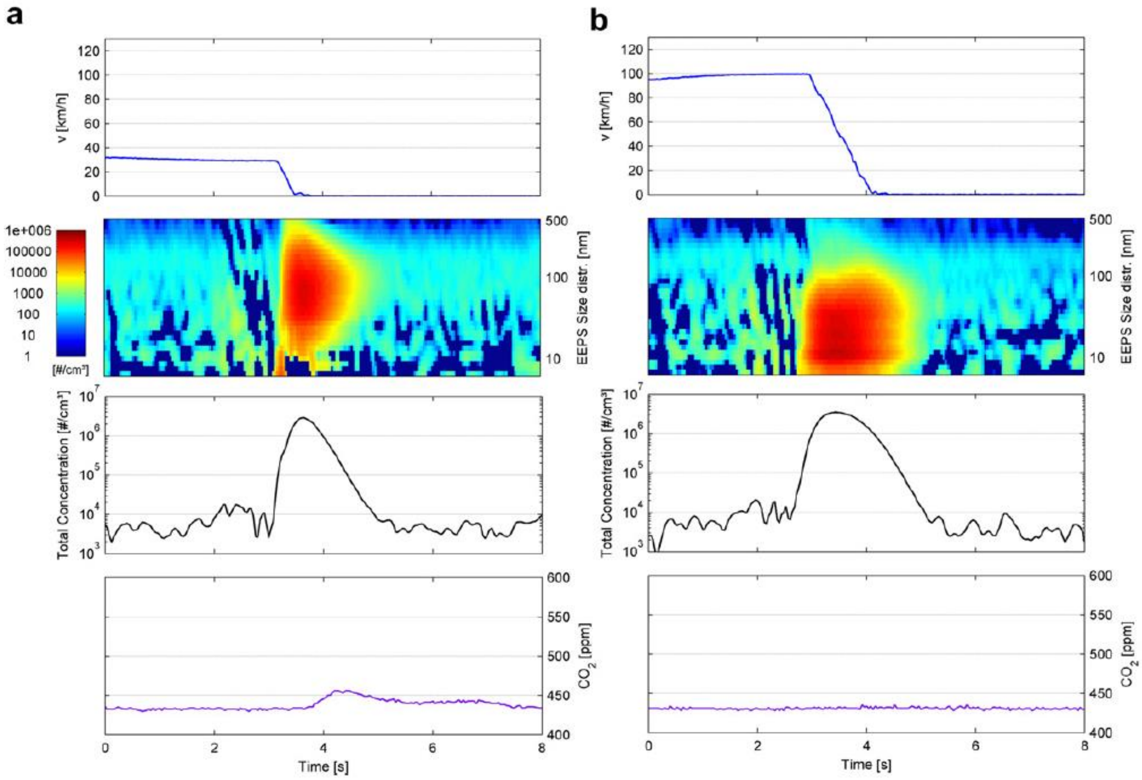


Figure 2-26: Particle size distribution, total concentration and CO_2 mixing ratio of full-stop braking from 30 km/h (left) and 100 km/h (right); Source: [185]

Other driver behaviours that influence tyre wear are not related to driving, but to maintenance and checks. Liu et al. (2022) [182] found that tyres not maintained at optimal inflation pressures tend to showcase uneven wear patterns. Specifically, tyres that are under-inflated tend to wear out more quickly at the sides of the tread and can cause excessive strain on the sidewalls which might lead to cracking, while over-inflated tyres mostly show wear in the mid-section of the tread. These issues can result in a tyre having a shorter life, increasing manufacturing and end-of-life impacts. The study Ricardo (2023) [192] performed for the UK's Department for Transport (DfT) on emissions from tyre and brake wear, confirms in its findings that volatile PN emissions significantly increase with lower tyre pressures. Routine tyre pressure checks in accordance with the maker's guidelines can significantly mitigate these wear issues.

2.6.2. Brakes

As identified in Section 2.1.3, brake wear is a significant source of particulate emissions, and this is especially true in urban areas characterised by heavy traffic. Frequent abrupt starts and stops, characteristic of aggressive driving, elevate particulate emissions stemming from brake wear. The particulates from brake wear are not just detrimental when inhaled, but they can also accumulate on surfaces, adding to the pollution from urban runoff.

Oroumiyeh and Zhu (2021) [188] studied how braking events result in noticeable surges in PM concentrations for both brakes and tyres. Notable spikes in $PM_{2.5}$ and PM_{10} levels from brakes and tyres during braking instances were detected and subsequently analysed for the influence of braking strength and weight. Figure 2-27 illustrates the relation between braking events and the generation of particulate matter.

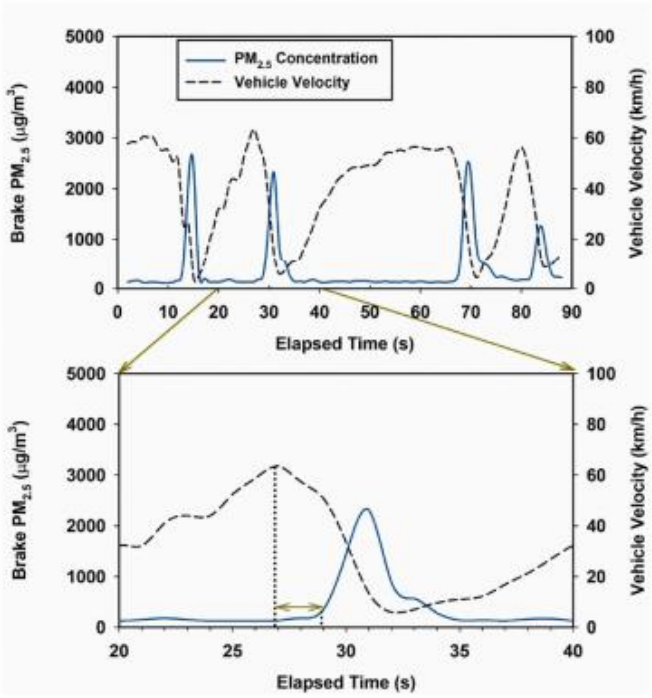


Figure 2-27: Relation between braking events and $PM_{2.5}$ concentrations; Source: [188]

Oroumiyeh and Zhu also establish that as braking becomes more aggressive, the vehicle's speed diminishes more swiftly, leading to a heightened deceleration rate [188]. During aggressive braking, the rapid reduction in speed results in the vehicle's kinetic energy being absorbed more quickly and converted into heat due to abrasive mechanisms, resulting in higher brake temperatures at the frictional interfaces and the emission of particulates of a range of sizes. Given that a greater frictional force is necessary to halt heavier vehicles, increased presence of brake wear particulates may be anticipated. To validate this, $PM_{2.5}$ and PM_{10} were measured from brake and tyre wear of three different vehicles during braking events of varied intensity (aggressiveness), as presented in Figure 2-28. As well as the vehicle size, braking deceleration rate was found to be an important factor for peak $PM_{2.5}$ and PM_{10} concentrations for all three test vehicles, confirming that driver behaviour influences the emission of particulate material from brakes. Brake particulates displayed a unimodal mass weighted particle size distribution, centring around a diameter of 3–4µm, these are smaller or finer when compared to tyre particulates which exhibited a modal diameter slightly greater, ranging from 4–5µm.

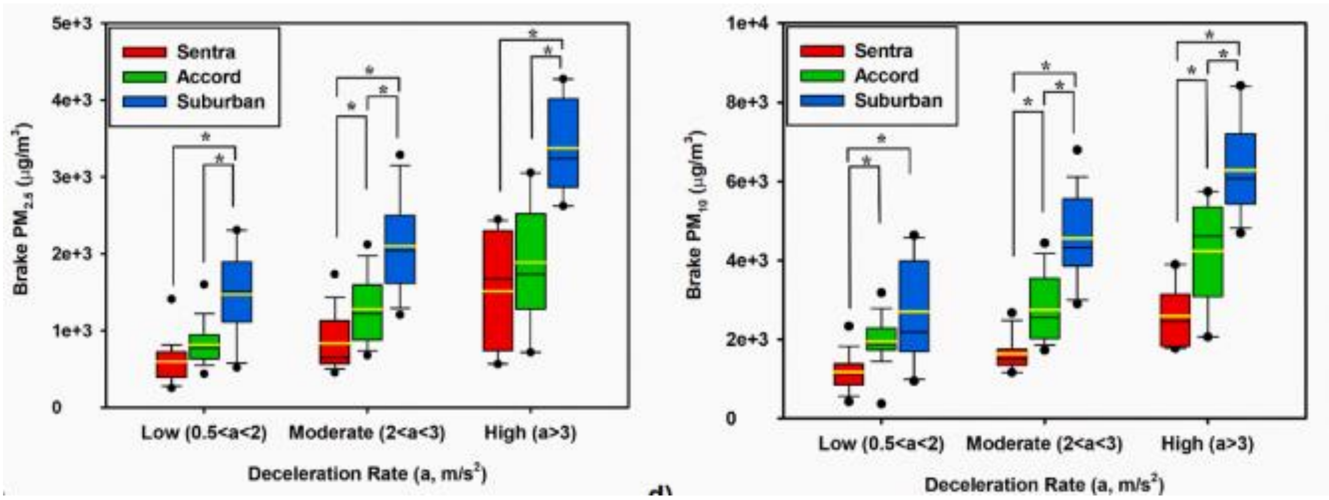


Figure 2-28: Measurement of $PM_{2.5}$ and PM_{10} concentrations in three different vehicles under three different deceleration conditions; Source: [188]

Hagino et al. (2015) [193] found that brake wear particles released during normal driving (outside of braking events) demonstrated emission levels comparable to those observed during steady deceleration and at initial velocities (<20km/h). The particle mass emissions during braking fluctuated depending on the brake system designs. Elevated emissions of brake wear particles were observed when aggressive braking was performed (characterised by high starting speeds and high deceleration rates). The magnitude of the particles emitted from brakes tended to be fine particles (less than 2.5µm) rather that the large ones (between 2.5 and 10µm). This is consistent with the findings of the report done by Ricardo (2023) [192] for the Department for Transport where it was found that PN emissions when braking from low speeds (<20km/h) were equivalent to background levels.

Driver behaviour influence in brake wear and particulate matter emission is also linked to the brake system design. Hagino et al. (2015) [193] observed test vehicles I and II (passenger vehicles) with disc brake systems and test vehicle III (medium sized truck) with drum brakes. Emissions from the disc brake systems generally rose with the starting speed at a given deceleration as illustrated in Figure 2-29 (where vehicle 1 corresponds to graphs a and b; and vehicle II corresponds to graphs c and d). On disc brake systems, at a consistent starting speed, such as 60 km/h, emissions appeared to grow with escalating deceleration. In contrast, the drum brake system (of vehicle III; graphs e and f) displayed an increase in emissions with a rise in the starting speed but did not exhibit a marked variation with deceleration levels. These patterns were equally evident when considering the total $PM_{2.5}$ and PM_{10} mass emissions from both deceleration and acceleration. At an initial speed of 60km/h and deceleration rates of 3m/s^2 (1.5m/s^2 for vehicle III), the $PM_{2.5}$ to PM_{10} mass ratios were 57% (for vehicle I), 72% (for vehicle II), and 85% (for vehicle III). Consequently, the emission magnitude of finer particles (less than 2.5µm) surpassed that of the larger ones (between 2.5µm and 10µm). In conclusion, aggressive braking will generate more emissions on disc brake systems, but driver behaviour has minimal influence in the emission of particulate matter when using drum brake systems.

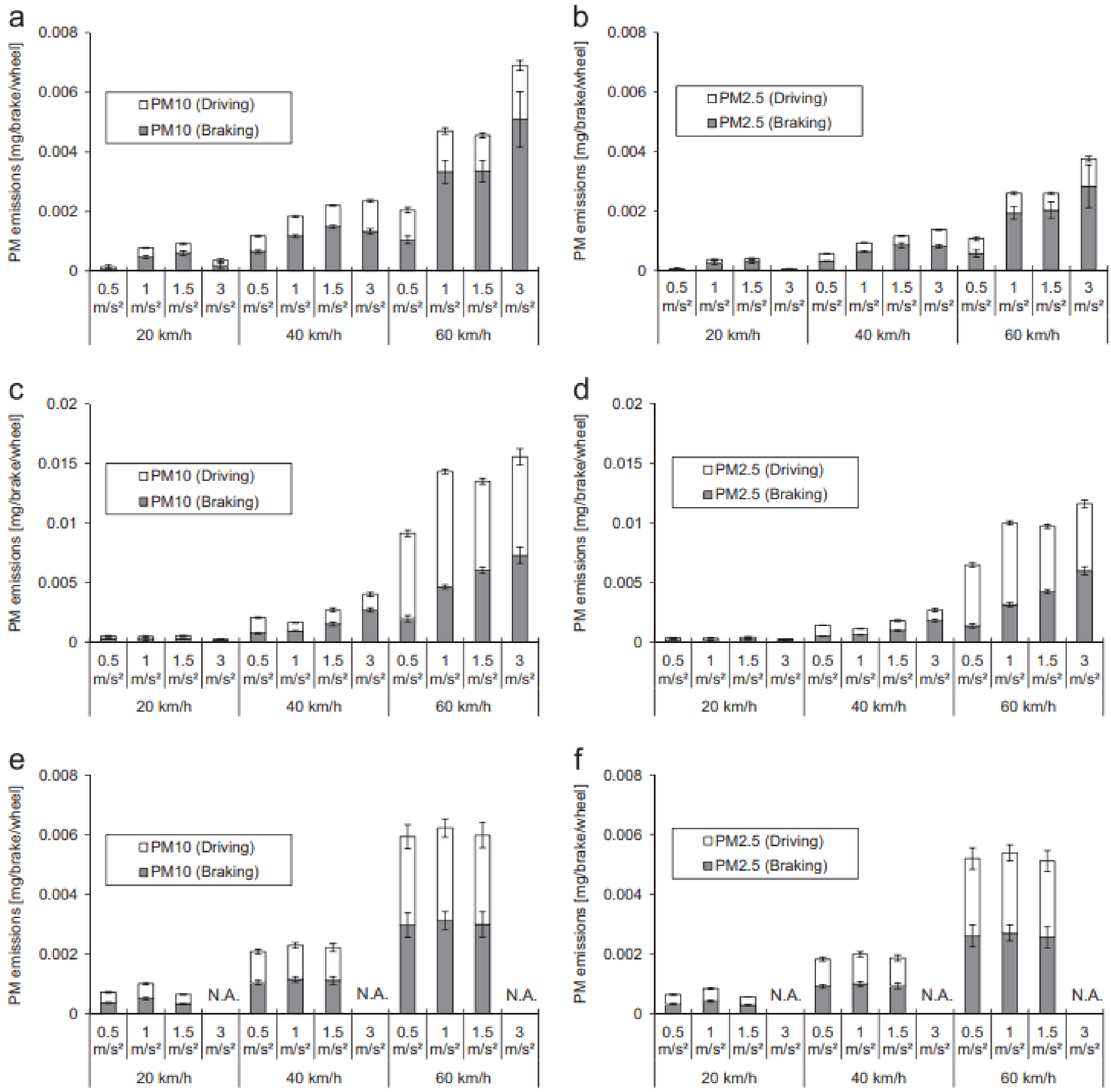


Figure 2-29: Average $PM_{2.5}$ and PM_{10} emissions in braking events at different starting speeds and deceleration rates in three different vehicles. Vehicle I (plots a, b), and II (c, d) had disc brakes, vehicle III (e, f) had drum brakes; Source: [193]

These findings about braking from higher speeds leading to an increased production of particulate matter are also supported by the findings from Vojtíšek-Lom et al. (2021) [194], whose tests show that when braking intensively from speeds of 40 km/h, the emissions per stop and per kWh remain relatively low. This indicates that when drivers adhere to city speed limits of around 50 km/h and drive minimising frequent accelerations and decelerations, emissions are minimised. As speeds increase, so do the particle emissions, especially with aggressive braking behaviours. Avoiding harsh braking at elevated speeds is essential to avoid the emission of particulate matter due to driver behaviour. Vojtíšek-Lom et al. (2021) [194] also show that there is a significant increase in particle production when braking from higher speeds like 175 to 100 km/h compared to the standard WLTP braking events at 20–70 km/h. The findings in this study are consistent with the thermal origin of the nanoparticles observed by Kukutschová et al. (2011) [116] and discussed in detail in Niemann et al. (2020) [195], with strong temperature effects observed by Mathissen et al. (2018) [185] and Zum Hagen et al. (2019) [111]. From a thermodynamic perspective, higher deceleration rates lead to higher local temperature at the friction surfaces where decomposition and volatilisation of material occurs.

Vojtíšek-Lom et al. (2021) [194] highlights that the emission of brake wear nanoparticles is influenced by both the initial speed and deceleration rate. Consequently, reducing harsh braking and high-speed braking can significantly lower these emissions. Although there is variation among different brake pads and no definitive emission thresholds are recommended, the data implies that lowering speed limits in congested areas could be beneficial. This aligns with the advantages of cautious, anticipatory driving, which not only enhances road safety and reduces fuel consumption, but also potentially decreases brake wear nanoparticle emissions. Additionally, Vojtíšek-Lom et al. (2021) [194] notes that intense or aggressive braking events, despite their infrequency, contribute substantially to total emissions and should not be overlooked.

2.7. Impact of road surface and design on environmental performance

Effective tyre-road interaction plays a crucial role in enabling safe and comfortable driving. This is a fairly complex sub-system of vehicle dynamics, essential for maintaining control of a vehicle, in acceleration, braking and cornering, but that can have significant impact on tyre wear as well [196]. Although road surface characteristics are essential to enable good tyre-road grip, there are arguments that asperities in the road surface can negatively impact road noise, rolling resistance (fuel efficiency) and tyre wear, raising concerns about its influence on the environmental performance of vehicles (and their tyres).

In the UK, the Manual Contract for Highways Works (MCHW) Series 900 [197] and 1000 [198] and Design Manual for Roads and Bridges (DMRB) CS 228 [199], 229 [200] and 230 [201] set the national specifications for materials, construction quality assurance, condition monitoring and maintenance assessment procedures for pavements. These have enabled engineers to design, build and maintain roads that enable safe and comfortable driving, but little consideration is given to the environmental performance of road pavements in use. Similarly, the recent introduction of road noise levels requirements in CS 230 [201] certainly represents a step forward. However, these standards do not advise on road construction specifications to minimise tyre rolling resistance and wear. There may be limited understanding of how an optimal balance between safety and environmental performance can be achieved, which is a barrier to redefining road surface properties and updating the related specifications accordingly.

This section of the study aims to provide an overview of road surface characteristics and the impact that these have on road safety and environmental performance and on the vehicles/tyres using them. An extensive review of the literature was carried out to identify the challenges and possible solutions that National Highways could consider minimising the production of Tyre Road Wear Particles (TRWP), road noise and rolling resistance without putting the safety of road users at risk.

Over the past few decades, research has found that various road attributes such as road geometry (e.g. sharp bends), pavement texture, porosity, wetness, and temperature play crucial roles in the production of TRWP [202], [203]. Focusing on road surface characteristics, unevenness and macrotexture have been identified to be the most influential factors on abrasion, especially at high speeds [196], [204], [205]. Andersson-Sköld et al. [206] concluded that microtexture can also impact TRWP at low speeds. For this reason, the following sections will focus on three properties:

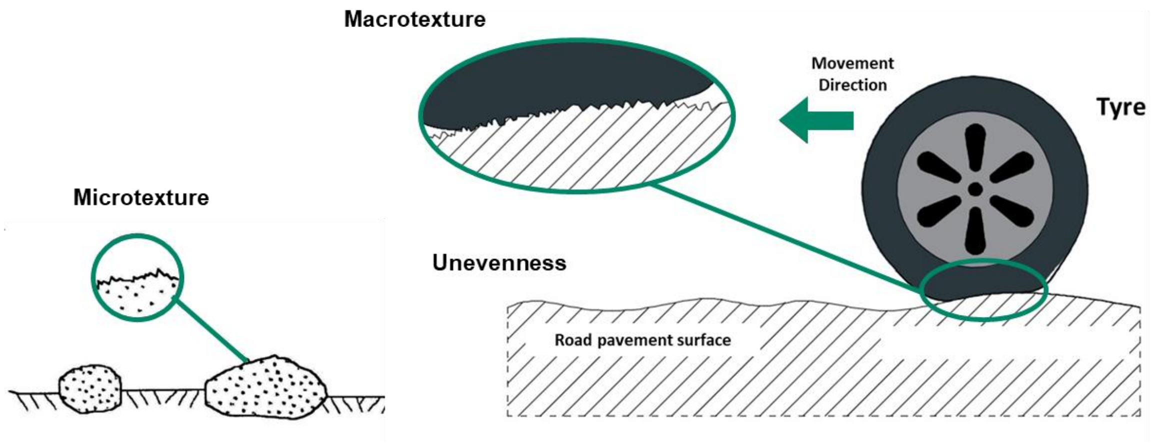
Unevenness: deviation of a pavement from the true planar surface in the range of 0.5m to 50 m.

Macrotexture: deviation of a pavement from the true planar surface in the range of 0.5mm to 50mm.

Microtexture: deviation of a pavement from the true planar surface for less than 0.5mm.

Figure 2-30 compares the order of magnitude of the road surface properties considered in the study.

Figure 2-30: Comparison of road surface properties and order of magnitude covered



An important consideration regarding road surface characteristics is that they are not constants, and they tend to deteriorate over time due to the effects of traffic loading and environmental effects. Focusing on the properties introduced above, recent studies [207] have shown how macrotexture is minimally affected by the polishing process, whereas microtexture can be significantly impacted. This is why national specifications require measurements to be collected at various stages of the lifecycle of the pavement, starting at construction [197], [198], and periodically throughout the rest of the pavement lifecycle [201].

Starting with TRWP which has been identified as a significant environmental impact of tyres (section 2.1.2), an extensive review of the literature is performed in this section to look at the effects of road surface characteristics on functional and environmental performance of road pavements in use. In Section 9, there are discussions around balancing the need to reduce TRWP, noise and rolling resistance and ensuring that the safety and/or functional performance of roads are not put in jeopardy. Ultimately, based on findings from the literature, recommendations are made to summarise what the impact of road surface characteristics is on each of the considered aspects, to drive continuous improvement within the sector and deliver environmentally optimal roads.

2.7.1. Tyre and Road Wear

Since studies have shown evidence that large proportions of oceanic plastics come from tyre wear (see Section 2.1.2.2), and research has been carried out by the tyre manufacturing industry to minimise the production of TRWP. Although it is clear that the issue is not just one sided, there appears to be less research considering the influence of the road surfaces. This may be due to the longevity of road surfaces, the requirements on pavement engineers to manage important road safety (grip and drainage) and noise characteristics, and adherence to well established standards limiting interest in road surface changes.

Recent research has found that the majority of particles resulting from tyre-road interaction consist of multiple components: rubber (from tyres), metals (from brakes and other vehicle components) and inorganic compounds (mainly salts and silica, from the road). Looking at the issue from a purely tribological perspective, it is evident that road surface characteristics significantly impact the production of TRWP, through abrasion. Two characteristics of the tyre and road materials are responsible for this:

Surface irregularity: asperities of one surface can act as abrasives on the other.

Hardness: softer materials are more prone to wear when in contact with harder surfaces.

Despite the fact that the difference in hardness usually drives tyres to wear faster than pavements, it must be considered that this characteristic of road materials is essential to deliver adequate levels of macro- and microtexture, and resistance of these to polishing, throughout the whole lifecycle of every pavement. Focusing again on road unevenness, macro- and microtexture, research has found these are the most influential factors on abrasion and TRWP [196], [204], [205], [206]. Although findings from the literature make clear that properties of the road surface can impact the production of TRWP (e.g. [196], [202], [203], [204], [205]), there are still plenty of open questions with regard to the mechanics of the phenomenon, both from a qualitative and quantitative perspective. In addition, it must be considered that, whilst low macro- and microtexture can be achieved by adopting relatively shallow and therefore cost-effective types of treatments, possibly helping with reductions in TRWP and other environmental aspects, these characteristics also serve to achieve adequate levels of skid resistance, potentially creating a conflict. On the other hand, low levels of road unevenness could be a way to deliver safe, comfortable and environmentally optimum roads, but they might be more difficult to achieve in construction due to deeper interventions required. This poses questions in regard to what the possible solutions to the problem could be, with financial sustainability performance that potentially clashes with environmental concerns.

In 2020, National Highways investigated defining an experimental programme to evaluate non-exhaust emissions associated with the performance and characteristics of the road surface [208]. The study identified that, thanks to their ability to simulate realistic tyre road interaction, devices like the Darmstadt Scuffing Device [209] and the Ulster Road Test Machine [210], show great potential for estimating the effect of macro- and microtexture on TRWP, with results close to the expected quantitative and qualitative nature of the problem [208]. However, concerns remain around the validity of the findings from laboratory tests, which cannot be directly compared to any network level sort of data analysis [208].

2.7.2. Skid resistance

Various factors such as driver behaviour, vehicle mechanics, environmental elements and pavement condition can influence road safety but, given its tight link to road accidents [211], skid resistance remains paramount to consider at all stages of the lifecycle of all pavements, starting from design. In fact, extensive research has demonstrated a link between skid resistance and safety outcomes, in numerous road accidents [212], [213].

Skid resistance is defined as the contribution of the road surface to the overall friction available at the interface between tyre and road [199]. Although there are several factors that influence pavements' skid resistance, with e.g. increases in temperatures leading to reductions in skid resistance [214], high hardness of aggregates linked to high skid resistance [215], and high porosity that can improve wet skid resistance [216], it is the macro- and microtexture of road surfaces that have the highest impacts. In this regard, studies have proven how appropriate levels of pavement macro- and microtexture contribute to provide adequate skid resistance and tyre-road frictional properties [210]. Typically, two components, hysteresis and adhesion, are recognised to be the primary contributors to skid resistance [217]. Whilst the hysteretic component results from the deformations of the tyre upon contact with pavement asperities, thus relying on macrotexture (which is important at high speeds and in wet conditions), adhesion heavily relies on the true contact area between tyre and pavement and microtextural properties of the road surface (important at low speeds and in dry conditions) [218]. For instance, recent investigations have estimated that macrotexture typically accounts for 90% of the friction when the vehicle speed surpasses 90km/h [219], [220], while microtexture becomes influential at speeds lower than 20km/h [221], [222].

In the UK, skid resistance is monitored annually, using the Sideway-Force Coefficient Routine Investigation Machine (SCRIM), the results converted to a Characteristic Skid Coefficient (CSC) and Investigatory Levels (IL) set to meet specific site category requirements, as specified in CS 228 [199]. This also provides guidance on how the measurements should be corrected to account for the effects of temperature, standardised to a speed of 50km/h and ultimately supplemented by measurements of macrotexture, which influences the loss of the hysteretic component of skid resistance, important at increasing speed. In terms of adhesive properties, DMRB CD 236 [223] provides guidance to ensure adequate levels of microtexture are provided to road vehicles and that the polishing effect does not become a problem throughout the lifecycle of a pavement. This allows UK road authorities to manage skid resistance on their road networks consistently and reduce the effects of skidding as a contributory factor in road accidents at a national scale.

In 2018, Highways England evaluated the effectiveness of Cold Applied Ultra-Thin Surfacing (CAUTS) on a few selected sites, with focus on textural and skid resistance regain and durability. Results show that post-treatment, all the considered sections comply with the appropriate ILs and macrotexture depth, both immediately post-construction and two years after treatment [224], possibly constituting a relatively rapid and cost-effective way to recover textural and skid resistance properties of the road in a sustainable manner.

2.7.3. Drainage properties

Water drainage on the pavement surface is another crucial aspect in pavement design. Accumulation of water on the pavement can impede visibility (due to splash and spray), diminish grip and eventually disrupt traffic [225]. In some situations, this may lead to hydroplaning which can be extremely dangerous for drivers [226].

Generally, pavement geometry, including cross-slopes and grades, is the most common countermeasure engineers use against the stagnation of water on the road surface [227]. However, from a pure road surface perspective, providing adequate levels of macrotexture is key to help dissipate water and reduce the risk of hydroplaning, especially at high speeds or under heavy rain events [228].

Research studies have highlighted that the risk of hydroplaning is influenced by factors such as water film depth (which depends on macrotexture), flow path, rain intensity, and pavement surface type [229], [230], [231]. In fact, by enabling faster water dissipation, macrotexture plays a crucial role in preserving the skid resistance of wet road surfaces [232].

Water flow path is highly linked with rainfall intensity, rain event duration and pavement properties (including geometry, texture, materials, and permeability) [233], [234]. Cross slope shortens flow path length, while longitudinal grade extends flow path length. On the other hand, pavement macrotexture allows the water to freely flow away from the immediate surface, preserving a minimum of tyre-road contact [235], and determining the amount of splash and spray generated at the tyre-road interaction [236].

Although quantifications are difficult to make and can be influenced by a number of factors (mentioned above), it is clear how adequate levels of macrotexture reduce the time needed to free the road surface from water [201], [237].

Porous Asphalt (PA) has been developed as a viable solution to improve the drainage properties of road pavements, but it was found to also benefit road noise. Due to the large voids, rainwater can infiltrate into the road surface and drain away from the connected pores in the road surface to the edge of the road surface [238]. Based on the case study of PA in the Netherlands, where the void content in PA reaches ~20%, the increased air void in PA benefits the drainage of the pavements [239].

2.7.4. Road noise

Road tyre noise is generated from interaction forces between the tyre tread and the road surface, the compression and decompression of air trapped between the tyre tread blocks and frictional forces between the tyre and the road surface. Vibration of the tyre leads to the production of low frequency noise (<1kHz) while high frequency noise (>1kHz) is created from the aerodynamic processes associated with the trapped air. The magnitude of these noise generating mechanisms depends on the characteristics of the pavement and varies with the texture, stiffness, and porosity of the surface layer [240].

Texture wavelengths in the macro and mega-texture range (0.5mm – 500mm) govern tyre/road noise. Maximum vehicle pass-by noise levels have been shown to correlate with texture amplitudes in the mega-texture range, with noise levels on pavements with transverse texture being higher than those on pavements with a random texture profile, for a given amplitude [240]. Typically, negative textured surfaces result in lower levels of vibration in the rolling tyre than positive textured surfaces.

The porosity of the road surface, which is correlated with the air void content, plays an important role in both the generation of tyre/road noise and the absorption of the sound propagated away from the tyre/road interface. Increasing porosity reduces the extent to which trapped air is compressed and decompressed, lowering aerodynamic noise. The sound absorption of the surface depends upon the thickness of the porous layer as well as the tortuosity – the ratio of the air path through the surface layer to the corresponding direct path through the surface layer [240].

The mechanical impedance, or stiffness, of the pavement is higher than that of the tyre and therefore reducing this property lowers the impact forces on the tyre and subsequent tyre/road noise. This can be achieved by replacing some of the stone aggregate with rubber aggregate, although such surfaces can have issues in terms of durability [241].

When considering negative texture surfaces, tyre/road noise can be reduced by making the surface as smooth as possible and increasing the mean profile depth of the surface layer [241]. These noise reducing properties can be achieved through good compaction, small maximum aggregate size (typically around 6mm) and high built in air void content (around 20%) [241].

Properties of both the tyre, such as rubber hardness, and the road surface, such as mechanical impedance, are affected by temperature and this can alter the noise generation. When measuring tyre/road noise, corrections for temperature are applied in accordance with ISO 13471 [242], [243]. Understanding the attribution of temperature changes to specific noise generating mechanisms is an ongoing research area but, in general, positive corrections are applied to measured levels when air temperature is above 20°C and negative corrections are applied when air temperature is below 20°C. In other words, higher noise levels are typically measured in cold conditions, likely due to higher impact forces associated with harder tyres and stiffer pavements.

Numerous studies have shown that tyre/road noise increases as road surfaces age [244], [245]. This arises from the degradation of surface layer due to road traffic and weather conditions. Broadly speaking, the road surface becomes less smooth, texture amplitudes increase, and detritus clogs up some of the voids reducing the surface porosity. The impact of these factors on road traffic noise varies depending on local conditions but it has been shown that thin surface course systems (TSCS) can lose around 0.5dB per year in acoustic performance [244].

There have been a wide variety of research studies involving practical demonstrations of new types of low noise road surface. For example, the pan-European project Persuade looked at trialling a poroelastic pavement with rubber aggregate [246]. Results indicated that the pavement was very quiet, but that durability was an issue. More recently, Highways England, the Mineral Products Association and Eurobitume UK funded work into creating a more durable low noise surface [247]. The resulting Premium Asphalt Surfacing System (PASS) achieved initial targets for durability and road noise, but further testing is required to prove how it performs in the long-term.

National Highways' requirements for pavement surfacing specify a TSCS as the default approach [223], with surfaces that are not low noise being prohibited for use in areas sensitive to noise or subject to exiting high noise levels. TSCS are quieter than hot rolled asphalt for which a departure from standard is now required.

2.7.5. Rolling resistance

Rolling resistance is defined as the combination of forces which act against the motion of an object rolling along a surface. With focus on tyre-road interaction, rolling resistance is the force resisting the motion of a tyre rolling along a road surface. It is good to notice that rolling resistance and skid resistance are separate and, in fact, whilst rolling resistance acts against a rotation of tyres, skid resistance (or friction) acts against slide.

Through each revolution, each tyre rolls and deforms under the weight of the vehicle and interaction with the shape of the road surface. This process causes vibrations and thus energy to be consumed, producing heat as a by-product, which fuel is used to compensate for. Although current specifications do not account for the effects of rolling resistance directly, it is clear how important it can be to rolling resistance is important as it impacts fuel usage or range from electric vehicles.

Although there are complexities which make quantifications difficult, including the effect of loading and environmental elements, there is a consensus that macrotexture impacts rolling resistance significantly, due to the larger asperities of the road surface, which induce higher deformations in the tyres. This has been quantified between 1.5% and 10% increase in rolling resistance, leading to increased fuel consumption, about 3% on average [248].

Another key characteristic of road surfaces that impact rolling resistance is road unevenness. Hammarstom et al. [249] have found that road roughness can increase rolling resistance by 19% up to 48% for cars and up to 47% for heavy trucks. Assuming that an increase of 5% in rolling resistance can lead to a 1% increase in fuel consumption, it can be inferred that road roughness can lead to an increase in fuel consumption of up to 10% [250], [251].

Although, some studies [252] suggest that microtexture can cause tyre deflection, to a small percent (smaller than other wavelengths), the general consensus is that microtexture does not affect rolling resistance [253]. This does suggest that, theoretically, smooth pavements with adequate levels of skid resistance can be achieved, enabling pavement engineers to deliver low rolling resistance pavements that are safe to drive on.

Table 9/12 and 9/13 in the MCHW Series 900 Clause 942 denote the minimum and maximum texture depths per 100m section depending on the road type, surfacing material and traffic speed. The tables start as low as 0.8mm for B, C, U and A roads with a speed under 80km/h and as high as 1.8mm for high-speed roads, preserving road users' safety but also setting a lower bound limit for the possible environmental benefits that can be achieved in use.

Achieving reductions in rolling resistance through changes in road unevenness is not always economically viable nor practical, as it requires replacing both the surface and binder course systems with new material. In fact, more recent studies have looked more into methods to improve surface regularity via advancing the paving quality assurance processes [254], and introduction of Low Rolling resistance Asphalt Mixtures (LRRAMs), characterised by adequate skid resistance properties and low macrotexture [248]. Results here show that the material characterised by the greater irregularities, often linked to higher road noise and TRWP, also showed the highest rolling resistance (3%-5% on average) [248]. This highlights how paving techniques and macrotexture levels could be two key areas to explore in order to enable environmentally optimal roads.

3. Characteristics of environmentally optimal tyres and brakes

3.1. Overview of the literature

The key findings from review of the life cycle environmental performance of tyres highlight that:

- Tyre use contributes the highest environmental impact, over a tyre's life cycle with key sources being CO_2 emissions from fuel use (resulting from influence of a tyre's rolling resistance) followed by tyre wear emissions resulting from abrasion with the road surface. Innovations improving the rolling resistance of tyres through design and formulation optimisation need to be evaluated. Similarly, investigations into tyre designs to reduce the release of tyre and road wear particles need to be intensified, following the availability of ample evidence on the accumulation and leaching of fine and ultrafine particulates leading to human toxicity and other adverse impacts on the ecosystem.
- The manufacturing or production of tyres, as indicted by literature, was determined to be the second most polluting life cycle phase; Key sources of emissions from the production phase include the release of respiratory inorganics from the processing of crude oil during the production of synthetic rubber, which also contributes to the increased non-renewable resource depletion. Scope for consideration of bio-based alternatives also need to be explored while effectively capturing impacts associated to bio-derived products, mainly land use, resulting biodiversity loss, biomass management or supply needed for commercial scale production.
- Potential strategies for circularisation of tyres, improving their resource efficiency through displacement of virgin tyres (and their materials) and improving the existing product's value through material recovery routes need to be investigated. Key trade-offs, in terms of shifting burdens across other impact indicators must also be assessed as a part of ongoing review.
- Tyre tread patterns, tread depth, rubber composition and road surface texture, in addition to a multitude of complex interactions across several factors have been found to contribute to tyre noise. Particularly traverse tread patterns have been found to produce more noise compared to circumferential patterns. Tyre labelling provides an indication of tyre-road noise. However, the differences in the testing specifications between tyre testing procedures (ISO) and "real-world" road surface and environmental scenarios has led to limitations in ascertaining definitive set of factors, thus hindering the development of optimised tyre designs.

Review of LCA of brakes suggest that:

- Manufacturing or production phase of brake discs and brake pads is the most polluting life cycle phase over a brake systems' life cycle; innovative material formulations used in designing brake discs and pads and processes/ activities involved in component production influence the production phase environmental footprint of these components.
- Use phase is the second most polluting life cycle stage across the life cycle of brake systems and this is due to the impacts from production of brake disc and pads far outweighing brake wear emissions, over the service life of the components. Increase in local temperatures of just +15°C over a critical temperature (typically between 150-250°C) has been found to exacerbate brake wear particle number emissions by about 5,000 times, these temperatures can be reached in high speed or repeated braking conditions even in normal driving. Therefore, formulations and design considerations that aid heat dissipation during braking is crucial for brake wear reduction and dust control. It is the smallest ultrafine particles that post the greatest threat to human health, and since even a large number of such particles is a tiny fraction of the total mass of particles lost, brake wear quantified as mass may not be a good measure of health impacts.
- Iron, brass and synthetic silica are some of the most commonly found components in the composition of brake wear dusts. The composition of brake wear emissions is highly influenced by the material formulation of brake pads and discs. Accumulation of these metals in varying particle sizes have been reported with, particularly, the fine and ultrafine fractions being found to penetrate through tissues into blood streams and deposit in other organs.

3.2. Expert analysis – Tyres

3.2.1. Impacts related to Tyre production

An introduction to life cycle assessment, as an overall approach to evaluating the environmental performance of products was made in section 2.1.1. Setting this context, an attempt was made to understand and summarise the key sources of emissions and environmental impact, by a tyre's life cycle stage (Table 3-1).

The life cycle inventory, that were provided for tyres in the analysed set of literature, showed consistency in the material selection and composition which is representative of the average estimates presented in Figure 2-5 in literature review section 2.1.2, except for studies which partially focus on bio-based Guayule rubber [7] [11]. An analysis of the production inventory confirms that the raw material acquired for tyre production dominates production-related emissions, particularly in terms of upstream processes burdens (crude oil extraction and processing to produce synthetic rubber). On the overall, manufacture of tyres for a vehicle over its lifetime, 20 barrels (imperial) of crude oil is required. Melting and moulding process of tyres tend to release significant amounts of harmful substances such as polyaromatic hydrocarbons (PAHs), benzothiazoles, isoprene, potential NOx and SOx emissions in addition to heavy metals such as zinc and lead. In the absence of appropriate production equipment or filtration mechanism, these emissions could lead to hazardous respiratory organics and inorganics that could be potentially carcinogenic to human health.

Guayule and Hevea rubber have been explored as a potential bio-based alternative, but the pathways to bio-based rubber production need to be thoroughly understood. From an analysis of these studies, the production related GHG impacts for Guayule rubber was found to be only slightly higher than that of conventional tyres (+6%), which was achieved only through the co-production of other valuable products alongside natural rubber production. None of the analysed literature related to bio-based products showcase coverage of land use and land use change impacts. Alternatively, some OEMs such as Continental, have developed approaches for use of recycled polyester yarn from PET bottles to produce textiles for carcass of the tyres [255]. Such a circular strategy is anticipated to displace the need for virgin materials required for tyre production and reduce the embodied energy of the innovative tyres. However, there is limited information on the cost considerations, in terms of the use of recycled polyesters and sustainably sources additives and fillers to be conclusive of this innovation.

The second key contributor to a tyre production overall environmental impact is the use of carbon black. Carbon black consists of more than 90% of pure form of carbon and is produced through incomplete combustion of heavy hydrocarbons. Therefore, carbon black is not only energy-intense but also carries a relatively high carbon footprint, with studies suggesting 2.4 tonnes of CO_2eq per tonne produced [256] [257]. Evaluating the techno-economic and environmental feasibility of producing carbon black from circularised routes (from ELTs), or producing them through pyrolysis of bio-derived feedstock (for example rice-husk ash [255] [258] appear to potentially provide significant savings of up to 50-75% in the overall GHG savings for carbon black. However, the feedstock costs can increase product costs substantially and could end up being expensive in the current market, especially when there is low demand for sustainably sourced tyre components and lack of regulatory restrictions on the use of fossil-derived materials. Meanwhile, more cost-effective and readily accessible alternatives such as nanoclay composites such HD silica and HD-HS (High-dispersion high surface area) silica appear to be environmentally optimal options (-25% compared to carbon black). These candidates at specific compositions appear to improve performance via reduced rolling resistance of up to 30% at specific compositions, compared to conventional tyres [44].

3.2.2. Impacts related to Tyre use

Use-phase of a tyre has been found to contribute nearly 80% of the overall life cycle impacts from the analysis of life environmental impacts reported by a number of studies [5] [6] [7] [9] [11] . Fuel consumption attributed to this phase through energy loss from a tyre's rolling resistance, is predominantly captured via cumulative energy demand (CED) Resulting CO_2 emissions is captured by the GWP indicator. While vehicle use itself is outside the scope of the LCA of tyres, tyre designs, supplemented by vehicle's characteristics such as age, segment/size and mass, are observed to increase wear and tear of tyres, deteriorating tyre grip over its service life. Besides the CO_2 emissions resulting from the share of fuel consumptions related to the rolling resistance of tyres, the release of coarse, fine and ultrafine particulate from the tyre use is also provided a relatively equal weightage across the reviewed studies.

Table 3-1: Summary of key sources of environmental burdens captured by various LCA impact indicators, at each of tyre's life cycle stage

Life Cycle Stages	Sources of Impact and key emissions (where available)	GWP	CED	ODP	AP	EP	ARD_MM	ARD_FE	HTP	PMF	ET
Raw material extraction and processing	Material and energy use	✓	✓				✓	✓			
	Crude oil extraction	✓	✓	✓	✓	✓		✓	✓		✓
	Fuel/ electricity use	✓	✓		✓	✓		✓			
	Aromatic compounds from crude oil extraction and its processing								✓		✓
Tyre production	Material and energy use	✓	✓				✓	✓			
	Polyaromatic hydrocarbons (PAHs), benzothiazoles, isoprene;								✓		✓
	Release of heavy metals such as zinc and lead			✓	✓				✓		✓
	Particulate matter (carbon black)	✓		✓					✓	✓	✓
	Release of NOx and SOx	✓		✓	✓	✓					
	Process waste to water					✓					
	Fuel/ electricity use	✓	✓		✓	✓		✓			
Product distribution	Fuel/ electricity use	✓	✓		✓	✓		✓			
Use	Uncontrolled release of particulate emissions (microplastics) from tyre wear	✓							✓	✓	✓
	Fuel use	✓	✓		✓	✓		✓			
EoL – Option 1 - Landfill	Release of harmful aromatic compounds								✓		✓
EoL – Option 2 - Incineratio n	Release of harmful chemicals from leaching										
	Fuel/ electricity use	✓	✓		✓	✓		✓			
	Release of NOx and SOx	✓									
	Energy consumption	✓	✓		✓	✓		✓			
	Material and energy use	✓									
EoL – Option 3 - Recycling	Particulate matter release								✓	✓	✓
	Process waste to water					✓					
	Release of NOx and SOx	✓									

Impact of external factors, particularly road surface, the environment (climate/ weather conditions), traffic load, traffic composition and the resulting downstream impacts of the particulates (emphasising the resulting human and eco-toxicity) are rarely covered as a part of standardised tyre-testing approaches. Incompatible road surfaces, in combination with poor tyre design or aged tyres, could potentially double rolling resistance thereby increasing fuel consumption, following the findings reported by Reeves et al, 2010. This could lead to roughly 10% increased fuel consumption in an average passenger car and a substantial 15-30% increase for LGVs. From a particulates perspective, concrete pavements have been observed to deteriorate with time, particularly from the addition of grid (salt and sand mix) to melt snow and ice. Eventually with the wearing course exposed to traffic conditions, the micro-texture of the road also deteriorates, subsequently wearing out the tyre treads [20] [259]. Similar observations have been made by a study in the US, which observed 1.4-2 times higher tyre and road wear particles to generate from vehicles being driven on Portland cement concrete surfaces [260]. The current lack of a dedicated harmonised approach to quantify and account for the impacts of these key parameters (in addition to tyre design and related life cycle emissions), in the tyre testing and labelling specifications creates an argument to modify current standardised tyre testing procedures to adopt a more robust and holistic approach.

3.2.2.1. Trends in Tyre and Road wear particulate generation

Tyre wear is commonly one of the largest sources of microplastic pollution to the environment. Tyres are a chemically complex and heterogenous mixture, with 5 to 10% additives that provide tyres stability, and durability over the production and use-phase. Tyre and road wear are classified as ‘microplastics’ owing to the presence of synthetic polymers (rubber and additives) in their road dust composition.

An analysis of the collected literature identified some key influencing factors pertaining to tyre composition and design which can affect the level of tyre and road wear particles produced. National Atmospheric Emissions Inventory (NAEI) analysed and quantified tyre particulates generated in different road types by a range of vehicle segments. These estimates were analysed to provide an indication of the key characteristics that contribute to the trends in particulates generation seen in Table 3-2. Some of the key influencing factors, besides road types and vehicle types, includes the tyre composition/ age, traffic composition and load which seem to impact road surfaces. Some of the other key influencing factors unaccounted for includes the environmental factors and tyre design.

Table 3-2: Emission factors for tyre and brake wear reported by UK National Atmospheric Emissions Inventory (NAEI) in 2017;

Vehicle type	Tyre wear PM_{10} emission factors *(mg/vehicle km)*			Tyre wear $PM_{2.5}$ emission factors *(mg/vehicle km)*		
	Motorways	Urban roads	Rural roads	Motorways	Urban roads	Rural roads
Passenger car	5.8	8.8	6.8	4.1	6.1	4.8
Motorcycle	2.5	3.8	2.9	1.7	2.6	2.0
Moped	-	3.8				
Light commercial vehicle	9.1	14	11	6.4	9.7	7.5
Heavy duty vehicle	31	47	27	9.6-22 [a]	14.5-33 [a]	12.2-27.8 [a]
Bus/ coach	14	21	17	9.8	14.8	12.2

Note
[a] Range for Rigid Vs Articulated HGVs

3.2.2.2. Environmental impacts on water quality, ecosystems and human health

Surface runoff has been identified as a major transportation pathway of TRWP from road surfaces to the surrounding environment, including roadside soils and or nearby watercourses [261]. The ecotoxicological impacts of TRWP in aquatic environments falls into two main categories: impacts caused by the particles themselves and impacts arising from the leaching of harmful chemicals embedded in TRWP into the environment.

There are a broad range of studies investigating the ecotoxicological impacts of TRWP on aquatic ecosystems, largely focusing on the acute toxicity of TRWP leachate on various aquatic species, including algae, fish, daphnids, mussels (in early life stages) and copepods [10]. As Baensh-Baltruschat et al. [10] elucidate in a review study, considerable variability in ecotoxicological impacts is observed between different studies. This variation is likely brought about by variability in experimental design, heterogeneity in TRWP composition (due to variability in the rubber recipes in tyres) and species sensitivity [10]. However, extrapolating the results of *in-vivo* ecotoxicological studies to likely real-world impacts is problematic as exposure conditions in *in-vivo* studies will differ to exposure of aquatic biota to TRWP in the field. [10]

Acute toxicity to TRWP leachate has been demonstrated for a range of species including fish, daphnids and copepods [10]. Additives, such as plasticisers, flame retardants, and vulcanisers are rarely covalently bonded to polymers, thus, readily leach into the aquatic environment. Prominent and recently well studied tyre additives include the antioxidant N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6-PPD). The oxidation product (6-PPD quinone) has been identified as the cause of acute mortality in coho salmon, resulting in mass mortality events during seasonal migration in the USA [29]. Ecotoxicological effects in aquatic organisms have also been associated with the presence of heavy metals (such as zinc, cobalt, cadmium and copper), organic compounds (such as phthalates and benzothiazoles) and resin acids in TRWP leachate [30], [10].

Research, however, surrounding the ecotoxicological impact of TRWP themselves (rather than their associated additives) remains relatively sparse [261]. Direct ingestion of TRWP by aquatic organisms can cause damage to internal structures such as the gastrointestinal tract, can cause blockages within the digestive tract or cause premature satiation; all of these impacts may in turn lead to reduced feeding [262]. Furthermore, TRWP additives may cause adverse impacts as leaching occurs after ingestion, upon exposure to digestive enzymes [262]. Schell et al. [263] reported TRWP ingestion in *Daphnia magna* (water fleas) impacted reproduction and survival rates after chronic exposure at environmentally relevant concentrations. However, other studies using different freshwater macroinvertebrate populations have reported conflicting results [264]. The impacts of TRWP ingestion is likely to depend on numerous factors including exposure concentration, particle size, how much is ingested, and the feeding mechanisms of a given species [263].

The prevalence of TRWP in the environment remains largely uncertain, as does the fate of these particles [265]. There is a consensus that surface run-off acts as the predominant exportation pathways of TRWP from road surfaces to roadside soil and watercourses in rain-dependent ‘pulses’ [10]. In surface runoff, TRWPs may enter drainage and sewerage systems in urban areas where road drainage is present [10]. The fate of TRWP in Wastewater Treatment Works is largely unexplored, however, Baensh-Baltruschat et al. [10] suggest that given the average density of TRWP particles of 1.3-2.2g/m^3, deposition of TRWP into sewage sludge is possible which may limit eventual release of TRWP to aquatic environments. However, TRWP in sewage sludge may be-reintroduced to the environment at landfill sites upon disposal or be used on land in agricultural fertilisers [10]. TRWPs that enter drainage networks may be also exported to waterways in combined sewage overflow spills. However, the behaviour of TRWP in watercourses remains uncertain; processes of biofouling, particle aggregation, deposition and sedimentation are all likely to influence the eventual fate of TRWP in the aquatic environment [266]. In a modelling study, Unice et al. [267] suggest that as high as 18% of all TRWP generated in the Seine watershed (France) may eventually reach freshwater courses, while 2% may reach the estuary.

Several studies have aimed to model the transport of microplastics in the environment, particularly to water bodies including underground sewers, estuaries and other surface waters have been modelled and reviewed. While there has been some methodological maturity in the estimation of the transport of these particles, there is little information from the LCA perspective, in terms of measurable and quantified impacts on ecosystem and human health. This requires a much more evolved analytical methodology, precise modelling studies to estimate transport, degradation, and retention of particulate emission in soil and water and dedicated ecotoxicological studies targeting impact on freshwater and marine species.

3.2.3. Impacts related to end-of-life tyres (ELTs)

Analysis of the key environmental impacts, including GHG estimates of the reviewed literature suggests that ELTs deliver GHG savings for scenarios including tyre recycling and incineration with energy recovery, particularly in cement kilns where relevant coal or pet coke are displaced. While the latter one of the dominantly encountered EoL scenarios for ELTs, globally, more innovative material recovery strategies to explore further have all been analysed as a part of this analysis, which include:

- Re-treading
- Production of recycled tyre crumb (RTC) (through ambient or cryogenic pulverisation) and reclaimed rubber tyres
- Production of recycled or recovered carbon black

A semi-quantitative evaluation of the environmental impacts estimated for the different EoL routes of the ELTs was undertaken. Tyres entering EoL routes other than disposal onto a landfill (illegal in the UK) have been generally found to deliver GHG savings to varying extent. Use of ELTs as alternative energy sources in cement kilns and for other energy must be looked at from two perspectives. Firstly, use of bio-based by-products, processed sewage pellets and non-recyclable plastics is steadily increasing as alternatives to coal [268]. While the long-term supply of these waste streams must be investigated, the use of tyres for energy recovery conflicts with the goals for UK's net zero strategies, particularly the steady electrification and decarbonisation of the industrial sector. Secondly, the embodied energy of tyres have been found to create a lesser case for their incineration with energy recovery. Tyres can consume nearly 200 GJ per ton across their "cradle-to-gate" production processes. However, they are able to deliver roughly less than half of this estimated energy consumed as energy outputs during their incineration for energy recovery, creating a scenario for energy loss. Therefore, material recovery options are recommended as the most environmentally optimal EoL management approach for ELTs.

Re-treading of ELTs evaluated as a material recovery strategy, following the above recommendations. From the analysis of reported GHG estimates for retreating, the process itself has been found to require 25% additional raw materials, taking generating almost 70% of GHG emissions, compared to new tyre production, provided the casing of the ELTs are in good condition. This particular "remanufacturing approach" is pursued only for HGVs as opposed to passenger cars tyres, with the reason being the cost of retreat tyres being 30-50% the cost of brand-new tyres or more expensive compared to tyres imported from Asia [269].

Production of ELT crumb rubber through recycling of tyres were also evaluated. Some of the key applications for recycled material, particularly the use of ground rubber in tyre rubber production, use in artificial turfs and other moulded objects were found to deliver significant GHG savings through virgin material displacement in these sectors.

Pyrolysis of ELTs will produce pyrolysis oil that can be used to produce carbon black has also been evaluated and found to provide low-impact carbon black (74-80% GHG savings compared to virgin carbon black). However, performance of this process in other impact categories need to be further evaluated.

The overall environmental impact reported by the various studies, that were analysed as a part of this analysis, have been tabulated in Table 3-3.

Table 3-3: Summary of environmental impact quantified for the different life cycle stages of a vehicle tyre in published literature

LCA Impact Indicator	Unit [a]	Tyre's key life cycle stages							
		Production		**Use**		**EoL Scenario:** *Incineration with ER*		**EoL Scenario:** *Pyrolysis/ reclaimed rubber*	
		Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
GWP	*$kgCO_2eq$*	$-1.3x10^1$	$5.5x10^1$	$5.5x10^2$	$8x10^2$	-4.2	$-5.5x10^{-2}$	$-2.6x10^4$	-
AP	*$kgSO_2$ eq*	$-1.9x10^{-2}$	$-3.5x10^{-1}$	$5.4x10^{-1}$	3.6	$-3.9x10^{-3}$	$-6.0x10^{-2}$	-	-
EP	*kg PO_4^{3-}*	$4.7x10^{-3}$	$3.1x10^{-1}$	$6.0x10^{-2}$	$4.6 x10^{-1}$	$-8.0x10^{-3}$	$-8.4x10^{-3}$	-	-
ODP	*kg CFC-11*	$-1.30x10^{-6}$	-	$8.5x10^{-7}$	-	$3.20x10^{-4}$	-	-	-
ARD_FE	*kg oil eq*	18.3	-	$1.8x10^2$	-	-	-	-	$-1.2 x10^2$
PMF	*$PM_{2.5}$*	$1.0x10^{-2}$	-	1.07	-	-	-	$1x10^{-2}$	$2 x10^{-2}$
ET_FW	*kg 1,4-DCB*	$3.0x10^{-2}$	-	3.0	-	-	-	$-1x10^{-2}$	-
ET_Ter	*kg 1,4-DCB*	$2.4x10^1$	-	9.5	-	-	-	$-4.8x10^1$	7.2

Notes:

- ***GWP: Global Warming Potential; AP: Acidification potential; EP: Eutrophication potential; ODP: Ozone Depletion Potential; ARD_FE: Abiotic Resource Depletion_Fossil Energy; PMF Particulate Matter Formation: ET_FW: Freshwater Ecotoxicity; ET_Ter: Terrestrial Ecotoxicity***
- ***Impact reported for over the functional unit of one tyre providing service of its functional life of over 40,000 vkm***
- ***Quantified results based on a number of studies employing a mix of impact assessment methods; Indicative results provided to highlight scale of contribution only, per life cycle stage. Studies are bound to have estimated these impacts employing unique boundary settings, assumptions, and scenarios (regional energy mix fuelling tyre production plants, tyre lifetime performance, regionally regulated drive cycles for vehicle use analysis and regionally variable tyre EoL treatment practices. The above figures, are therefore, for indicative purposes only.***

3.3. Expert analysis – Brakes

3.3.1. Impacts related to Production of Brake systems

An analysis of the one and only moderately detailed life cycle inventory of brake production, published by Gradin et al (2020) was undertaken. This evaluated initiated with the review of this inventory and identifying key sources of emissions and which particular impact indicators capture these emissions (Table 3-3). In addition to the preliminary identification, review of the brake system inventory demonstrated the use of scrap cast iron for the brake discs and key materials required to create friction mix for the brake pads, which include magnetite, magnesium oxide, graphite, copper, brass and steel for the backplate. Most of these materials, except the scrap cast iron in the brake disk sourced from closed loop-recycling, are likely to trigger significant impacts in terms of metal scarcity captured via abiotic resource depletion_ metals and minerals (ARD_MM). Ore mining activities associated with the extraction of metals has could also lead to human toxicity impacts (with carcinogenic effects). The use of reinforcing fibres such as polyacrylonitrile compounds, heavy metals such as zinc, copper and chromium for the production of the friction formulation, could contribute to ecotoxicity, if not captured via process wastewater.

national highways

Table 3-4: Summary of key sources of environmental burdens captured by various LCA impact indicators, at each of brake system's life cycle.

Life Cycle Stages	Sources of Impact and key emissions (where available)	GWP	CED	ODP	AP	EP	ARD_MM	ARD_FE	HTP	PMF	ET
Raw material extraction and processing	Mineral extraction (e.g., Al, Fe alloys, Steel, Cu, Co, Silicates etc)	✓	✓	✓	✓	✓	✓		✓	✓	✓
	Fuel/ electricity use	✓	✓		✓	✓		✓			
	Heavy metals released			✓	✓				✓		✓
Brake disk and pads production and assembly	Emissions from friction material production	✓		✓	✓	✓			✓		✓
	Heavy metals released from disc coating			✓	✓				✓		✓
	Release of NOx and SOx from high temperature processes	✓		✓	✓	✓					
	Process waste to water					✓					
	Fuel/ electricity use	✓	✓	✓	✓	✓	✓		✓		
Product distribution	Fuel/ electricity use	✓	✓	✓	✓	✓	✓		✓		
	Fuel use	✓	✓	✓	✓	✓	✓		✓		
	Uncontrolled release of particulate emissions from brake wear	✓							✓	✓	✓
EoL product transport	Fuel/ electricity use	✓	✓	✓	✓	✓	✓		✓		
EoL - Landfill	Release of harmful aromatic compounds								✓		✓
EoL – Incineration	Release of harmful aromatic compounds								✓		✓
	Fuel/ electricity use	✓	✓	✓	✓	✓	✓		✓		
Product EoL - Recycling	Recycling - Metal waste								✓		✓
	Fine particulate matter								✓	✓	✓
	Process waste to water					✓					
	Release of NOx and SOx	✓									
	Fuel/ electricity use	✓	✓	✓	✓	✓	✓		✓		

3.3.2. Impacts related to use of Brake systems

Brake discs are usually made of components that improve the disc performance rendering high-wear resistance. Brake discs are expected to last longer than brake pads. Nevertheless, the abrasive action between brake discs and brake pads generates significant amount of brake dust. Brake dust is often characterised by the presence of mainly iron and fractions of titanium, chromium, graphite, brass and silica[25]. Conventional brake systems, which do not have any kind of specialist friction mix or design considerations tend to release significant amounts of particulate matter which is contemporarily captured in LCA via particulate matter formation (PMF).

3.3.2.1. Impact of interaction between brake systems, tyres and road surface

Currently, there is limited evidence on trends in brake wear particulate generation. However, attempts have been made to understand the additional factors that could exacerbate brake wear particulates produced. Provision of adequate 'braking power' is an essential aspect of safety on the roads and in a way, construction. Additionally, the frequency of maintenance of road surface and the environmental factors (weather conditions) also contribute to the overall 'braking efficiency'[26] of the vehicle. In this case, interactions between the tyres and the road surface could be hypothesised to contribute to the demand and quality of friction provided by the brakes on tyres, which subsequently could impact brake wear emissions.

Similar to the characteristics observed for tyres in section 0, environmental factors (e.g. wet conditions) could affect a tyre's skid-resistance, which in addition to other factors, like tread loss, could lead to relatively higher levels of friction/ abrasive action causing brakes to grind against the tyres. This is demonstrated by how "braking distance", during wet or snowy conditions, tends to increase compared to dry season. While this is merely an observation made as a part of this study, further evidence on the dynamics between the three main contributors to this interaction (brakes, tyres and roads) is required. Literature search yielded no studies that clearly explore the interaction or importance of environmental factors on brake dust generation.

3.3.2.2. Environmental impact on water quality, ecosystem and human health

No clear distinctions are made on the destination of particulates originating from the brake discs or pads, in the environment, from sampling study undertaken by the reviewed articles [10] [27] [58]. Kole et al. [27] have found predominantly a heterogenous mix of water and soil contaminants which include synthetic polymers, rubber, zinc, road wear, in addition to brake and tyre wear. However, similar to the tyre wear, brake wear materials are found in higher concentrations immediately by the road banks, whereas some are found to be transported by run-offs into nearby water bodies [27] [56]. Run-off often captured by the wastewater treatment plant are subjected to a significant level of fine particulate filtration. However, on average 19.8% of microplastics were found to pass through the treatment plant processes.

The atmospheric transportation and fall-out of brake wear particle matter into watercourses can impact aquatic ecology [270]. Brake wear particulates can contain a substantial amount of iron, as well as other elements including copper, zinc, tin, chromium, aluminium, silicon and sulphur. Introduction of these elements to aquatic environments can lead to ecotoxicological impacts and water quality degradation. Volta et al. (2020) report that brake wear particulate debris exposure to freshwater algae *Pseudokirchneriella subcapitata* demonstrated clear toxicological effects on algal reproduction, as well immobilisation in *Daphnia magna* (water flea), a species with high sensitivity to heavy metal pollution. However, there persists a considerable research gap in the impact of brake wear particular matter on aquatic biota, thus, highlighting the need for further research.

In a baseline scenario, $PM_{2.5}$ and PM_{10} are some of the most commonly reported brake wear emissions metrics which are anticipated to have direct air quality impacts leading to affecting respiratory issues and leaching into harmful chemical in lung tissues [18] [52] [27]. Iron dust has been found to create reactive oxygen species in the respiratory lining tract affecting the performance of antioxidants and metal binding proteins in humans. Moreover, accumulation of these metals in varying particle sizes, particularly the fine and ultrafine fractions, have been found to penetrate through tissues into blood streams and deposit in other organs [58]. Particularly, copper, iron, lead and nickel from brake wear

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[25] There is limited release of copper from brakes due to the reduced copper content added to the brake pads stemming from copper limits (max of 5% in 2021) exercised in the federal Clean Water Act mandate (in the US) [].
[26] Expressed as a percentage, braking efficiency is the ratio of the force of friction in the brake system and the weight of the vehicle

have been documented to toxic effects on green alga *Raphidocelis subcapitata* and altered germination and growth patterns on barley (*Hordeum vulgare*) and white mustard (*Sinapis alba*). [59] [60]

3.3.3. Impacts related to EoL of Brake systems

In the UK, brake discs are predominantly recycled by disposal onto sorted scrap metal, in accordance to the Waste Framework Directive 75/442/EEC [271]. Brake discs are contemporarily 100% recyclable and already contain recycled metallic fractions, by default. Worn out brake pads from the maintenance phase and EoL tend to be dismantled with up to 90% by mass of the steel backplate recycled [51]. The complex formulation of the friction material on the other hand, could lead to challenges in recycling. Therefore, the steel backplate is recycled in electric arc furnaces and extracted using metallurgical process, with the residual friction material being lost as waste in the process.

Recycling iron from the EoL vehicle components is likely to reduce the overall impact of mineral scarcity, providing relevant LCA modelling scenarios for brake systems is adopted. For example, recycling of metals from the brake discs and brake pads, recovers the embedded embodied carbon and energy associated with the material, which depending on the quality and performance of the metal could support their closed-loop (back into automotive parts manufacture) or open-loop (use in other products of other sector) re-integration into consumption. On the overall, the life cycle environmental performance of brake systems, based on studies analysed and discussed above have been tabulated in Table 3-5

Table 3-5: Indicative life cycle impacts quantified and reported from reviewed sources for brake discs and brake pads

Impact indicators	Units	Reported impacts
Global warming potential	kgCO_2eq	9.00E+01
Ozone formation potential	kg NOx eq	2.00E-01
Particulate matter formation	kg $PM_{2.5}$ eq	9.00E-01
Acidification potential (terrestrial)	kg SO_2 eq	6.00E-01
Eutrophication potential (Freshwater)	kg P eq	1.00E-01
Ecotoxicity terrestrial, freshwater and marine	kg 1.4 DCB eq	1.49E+01
Human toxicity – carcinogenic	kg 1.4 DCB eq	4.60E+01
Human toxicity – non carcinogenic	kg 1.4 DCB eq	3.65E+04
Mineral resource scarcity	kg Cu eq	1.53E+00
Fossil resource scarcity	kg oil eq	4.79E+01
Water consumption	m3	2.15E+02
Note: *Impact reported for a functional unit defined as the deceleration of a vehicle over its service life of 200,000 vkm* ***Based on ReCiPe 2016 midpoint impact assessment method*** ***Source:*** **[49] [51]**		

3.4. Evaluation

3.4.1. Tyres

From the perspective of a tyre's life cycle, a tyre's use phase has been determined to inflict the most environmental impact, compared to other life cycle stages (production and disposal). The two main contributors to this impact include a tyre's rolling resistance, which contributes to added fuel consumption and CO_2 emissions; and secondly by a tyre's wear rate leading to the release of significant amounts of coarse, fine and ultrafine tyre and road wear particles, over the vehicle's lifetime. Studies into the pathways by which these particulates are transported into the environment suggest that they have been found to accumulate along the road banks in the soil or be carried into surface waters or storm drains into wastewater treatment plants. Particulates released into the environment, over time release harmful leachates that lead to acute toxicity in freshwater, terrestrial flora/ fauna. They have also found to deposit in human organs, affecting optimal organ functioning in humans, particularly in lungs.

Tyres in general have been found to wear at varying rates, depending on their age and road type, with an average passenger car releasing PM_{10} emission of between 5.8-8.8mg/vkm and $PM_{2.5}$ emission of about 4.1-6.1mg/vkm. Tyre design and material composition has a significant role in emission production at the use-stage, which will be explored in Section 5.

Poor performance characteristics, particularly rolling resistance, can be exacerbated by the vehicle's characteristics such as age, segment/size and mass can increase wear and tear of tyres, and road type (e.g. urban or rural roads) deteriorating tyre grip over its service life. Tyre designs which are incompatible with the vehicle specifications, in combination with the road surface characteristics and environmental factors (particularly wet and cold conditions) could lead to a myriad of impacts on the tyre's performance. With the added influence of the road surface, the micro and macro-deformation of tyres on the sidewalls have been found to increase fuel consumption by 5-10% for an average passenger car and by 15-30% for LGVs. Also, poor tyre drainage capabilities (influenced by the tread depth and pattern), combined with potential thick films of water on road surface, could lead to lack of grip, affecting a tyre's skid resistance. Lack of ideal conditions for tyres could lead to 'skidding' and thus an increased generation of coarse, fine and ultra-fine tyre and road wear particles. Under standard conditions (dry weather), road composition, particularly concrete roads appear to wear conventional tyres more than asphalt roads. This is because, asphalt roads are composed of materials on their surface course that prevents it from deteriorating or 'polishing' due to high traffic loads or weather conditions, as opposed to concrete roads. Therefore, investing efforts into identifying and promoting tyre designs and tyre types that are compatible with the relevant vehicle specifications and regional environmental factors and prevalent road types is the first step to optimising a tyre's environmental performance.

The first step to this would be establishing a dedicated harmonised approach to quantify and account for the impacts of road surface, the environment (the elements and other uncontrolled factors, for example, traffic load), as a part of the standard protocol for tyre performance testing. From the viewpoint of road network management, regular monitoring and maintenance of road surface that enable the retention of desired micro and macro texture and surface drainage characteristics, would be environmentally beneficial, and also, ensure optimum performance of the tyres. Additionally, efforts into innovation of wear-resistant tyre compositions at tyre design and production phase could positively impact emissions from the tyre use-phase.

Tyre production was found to contribute the second highest level of life cycle emissions, primarily due to the demand for fossil fuel/crude oil required to produce synthetic rubber and secondly due to high carbon intensity material, carbon black, used as a filler in conventional tyres. Circularisation of ELTs (end-of-life tyres) to produce crumb rubber that can be innovatively introduced into new tyre manufacture could significantly displace material and energy demand for virgin rubber production. Bio-based alternatives to conventional tyres have been explored but none of the studies have been found to thoroughly investigate the land use and land use change (LULUC) impacts associated with cultivation of rubber in high carbon soil sites globally. In the case of bio-based products, this is a key determinant in the thorough evaluation of the environmental credentials, as opposed to conventional candidates. Alternatively, "green silica" a bio-based alternative to carbon black, which is synthesised from waste flows (e.g. rice husk ash) and similar waste-derived or circularised candidates are worth further investigation, however, including the coverage of their land use contributions.

3.4.2. Brakes

Over the course of the life cycle of a brake system, the production phase was determined to inflict the most environmental impact. The key emission contributors identified in brake production were the energy consumption associated with the coating of friction formulation onto the brake discs, which was captured by the relevant indicators such as global warming potential and abiotic resource depletion. Secondly, the use of some key metals such as tungsten carbide (an energy-intense compound), brass and other component metals contributed to metal depletion. However, the use of recycled components and the current industrial practice of recycling brake discs by 90% by mass, has led to a neutralising some of the key environmental burden from this phase.

During the use-phase, the friction between brake discs and pads, from brake application, wears out the rotors and the brake pads requiring their periodic replacement. There has been limited evidence on the impact of road surface on brake performance characteristics, although road design may influence the frequency and force of brake application, and thus the temperature of and emissions from the brakes. $PM_{2.5}$ and PM_{10} emissions characterised by the presence of copper, chromium and iron are some of the most reported brake wear emissions. More specific emission profile from brake wear is dependent on the friction material formulation and process used for coating on the brake discs and pads in more recent vehicles. There has been continued research efforts on developing high-resistance, local thermal diffusing, low-environmental impact friction materials for brake system. This stems from findings by the AQEG who have identified that an increase in friction-generated local temperature by even +15°C above 170°C could result in 5,000 times more fine and ultrafine particle number emissions, and a similar study that showed particulate emissions increased several magnitudes over a critical temperature in the range 150-250°C (see section 2.3.2.1), these temperatures can be reached in high speed or repeated braking conditions even in normal driving. These emissions have been found to affect respiratory issues and leaching into harmful chemicals in lung tissues, iron dust has been found to create reactive oxygen species in the respiratory lining tract affecting the performance of antioxidants and metal binding proteins in humans. Moreover, accumulation of these metals in varying particle sizes, particularly the fine and ultrafine fractions, have been found to penetrate through tissues into blood streams and deposit in other organs.

A majority of brake discs made of iron are 100% recyclable and already contain recycled metallic fractions, by default. Worn out brake pads from the maintenance phase and EoL are assumed to be subjected to extractive metallurgy (in EAFs) to extract the 90% (by mass) steel backplate, while the rest of the friction material are left as residue. The complex formulation of the friction material on the other hand, could lead to challenges in recycling the pads. As a result, the friction coating of the pads is either disposed in a landfill or incinerated (with or without energy recovery). Owing to the energy intense nature of production of brake pads, strategies for materials recovery have been explored. Feasibility of material recovery from brake pads to produce recycled brake pads were evaluated, based on an experimental study. With comparable tribological properties, recycled brake pads also reduced GHG emissions by 36% and energy consumption by 34% savings, compared to virgin brake pads. It is crucial to note that these results are based on experimental tests and may not be adapted for industry practice yet. Moreover, the economic feasibility of recycling and producing recycled brake pads has not been assessed in the open literature to date. Additionally, the performance of these brake pads in real world scenarios (road surface and varying weather conditions; different vehicle types etc) and relevant brake wear emission profile under relevant scenarios need to be arrived at to be conclusive of the alternative candidate's environmental performance.

4. Assessment of current and proposed regulations and standards

A review of regulations and standards relevant to the environmental impacts of brakes and tyres was carried out in Section 2.2, considering all life-cycle stages, and a detailed index of the regulations and standards identified is provided in Appendix 2 – Regulations and standards index. The index tables provide a high-level summary and include details and attributes of each mechanism including the life cycle stage and environmental impacts affected, and the overall relevance to the environmental impacts of tyres and brakes. Section 2.2 also reviewed some literature sources which discussed current and potential regulation. This section discusses the most significant regulations and standards applicable in the UK, identifies where there may be different regulations in other regions, and highlights potential developments through proposed regulations and standards in development.

Before detailing regulations and standards that focus on the environmental performance of tyres and brakes, it is important to understand the various regulations and standards relating to their general safety and performance, since these requirements must be met when considering environmental performance improvements. Therefore, this section starts with an overview of the key safety and performance standards and regulations applying to tyres and brakes, then explores the standards and regulations covering their environmental impacts over each of their life cycle stages of production, use, and end-of-life.

The labelling standard for tyres in the UK was described in Section 2.4.1, this includes a rating of rolling resistance (for fuel efficiency and CO_2 emissions), wet grip, and noise.

4.1. Safety and performance

The United Nations Economic Commission for Europe (UNECE), of which the UK is a contracting party, provides a series of internationally agreed and harmonised road vehicle regulations that allow reciprocal recognition of vehicle or component approvals between contracting parties. Regulations relating to tyres and brakes include UNECE Regulation No. 13, 30, 54, 90, 108, 109, 141 and 142 (see Appendix 2 – Regulations and standards index). These regulations are referenced in the UK's 'The Road Vehicles (Construction and Use) Regulations 1986' and 'The Road Vehicles (Brake Linings Safety) Regulations 1999', and the EU's Regulation (EU) 2019/2144 on 'type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the protection of vehicle occupants and vulnerable road users'. For example, UNECE Regulation No. 30, 'Uniform Provisions Concerning the Approval of Pneumatic Tyres for Motor Vehicles and their Trailers', includes requirements relating to tyre markings, dimensions, load/speed performance tests and treadwear indicators (i.e., 4-6 indicators indicating 1.6mm tread depth). Similar for brakes, UNECE Regulation No. 13, 'Uniform Provisions Concerning the Approval of Vehicles of categories M, N and O with Regard to Braking', and 13-H (for passenger cars) provides specification and testing requirements for both friction brakes and electric regenerative braking systems. This includes a requirement that brake linings shall not contain asbestos due to its risks to human health, particularly vehicle technicians. UNECE Regulation No. 90, 'Uniform provisions concerning the approval of replacement brake lining assemblies and drum brake linings for power-driven vehicles and their trailers', requires that replacement brake linings shall have deceleration performance within ±15% of the original brake lining assembly's performance, and ±8% for replacement brake discs or drums.

Tyre pressure monitoring systems have been mandatory in Europe since 2009 (EU Regulation No. 661/2009, now repealed by (EU) 2019/2144), with type approval requirements set by UNECE Regulation No. 141. The use of tyre pressure monitoring systems reduces the dependency on drivers to check tyre pressures and can enhance both safety and environmental performance of tyres (rolling resistance, wear and noise).

The Road Worthiness Directive (2014/45/EU) provides over-arching (minimum) requirements for Member States to have in their legislation regarding the in-use testing of the roadworthiness of road vehicles. Article 6 covers the "contents and methods of testing" and refers to Annex 1 of the Directive which covers roadworthiness requirements for both brakes and tyres. The MOT inspection manuals for cars and passenger vehicles and heavy-duty vehicles provide the interpretation and requirements of the Road Worthiness Directive for Great Britain (GB). The manual contains further details/ guidance for tyre and brake testing. For tyres, the manual specifies a minimum tread depth of 1.6 mm and also involves checking load and speed ratings for some vehicle categories.

4.2. Production

4.2.1. Current regulations and standards: UK

No regulations affect the environmental impacts of brake and tyre production in isolation (other than limiting material content for use emissions or safety purposes) but their manufacture comes under general legislation that addresses the environmental impacts of industry and of resource use.

Manufacturing emissions

The 'Industrial Emissions Directive' (2010/75/EU) aims to address the entire environmental impacts of industrial installations including emissions to air, water and land, generation of waste and noise, use of energy and raw materials, prevention of accidents, and site closure. Permits to operate and compliance with specified conditions may be required. The scope of the legislation includes the production of synthetic rubber and steel, which are both used in the production of tyres or brakes. The UK's 'Environmental Permitting (England and Wales) Regulations 2010' requires permitting for manufacturers of new tyres if this involves the use in any 12-month period of 50,000 or more tonnes of one or more of the following: natural rubber, synthetic organic elastomers, and other substances mixed with them.

The UK Emissions Trading Scheme (UK ETS) replaced the UK's participation in the European Union Emissions Trading Scheme (EU ETS) on 1 January 2021, and is established through The Greenhouse Gas Emissions Trading Scheme Order 2020[27]. The UK ETS Authority established the scheme to increase the climate ambition of the UK's carbon pricing policy, while protecting the competitiveness of UK businesses. Emissions trading schemes use the 'cap and trade' principle, where a cap is set on the total amount of certain greenhouse gases that can be emitted by sectors covered by the scheme. The UK ETS applies to aviation and 'installations' in the UK. For installations, the scheme applies to regulated activities which result in greenhouse gas emissions, including combustion of fuels on a site where combustion units with a total rated thermal input exceeding 20MW are operated (excluding incineration of hazardous or municipal waste). According to the European Tyre and Rubber Manufacturers' Association (ETRMA)[28], the use of steam from combustion units used in the tyre manufacturing process is the major factor that determines inclusion of tyre manufacturing in the scope of ETSs. Similarly, the energy consumption during the manufacture process of brakes components or their materials may fall under the scope of ETSs, depending on the rated thermal input. The production of iron and steel, used in the manufacture of brake disc and pads and tyres, falls under ETS. The UK and EU ETS are linked to the introduction of proposed Carbon Border Adjustment Mechanisms (CBAMs) discussed below in Section 4.2.3.

Scarce resources

In 2017, the EU announced an updated list of critical raw materials for the EU as part of the EU Raw Material initiative[29], which also applied to the UK. The list included natural rubber as a new critical raw material and noted that the EU had a 100% import reliance rate, with main global producers being Thailand (32%), Indonesia (26%), Vietnam

[27] See https://www.legislation.gov.uk/uksi/2020/1265/contents
[28] See https://www.etrma.org/wp-content/uploads/2019/09/20100421_emission_trading_scheme_tyre_industry.pdf
[29] See https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0490

(8%) and India (8%). Schedule 17 of the UK's Environment Act (2021) introduced requirements for the use of forest risk commodities in commercial activity in the UK. Three key requirements were introduced for regulated businesses: they are prohibited from using illegally produced forest risk commodities, they must establish and implement due diligence systems, and they must provide annual reports on their due diligence systems to relevant authorities. Secondary legislation is necessary to translate the requirements of Schedule 17 into practical operations and define which commodities will fall under the scope of regulations. This secondary legislation is not yet laid out, and some further information on this is provided in Section 4.2.3.

4.2.2. Current regulations and standards: Other regions

In 2023, the EU introduced Regulation (EU) 2023/1115, known as the EU Deforestation-Free Regulation (EUDR), which is similar to the UK's Schedule 17 of the Environment Act 2021. Under the regulation, any operator or trader who places certain commodities, including rubber, on the EU market, or exports from it, must be able to prove that the products do not originate from recently deforested land or have contributed to forest degradation. The compliance deadline for the regulations is December 2024. The European Commission, Indonesia and Malaysia have agreed to set up a Joint Task Force to strengthen the cooperation for the implementation of EU's deforestation regulation, with particular focus on rubber, amongst others[30]. The Global Platform for Sustainable Natural Rubber (GPSNR) has developed various measures aimed at improving the sustainability of the natural rubber supply chain, including developing frameworks and recommendations. Some sources[31] note that while groups like the GPSNR and their members have made great progress in this area to reduce deforestation related to natural rubber, the EUDR requires additional traceability and reporting requirements to prove compliance and ensure that their supply chains are truly sustainable.

The Corporate Sustainability Reporting Directive[32] (CSRD 2022/2464/EU) also entered into force in the EU in 2023. The directive requires all large companies and all listed companies (except listed micro-enterprises) to provide information regarding their evaluations of social and environmental risks and opportunities, alongside the impact of their activities on people and the environment. The updated regulations aim to ensure that investors and other interested parties can obtain the necessary information to evaluate how companies affect both society and the environment, as well as enabling investors to evaluate financial risks and opportunities stemming from climate change and other sustainability concerns.

In 2021, China introduced the Green Product Assessment for Tyres standard (GB/T 40718-20210) which applies to tyre manufacturers that would like to label tyres sold in the Chinese market as 'green' as part of the voluntary China Green Product (CGP) scheme (discussed further in Section 4.3). The standard includes requirements related to all life cycle stages. Requirements related to tyre production includes emissions limits for rubber production, energy consumption and management, environmental management, occupational health and safety, chemical limits (such as heavy metals, polybrominated biphenyls (PBBs) and PAHs), and resource properties indicators (including the amount of natural rubber, synthetic rubber and reclaimed rubber).

4.2.3. Future developments

Manufacturing emissions

Both the UK and EU have plans to implement Carbon Border Adjustment Mechanism (CBAM) regulations which aim to tackle 'carbon leakage'[33] by putting a fair price on the carbon emitted (Scope 1, 2 and 3) during the production of carbon intensive goods that are entering the UK or EU, and to encourage cleaner industrial production in non-UK/EU countries. In this way, CBAM compliments ETS by ensuring that domestic manufacturing and imports are subject to comparable carbon pricing. The EU CBAM is currently in the transition phase (2023-2026) which will allow the gradual

[30] See https://www.eeas.europa.eu/delegations/indonesia/european-commission-indonesia-and-malaysia-agree-set-joint-task-force-strengthen-cooperation_en
[31] See https://www.banqu.co/blog/how-to-ensure-sustainable-rubber and https://www.reuters.com/sustainability/sustainable-finance-reporting/comment-why-are-rubber-companies-keeping-investors-dark-over-deforestation-risk-2023-05-25/
[32] See https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en
[33] According to the European Commission, "carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions. The risk of carbon leakage may be higher in certain energy-intensive industries."

introduction of CBAM to be aligned with the phase out of free allowances under the EU Emission Trading Scheme (ETS). The EU CBAM will enter full implementation in 2026. UK CBAM is currently under consultation with plans for implementation by 2027. The products covered by UK and EU CBAM are summarised in Table 4-1 below.

Table 4-1: Comparison of sectors included in the scope of the first phase of UK and EU CBAM regulations

Sector	UK CBAM[34]	EU CBAM[35]
Aluminium	✓	✓
Cement	✓	✓
Ceramics	✓	
Fertilisers	✓	✓
Glass	✓	
Hydrogen	✓	✓
Iron & Steel	✓	✓
Electricity		✓

During the negotiations for EU CBAM in June 2022, the ETRMA released a statement[36] regarding the scope of materials included in CBAM. At that time, the ETRMA stated that the original scope of CBAM targeted approximately 15% of the weight of a tyre, and any decision to include organic chemicals in the scope would lead to this number increasing to approximately 50% and increase the potential effect of CBAM on the tyre industry.

Scarce resources

At COP28 in December 2023, it was announced[37] that initial secondary legislation to enforce Schedule 17 of the UK's Environment Act (2021), which has not yet been laid out, will focus on four commodities identified as key drivers of deforestation: cattle products (excluding dairy), cocoa, palm oil and soy. The legislation will only apply to organisations using these commodities in UK supply chains that have a global turnover of over £50 million. Currently, this does not include natural rubber. This has been noted as a weakness of the proposed legislation[38].

4.3. Use

4.3.1. Current regulations and standards: UK

Labelling

The European Commission Regulation (EC) No 1222/2009, 'Labelling of tyres for fuel efficiency and other essential parameters', provides requirements for labelling of tyres and is applicable in GB. Note that the newer version of this regulation (2020/740) is applicable to the EU as discussed in Section 4.3.2 below. The regulation provides standardised rating and labelling for key attributes (fuel economy, wet grip, and noise) for tyres. The testing requirement for these parameters are detailed in UNECE Regulation No. 117. More details on these regulations are provided in Section 2.4.1.

Particle emissions

The 2023 UN Global Technical Regulation (GTR) No. 24 on 'Laboratory Measurement of Brake Emissions for Light-Duty Vehicles' provides a worldwide harmonised methodology for the measurement of brake wear particulate matter and particle number emissions from brakes used on Light-Duty vehicles. This UN GTR defines the test cycle, minimum system requirements, test conditions, and equipment preparation to execute the WLTP-Brake cycle using

[34] According to the UK CBAM Factsheet (2023), further detail, including the precise list of products in scope, will be the subject of consultation in 2024.
[35] According to the European Commission, during the transition phase "the product scope will be reviewed to assess the feasibility of including other goods produced in sectors covered by the EU ETS in the scope of the CBAM mechanism, such as certain downstream products and those identified as suitable candidates during negotiations."
[36] See https://www.etrma.org/wp-content/uploads/2022/06/20220623_ETRMA-CBAM-Statement_F.pdf
[37] See https://www.gov.uk/government/news/supermarket-essentials-will-no-longer-be-linked-to-illegal-deforestation
[38] See https://friendsoftheearth.uk/climate/cop28-uk-govt-announces-new-global-deforestation-law

brake dynamometers. It also provides requirements for the design and set up of test systems to measure brake emissions, including requirements on calibration and validation of test equipment.

The UK's Clean Air Strategy 2019 sets out proposals in detail and also indicates how devolved administrations intend to make their share of emissions reductions. It complements three other UK government strategies: the Industrial Strategy, the Clean Growth Strategy and the 25 Year Environment Plan. The Clean Air Strategy makes specific mention of tyre and brake emissions and states that the UK Government will work with international partners to research and develop new standards for tyres and brakes to enable them to address toxic non-exhaust particulate emissions from vehicles, which include micro plastics, and can pollute air and water.

General pollution

The 2000/60/EC Water Framework Directive establishes a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. The directive requires EU members states and GB to protect all water bodies and ensure that specific measures are taken to reduce or prevent discharges, emissions and losses of priority substances into the aquatic environment. This could include particle emissions from tyres and brakes, however, Trudsø et al. (2022) [61] note that the list of priority substances listed in the Water Framework Directive does not overlap with any of the substances known to leach out from tyres, such as aniline and benzothiazoles or 1-indanone. Therefore, these substances are not searched for or monitored under the framework [61].

Metal and chemical content

The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations were first brought into force in the EU in 2006 (EU REACH, Regulation (EC) No 1907/2006), and from 2021 the UK moved to its own version (UK REACH) that corrected deficiencies to ensure that the legislation operated effectively in the domestic context of GB after exiting the EU. The REACH regulations are the main EU/UK laws to protect human health and the environment from the risks that can be posed by chemicals. Companies are responsible for collecting information on the properties and uses of the substances they manufacture, import or place on market above one tonne a year, and importers and suppliers of tyres and brakes need to abide by the obligations under REACH.

The group of chemicals that are relevant to tyres, which are on the Candidate List and Restriction under REACH, are polycyclic aromatic hydrocarbons (PAHs). REACH Annex XVII lists eight different PAHs that are restricted under the REACH regulation, which limits their use in extender oils which are used to produce tyres if they contain:

- more than 1 mg/kg (0.0001% by weight Benzo[a]pyrene BaP)
- more than 10 mg/kg (0.001% by weight) of the sum of all listed PAHs

These PAH restrictions were first introduced more generally in Directive 2004/107/EC and then specifically for extender oils for tyres in Directive 2005/69/EC.

Polymers are currently exempt from registration and restriction under REACH until a practicable and cost-effective solution for the selection of polymers posing a risk to human health or the environment can be found. Initial analysis by an OECD Expert Group[39] supported the contention that polymers meeting low concern criteria (PLC) have insignificant human health or environmental impacts, which in turn, supports reduced regulatory requirements for these polymers. However, based on the absence of harmonised application of criteria for determining PLC and recent scientific advances in this area, OECD guidance is that the regulatory schemes of individual countries should be consulted.

In terms of relevance to brakes, REACH prohibits the placing on the market of articles which contain asbestos fibres, which is also a requirement of 'The Road Vehicles (Brake Linings Safety) Regulations 1999' and UNECE Regulation No. 13 and 90. The 'End of Life Vehicles (ELV) Directive' (2000/53/EC) requires members to ensure that materials and components of vehicles put on the market after 1 July 2003 do not contain heavy metals including Lead (Pb), Hexavalent Chromium (Cr VI), Cadmium (Cd) and Mercury (Hg) other than in specified cases listed in Annex II. This is especially relevant to brakes.

4.3.2. Current regulations and standards: Other regions

Metal and chemical content

In 2010, the States of California and Washington in the US introduced what have become known as the 'Better Brakes Laws' (Senate Bill (SB) 346 and 65570) which limited the amount of copper, certain heavy metals, and asbestos in brake pads sold in their respective states. While the limits on heavy metals such as Cr (VI), Pb, Hg and Cd are similar

[39] See https://www.oecd.org/env/ehs/oecddefinitionofpolymer.htm/1000

to the ‘End of Life Vehicles (ELV) Directive’ (2000/53/EC) in the EU, the limitation of copper in brake pads is a unique limitation introduced in the ‘Better Brake Laws’. In 2015, the United States Environmental Protection Agency, states, and the automotive industry signed a memorandum of understanding to reduce copper and other materials in brake pads for motor vehicles in sold in all 50 US states, known as the ‘Copper-Free Brake Initiative’. The voluntary initiative generally followed the limits introduced in ‘Better Brakes Laws’, as detailed below along with the designation levels and implementation timeline:

- Level A: The use of the following non-copper constituents in brake friction materials required phase out by 2015 (California and Washington banned their sale)
    - asbestiform fibers in concentrations exceeding 0.1% by wt
    - cadmium and its compounds in concentrations exceeding 0.01% by wt
    - chromium (VI)-salts in concentrations exceeding 0.1% by wt
    - lead and its compounds in concentrations exceeding 0.1% by wt
    - mercury and its compounds in concentrations exceeding 0.1% by wt
- Level B: Copper and its compounds: concentrations exceeding 5.0% by weight phased out by 2021,
- Level N: Copper and its compounds: concentrations exceeding 0.5% by weight phased out by 2025

Labelling

The European Commission revised the Tyre Labelling Regulation in 2020 (EU 2020/740), which came into force in 2021, with minor changes including how efficiency and wet grip are rated as A-E, and the addition of suitability for snow grip and ice grip[40]. This means tyre labels used in Europe (and Northern Ireland) differ slightly from those used in GB as detailed in Section 2.4.1, although there is still no rating for tyre wear/abrasion.

The US Code of Federal Regulations (CFR) § 575.104, ‘Uniform tire quality grading standards’ (UTQG) is somewhat like the EU tyre labelling regulations but requiring relative information on the performance of tyres with regards to treadwear, traction and temperature resistance. The tyre treadwear rating (TWR) provides information which is intended to inform the customer about the expected durability (life expectancy) of the tyre and is printed on the sidewall of tyres. It is a comparative figure, with, for example a tyre having a TWR of 400 being expected to last twice the distance of a tyre with a TWR of 200. Similarly, CFR § 575.106, ‘Tire fuel efficiency consumer information program’, requires provision of information indicating the relative performance of replacement passenger car tyres in the areas of fuel efficiency, safety, and durability. Some further detail on these regulations is provided in Section 2.4.1.

As noted above in Section 4.2.2, China introduced the voluntary China Green Product (CGP) label, and tyres can be labelled under the CGP scheme if they meet conditions across the entire lifecycle of the tyres set by various other standards which this standard refers to. If the tyres meet all requirements, they can receive the 'all-green products' CGP label, if they meet at least one of the requirements then they can receive the CGP label for 'green-related products'.

The Japan Automobile Tyre Manufacturers Association (JATMA) Tyre Labelling System for Fuel-Efficiency Tyres has been in operation since 2010 with the purpose of providing consumers with accessible information. It was established as an industry voluntary standard to classifying and labelling rolling resistance performance and wet grip performance. Since its introduction, it has rapidly been rolled out and over 80% of tyres in Japan are now classed as ‘fuel efficient’ as of 2022.

For brakes, the ‘Copper-Free Brake Initiative’, mentioned above, introduced marking and package labelling requirements known as the Automotive Aftermarket Suppliers Association (AASA) Leafmark, as shown in Figure 4-1 below. Compliance designations (A, B, & N) correlate with the various phases of the implementation timeline of the initiative.

[40] https://www.etrma.org/key-topics/tyre-regulations/

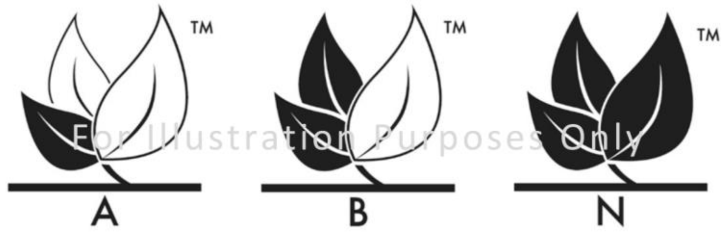

Figure 4-1: AASA Leafmark designations A, B & N (Source: AASA[41])

4.3.3. Future developments

Particle emissions

Increasing interest in understanding the measurements of and potential regulation for brake and tyre wear particles has led to work at UN ECE working groups to develop new standards. Global Technical Regulation No. 24 was adopted last year (including by the UK and EU) setting a procedure for measuring PM_{10} emissions from brakes using a brake dynamometer test rig[42]. A standard for measuring the abrasion rate of tyres is also in development and expected to be in place by late 2025[43]; proposals would use either a fixed test route or a dynamometer rig test to compare candidate tyres against a reference tyre, in a similar manner to the US treadwear standard. Note that the brake standard measures the emitted particles (PM_{10}), but the tyre standard measures the mass lost/abraded which would include material deposited on the road as well as airborne particles. (Research suggests airborne particles comprise less than 10% of all abraded particles [272], [273], Section 2.1.2.2). By providing a repeatable and comparable measurement method, these standards enable the introduction of regulation of NEE. They also provide a mechanism for comparative performance that could be used in product labelling as with the US treadwear standard.

The European Parliament has been considering proposals for Euro 7 emissions standards for light and heavy duty vehicles which are to include limits on brake emissions and tyre wear for the first time. The first proposals were published in November 2022 although they have been subject to amendments and are not yet agreed[44]. As such, the introduction date is not yet clear but is likely to be around 2027 for light-duty and 2029 for heavy duty vehicles. Key missing details are the finalised UN GTRs regarding the technical procedures for quantifying brake wear and tyre emissions. Although the draft sets out that limits will apply to brakes and tyres of both light and heavy duty vehicles, and that limits will reduce from 2030, the only limit set in the draft regulation is for light duty (M1, N1) class vehicle brakes at 3mg/km until 2030. Limits should be agreed by UN ECE working group, along with the measurement procedure, or stated by the Commission by the end of 2025. The UN GTR standards, which are under development for brake emissions and tyre wear will be used to determine compliance with the limits.

Labelling

The EU's proposal for a new Ecodesign for Sustainable Products Regulation (ESPR), discussed in further detail in Section 4.4.3, will include tyres in its scope of priority products and introduces a new Digital Product Passport[45] that will provide information about products' environmental sustainability and help consumers and businesses make informed choices when purchasing products, facilitate repairs and recycling and improve transparency about products' life cycle impacts on the environment.

Rolling resistance / energy efficiency

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[41] https://www.epa.gov/sites/default/files/2015-11/documents/copper_brakepads_mou.pdf
[42] Source: https://unece.org/environment/press/unece-adopts-groundbreaking-regulation-introducing-methodology-measure-particle and GTR 24: https://unece.org/transport/standards/transport/vehicle-regulations-wp29/global-technical-regulations-gtrs
[43] Source: https://www.greencarcongress.com/2024/02/20240220-unece.html and https://wiki.unece.org/pages/viewpage.action?pageId=160694352
[44] Sources: https://www.europarl.europa.eu/news/en/press-room/20231207IPR15740/euro-7-deal-on-new-eu-rules-to-reduce-road-transport-emissions and https://www.europarl.europa.eu/doceo/document/TA-9-2023-0394_EN.html and https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2022/0365(COD)&l=en
[45] See https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en#the-new-digital-product-passport

Since 2003, the California Energy Commission (CEC) has been mandated, under the Assembly Bill 844 (Nation, 2003), to adopt and implement a statewide Replacement Tire Efficiency Program[46] for replacement tires for passenger cars and light-duty trucks. The aim of the program is to ensure that replacement tires sold in California are at least as energy efficient (in terms of rolling resistance) as the tires sold as original equipment on the vehicles. The CEC has been conducting research for implementation of the program but has not set a hard deadline for establishing its mandate[47].

4.4. End of life and circular economy

4.4.1. Current regulations and standards: UK

The treatment of brakes and tyres at their end-of-life comes under wider legislation that addresses the environmental impacts of industry, although there is also regulation targeted at vehicle components and directly at tyres.

Waste

The Council of the European Union Council Directive 1999/31/EC on the landfill of waste provides measures, procedures and guidance to prevent and reduce the negative impacts on the environment that might result from the landfilling of waste.

European Parliament Waste Framework Directive 2008/98/EC applies to all waste streams generated in the EU, regardless of their origin or source and sets out concepts and definitions related to its management including recovery, recycling and disposal. The directive introduces a waste hierarchy which prioritises waste management options based on their perceived environmental impact. The hierarchy consists of the following steps in order of priority: prevention, preparation for reuse, recycling, other recovery options (e.g. energy recovery) and finally disposal. End-of-life vehicles must be treated and disposed of in accordance with the waste hierarchy, tyres typically fit into the ‘other recovery options’ as they can undergo processes such as incineration or pyrolysis for energy recovery.

UK Parliament The Environmental Permitting (England and Wales) Regulations 2010 provides a streamlined framework that sets compliance conditions for integrated pollution prevention and control, waste management and landfill, water policy, groundwater protection and radioactivity. The regulations require every regulated facility to be operated under the authority of an environmental permit.

Re-use/recycling/circularity

The European Commission End of Life Vehicles (ELV) Directive (Directive 2000/53/EC) prohibits the use of hazardous substances when manufacturing new vehicles in Member States as well as Great Britain. According to article 4(2)(a), for new vehicles post 2003, substances including lead (Pb), cadmium (Cd) hexavalent chromium (Cr VI) and Mercury (Hg) are banned. While there are exceptions to this ban pertinent to spare parts for vehicles before 2003, this notably excludes brake lining. The directive also mandates that manufacturers take into full consideration and facilitate the reuse, recycling and recovery of vehicle components and materials and that all members of the vehicle production supply chain should integrate an increasing quantity of recycled materials in vehicle components. For tyres and brakes, the directive also highlights minimum technical requirements for its end-of-life treatment. Tyres should be separated from other materials destined for shredding in such a way that they can be effectively recycled as materials and should be stored appropriately to prevent secondary hazards and excessive stockpiling. Brakes and particularly their fluids should be appropriately drained and stored safely.

Like the ELV directive, the European Commission Directive 2005/64/EC on the type-approval of motor vehicles regarding their reusability, recyclability and recoverability lays down administrative and technical provisions and applies to new models and models already produced in Member States and Great Britain of vehicles including cars and light commercial vans. The directive aims to minimise the environmental impact of end-of-life vehicles by mandating that vehicles may only be sold if they may be re-used and/or recycled to a minimum of 85-95% by mass dependent on their category. Special purposes vehicles and vehicles produced in small series are exempt.

UK Environment Agency (EA) SR2021 No. 13 on ‘storage and mechanical treatment of end-of-life tyres for recovery’ aims to ensure that end-of-life tyres (ELTs) are managed in an environmentally responsible manner, minimizing risks to human health and the environment while promoting their recovery and reuse. No more than 5,000 tonnes of ELT tyres can be accepted at a storage facility each year, and no more than 100 tonnes of ELT can be stored at any one

[46] See https://www.energy.ca.gov/programs-and-topics/programs/replacement-tire-efficiency-program
[47] See https://www.moderntiredealer.com/retail/article/23000979/california-moves-closer-to-fuel-efficiency-mandate

time. There is an emissions and monitoring element which stipulates that there must be no point source emissions to water, air or land except via accepted sewerage liquid and tanker disposal off-site.

UNECE Regulation 108 & 109: "Retreaded pneumatic tyres for passenger cars and their trailers" (108) for Commercial vehicles and their trailers (109). This regulation applies to the production of retreaded tyres intended to be fitted to private cars and commercial vehicles and their trailers. Technical requirements for retreaded tyres are covered. Performance characteristics covering parameters such as traction, tread wear, rolling resistance and resistance to hydroplaning as well as their load-carrying capacity and speed rating requirements to ensure safe operation under various driving conditions. Additionally, the regulation covers the materials and processes of retreaded tyres such as the composition of tread rubber compounds used in retreading including factors such as hardness and abrasion resistance.

4.4.2. Current regulations and standards: Other regions

The (EU) 2021/1199 regulations on 'polycyclic-aromatic hydrocarbons (PAHs) in granules or mulches used as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications' places limits on the amount of PAHs allowed in materials used for these applications in the EU. As ELTs are often processed into granules for these applications, the limits introduced could impact secondary use options for ELTs. However, the limit value of 20 mg/kg (0.002% by weight) of the sum of all listed PAHs is twice the value of the limit imposed by the REACH and similar regulations described in Section 4.3.1 above, therefore, ELTs that comply with REACH limits would already comply with these regulations. Use of older tyres that may have higher PAH values may potentially be limited.

According to the United States Environmental Protection Agency (EPA)[48], ELTs are managed primarily at the state level, with about 48 states having specific laws or regulations dealing with ELT management. Some typical features include:

- Funding via taxes or fees on automobiles or tyres.
- Market development activities.
- Licensing or registration requirements for scrap tyre haulers, processors and some end users.
- Manifests for scrap tyre shipments.
- Requirements regarding who may handle scrap tyres.
- Financial assurance requirements for scrap tyre handlers, storage facilities, and disposers.
- Tyre pile clean-up.

According to the EPA, fees are also collected by many states to fund the management of scrap tyres or stockpile cleanup. Fees often range between 0.50-2 US$ per passenger car tyre, and 3-5 US$ for truck tyres. These fees are generally assessed on the sale of new tyres or on vehicle registrations.

4.4.3. Future developments

The EU's proposal for a new Ecodesign for Sustainable Products Regulation (ESPR) was published in 2022 and aims to establish a framework to set ecodesign requirements for specific product groups to significantly improve their circularity, energy performance and other environmental sustainability aspects. A provisional agreement on ESPR was reached in December 2023 and provided a list of high impact products that will be given priority for regulation, which inlcuded tyres.

According to the European Commission[49], the new ESPR requirements will go beyond energy efficiency and aim to boost circularity, covering, among others:

- product durability, reusability, upgradability, and repairability
- presence of chemical substances that inhibit reuse and recycling of materials
- energy and resource efficiency

[48] See https://archive.epa.gov/epawaste/conserve/materials/tires/web/html/laws.html
[49] See https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

- recycled content
- carbon and environmental footprints
- available product information, in particular a Digital Product Passport

5. Performance optimisation, trade-offs and conflicts

5.1. Overview of the literature

For **tyres**, research highlights the key performance parameter trade-offs for tyre manufacturers, known as the ‘magic triangle’, between rolling resistance (fuel efficiency), wet grip (safety), and abrasion/wear resistance (tyre life). Generally, an improvement in one of these parameters will worsen at least one of the other two. However, research shows that some of these compromises between performance parameters have been overcome using innovative materials, such as HD or HD-HS silica, both of which have shown improvement of all three parameters. Noise is an additional parameter to be considered, which may also have an impact on the other three parameters.

Key parameters and technologies to be optimised to reduce the use-phase environmental impacts of tyres included:

- Reduction in rolling resistance to improve fuel efficiency, such as through using nanomaterials (HD/HD-HS silica and nanoclay) and porous tread designs.
- Improved wear resistance to reduce particle emissions, such as though the use of HD/HD-HS silica, and the elimination of tyre vent spews either during or after the manufacture process.
- Reduction in noise, such as through optimised tread designs.

Key parameters and technologies to be optimised to reduce the manufacture and end-of-life impacts of tyres included:

- Sustainable sourcing of materials, such as alternative rubber matrix materials (guayule and Russian dandelions), green silica and other natural fillers.
- Increasing tyre life to reduce waste, such as through the use of additives to improve ageing resistance and self-healing properties of tyre rubber.
- Improvements in reuse, recyclability, and use of recycled content, such as through the retreading of tyres, and the processing of end-of-life tyre rubber as secondary raw materials for new tyres, including tyre pyrolytic oil, pyrolytic carbon black, devulcanised rubber granules, and recycled PET from complex waste.

For **brakes**, the literature has investigated various materials used in brake components which mainly cover discs, binders, fillers, and fibres. For each material, its effect on the coefficient of friction (braking distance) was analysed as an indicator for performance and this was usually complimented with a study into its wear resistance which offers insight into its environmental emission parameters. In general, many of the materials studied showed that its use would decrease wear rate and increase the coefficient of friction. However, most studies have been limited to laboratory tests in a controlled environment, and issues such as price have limited their real-world application.

Key parameters and technologies to be optimised to reduce the use-phase environmental impacts of brakes included:

- Coating brake discs with materials like Ni-based alloy or HVOF coatings has been studied as a solution to reduce wear and particle emissions. These coatings improve wear resistance and reduce particle emissions.
- Research into alternative materials for both brake discs and pads are ongoing. Various materials, including composites with clay, aluminium, and titanium, have been explored to reduce wear and environmental impact. Many of these materials exhibit strong coefficient of friction values and wear resistance compared to traditional brake disc and pad materials.
- The use of alternative binders like lignin and geopolymers has been proposed to replace traditional phenolic resins, reducing environmental impact, and improving friction properties.
- The use of Regenerative Braking Systems (RBS) found in electric and hybrid vehicles can significantly reduce the need to utilise traditional friction brakes, leading to substantial reductions in brake wear emissions.

Key parameters and technologies to be optimised to reduce the manufacture and end-of-life impacts of brakes included:

- Industrial by-products and waste materials, such as waste tyre rubber and fly ash from coal combustion, have been explored as additives to brake friction materials during manufacturing. These materials can improve the performance of brake components while repurposing waste.
- Improvements to recycling and reuse technologies: The metals used for brake callipers and discs are typically well suited to recycling and the use of recycled content. Brake pads are non-degradable and thus challenging

to recycle. Brake pad recycling methods have been explored, such as high-temperature thermal decomposition and embrittlement using liquid nitrogen, to facilitate the separation of pad layers.

It should be noted that while some of these technologies to reduce the environmental impacts of tyres and brakes are already entering the market or close to commercialisation, others are at a research stage and may be some way from being ready for mass deployment. Literature is not always clear on the readiness of technologies or the challenges of and timescales to reach commercialisation.

5.2. Stakeholder feedback – Tyres

As outlined in Section 1.3.2, a selection of stakeholders across the tyre industry and research were contacted with interviews carried out, and written submissions provided. The questions discussed (listed in Appendix 1) built on the findings of the literature review and explored the environmental impacts of tyres, future legislation and other drivers for reducing impacts, and the potential technologies being used and developed to minimise environmental impacts from tyres and their manufacture.

5.2.1. Drivers for minimising environmental impacts

Euro 7 and other regulations

Stakeholders stated that regulations are a key driver for minimising the environmental impacts of tyres, with the Euro 7 regulations on tyre emissions expected to be important to drive change in limiting tyre abrasion. One research expert observed that Euro 7 is fundamental for the next 10-year outlook and that there will be immediate positive impact from the moment of implementation. This applies particularly to C1 tyres (i.e. tyres used in passenger cars) because the proposed methods seem to be more mature compared to other tyre categories, and C1 tyres account for approximately 60% of the overall microplastic emissions from the road transport sector. The BTMA noted that in the original equipment sector, only new vehicles will be affected (average car life is 16 years). In the replacement market, the impact will be progressive as stocks of no longer compliant tyres with lower abrasion resistance are exhausted (approximately 30 months) and motorists replace their tyres (average tyre life is 4 years). While there is currently no plan for Euro 7 to be adopted in the UK, the Euro 7 regulations for tyres rely on UNECE's work to develop standardised measurement methods for tyre abrasion and associated limits for UN Regulations which is expected to be adopted by the UK.

Dialogue has been engaged around the EU's Eco-design for Sustainable Products Regulation (ESPR[50]), which aims to improve EU products' circularity, energy performance and other environmental sustainability aspects, and tyres may be the first wave of products that will be regulated. The BTMA noted that ETRMA supports the inclusion of tyres in the first wave of EU ESPR regulation as a means of recognising and further supporting increased use of sustainable raw materials and product life extension measures like retreading. Recent UNECE regulations[51] aim to reduce rolling resistance by ~9% for new tyre types from 2024 and existing tyre type from 2026 while improving minimum wet grip performance, and it's estimated that between a quarter to a half of tyres on the market won't meet these requirements. Compliance with deforestation regulations and pressure from EU regulations are pushing the industry to make changes related to the sourcing and use of natural rubber in tyres. The BTMA noted that European tyre manufacturers have had a longstanding commitment to ethical and sustainable sourcing of natural rubber[52].

Euro 7 tyre emission proposals are not yet fully defined, and Michelin noted the extent of its impact will depend on the thresholds that are put in place, how ambitious they are, and the timing of implementation. The BTMA noted that UK and EU governments have high ambition for significantly and urgently reducing particulate emission and much of the Euro 7 negotiation on tyres has been about timing. If the regulations are ambitious and enforced and implemented quickly, the regulations could force manufacturers of poor performing (high abrasion) tyres to either improve their products or find different markets for their tyres. The BTMA noted that it's the regulator's role to set standards that remove lower performing products from the market. A similar perspective was given by a research stakeholder who did not expect the tyre industry to need to make any major innovations for the first wave of Euro 7 regulations. As shown in the ADAC study [75] (see Section 2.4.1), there are already tyres on the market with low abrasion while keeping good safety and rolling resistance performance. Respondents noted that R&D and production costs increase

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[50] See https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en
[51] See UN Regulation No 117, https://unece.org/sites/default/files/2022-02/GRBP-75-30e.pdf
[52] See GPSNR: https://sustainablenaturalrubber.org/about-us/

when improving environmental properties, which can make it harder to compete, especially when many consumers' purchasing decisions are focused on cost. Legislation can ensure a level playing field mitigate this by ensuring all products must comply to a minimum standard.

The BTMA noted that since 2009, the car industry has been following a regulatory trajectory to reduce CO_2 emissions, and so demanding lower rolling resistance from tyres. Low rolling resistance tyres were offered in the market from around 2000. Since improving rolling resistance can adversely affect wet grip, the two parameters need to be regulated together to avoid industry from sacrificing safety to meet regulatory requirements. Wet grip declines as tread depth decreases, therefore, testing should be performed in the worst as well as the best case. From 2024, new tyres will be tested for wet grip in a worn state in which they will need to meet a minimum of 88% of the wet grip performance of the new unworn tyre, which could provide confidence to maximise the use of a tyre. As tyre tread wears down the tread becomes less stiff, hysteresis is reduced, and so rolling resistance is reduced. The BTMA reported that tyres nearing minimum tread depth have 30% lower rolling resistance than when new, and wear 50% more slowly. Ensuring the maximum wear out of a tyre is therefore environmentally beneficial from the perspectives of GHG emissions, particulate emissions, and of course life cycle (manufacture and disposal).

Customers

Stakeholders also mentioned customers as a driver for improving environmental performance of tyres, although corporate customers appeared more likely to use environmental information to inform purchase. Demand for more environmentally responsible products and information tends to come from fleet operators and OEMs first, then private consumers later. OEMs and fleet operators value the fuel and CO_2 savings of low rolling resistance tyres. Stakeholders noted that while consumers may say they value environmentally responsible products, their buying behaviour may not reflect that. For instance, although tyre labelling regulations provide customers with objective information to inform their purchase decisions, for many customers price is the main factor influencing their buying decision. Customers will need to be persuaded to absorb the extra cost (if any) for more environmentally responsible products.

Cost of sourcing materials

The cost of sourcing alternative materials was highlighted as an issue. However, in some cases, limited supply of one source of raw material can lead to an accelerated search for alternatives. This can lead to the alternatives becoming less punitive in price, making them more competitive. The BTMA provided an example of the supply chain issues for carbon black caused by the war in Ukraine which affected the European tyre industry. In Europe, alternatives have since become more economically competitive. However, this is not the same in other regions such as Asia, since they have different supply chains.

5.2.2. Minimising use-phase environmental impacts

Stakeholders highlighted the various strategies to minimise the use-phase environmental impacts of tyres, which were in alignment with the findings of the literature review in Section 2.

As noted in the review of literature, rolling resistance is caused by the flexing of the tyre and tread and impacts the emissions of the vehicle. The use of HD silica was noted as a key material change to reduce hysteresis and improve rolling resistance and tyre abrasion resistance. The BTMA noted that tread depth of new tyres has decreased over time to improve rolling resistance performance, from around ~8mm to around ~6-7mm, and an indirect consequence of this change is that tyre abrasion has also improved to maintain tyre life. Michelin has been making improvements to rolling resistance since 1946 when the radial tyre was developed. These changes are expected to continue incrementally, largely because adjusting rolling resistance has an impact on other crucial criteria such as grip - and vice versa.

The important relationship between grip and rolling resistance was also highlighted by stakeholders, where increasing wet grip may also increase rolling resistance. One stakeholder mentioned concerns from industry relating to potential increases in tyre noise that could result from improving wear resistance of tyres, iterating the need for balance between performance parameters such as noise, rolling resistance (fuel efficiency), wet grip and wear. Therefore, it is very important to balance both safety and environmental performance parameters when aiming to minimise environmental impacts of tyres.

The toxicity of tyre materials was mentioned as an area of focus right now, with industry and academia recognising that knowledge is still limited in terms of understanding the environmental impact of tyre materials. The properties of these materials and impacts change with temperature and other factors so more research is required to understand them. TIP mentioned that they are mindful of an evolving scientific understanding of tyre and road wear particles (TRWP), including research that has reached different conclusions about potential environmental impacts, so they continue to support independent research to improve the knowledge base. Whilst disparities in study findings may confirm the need for additional research, they are aware that scientific research has shown that the outcome of toxicity studies for tyre-related particles depends on the test material used in the study, the species tested, and the exposure concentrations and endpoints evaluated. They therefore work toward, and encourage, the use of standard methods and materials to further improve the reliability of the science that comprises the global state of knowledge on TRWP.

5.2.3. Production and EoL/circularity aspects

For production, end-of-life (EoL) and circularity aspects of tyres, stakeholders highlighted several strategies that are being implemented or investigated to improve environmental performance.

The first key area was raw material consumption, where industry has been looking for alternatives to natural rubber for a number of years. The BTMA noted that natural rubber has unique characteristics, such as strain crystallisation, that make it difficult to replicate with synthetic materials. This allows tyres with natural rubber to have higher load bearing capacity than synthetic elastomers, and so tyres for HDVs contain more natural rubber than those for LDVs. A key concern with the sourcing of natural rubber is deforestation as rubber trees are only able to grow in certain regions around the world due to specific climatic conditions. Demand for natural rubber is ever increasing as populous nations, such as China and India, become increasingly motorised. The risks of deforestation is expected to be reduced by pressures from different regulations, such as the EU Deforestation Free Products Regulation[53] which entered into force in June 2023, and the UK's Environment Act 2021[54], which refers to forest risk commodities (FRCs). The BTMA noted that the Global Platform for Sustainable Natural Rubber (GPSNR[55]) has been working towards addressing social and environmental issues associated with the cultivation of natural rubber and ensuring compliance with regulations. There is also a strategic motivation to not be fully reliant on natural rubber from trees due to business continuity risks of the supply chain – such as natural disaster, political barriers, or even diseases that may affect the plant species. In terms of alternatives to natural rubber, both Russian Dandelion and Guayule were mentioned as promising substitutes. Russian Dandelion is already in industrial production for tyres, where a mix of rubber tree and dandelion are used. The BTMA pointed out that an attraction of Guayule is that it grows in semi-arid countries which minimises competition with the growth of food products. The use of natural waste products, such as rice husks, to produce green silica for tyres were also mentioned as sustainable material alternatives to conventional silica.

Michelin stated its target to include 30% sustainable renewable or recyclable material materials in its tyres by 2023 had been achieved, with the next milestones being 40% by 2030, and 100% by 2050. The company also aims to design tyres that last longer, produce less waste, and less CO_2. Waste production by the company has decreased significantly over the last decade, while also increasing energy efficiency and minimising CO_2 emissions during manufacturing, including the use of renewable energy such as solar.

Active Tools noted the relevance of tyre repair kits in displacing the need for spare wheels in cars which saves weight, noting that for this reason only 3% of new cars sold now have a spare wheel supplied. Additional weight is identified as contributing to tyre and brake wear in Section 8.2.1, as well as increasing fuel use and CO_2 emissions. They also pointed out that the fluid used in their puncture repair kits is non-toxic and biodegradable. The company is actively pursuing strategies to use renewable energy and recycled materials during manufacturing processes of their product where possible.

In terms of EoL for tyres, several strategies and issues were brought up. Since rubber is not a thermoplastic, there are challenges with recycling rubber in a manner that would produce secondary raw material with the same properties and performance as the virgin material. Therefore, there has been interest from industry in chemical recycling to produce pyrolysis oil to manufacture a sustainable version of carbon black, and the use of pyrolysis gas in the synthesis of butadiene used in synthetic rubber at an industrial scale. Michelin mentioned that they have projects going on in this area. The BTMA suggested there could be the potential for around half of waste tyre material to be recycled back into raw materials for tyres in 10 years' time.

Stakeholders said the UK exports many EoL tyres to other countries, especially India, for low grade heat recovery. Concern was also raised that tyres were being burnt in the UK for cement production, due to their high calorific

[53] See https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en
[54] See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1080235/due-diligence-uk-supply-chains-summary-of-responses.pdf
[55] See https://sustainablenaturalrubber.org/

content. These EoL strategies can have high environmental and health implications. To mitigate these issues, some stakeholders voiced that stronger government policy such as extended producer responsibility is needed to create a closed loop where manufacturers are responsible for what they produce. A sustainable market within the UK and EU is required to create a circular economy for tyres. This may require measures such as digital waste tracking and removal of certain tyre collection exemptions that could allow some tyres to escape proper disposal.

The BTMA noted that retreading of EoL tyres has been focused heavier duty tyres, such as truck and aircraft tyres, where retreading is more economical. Retreading of car tyres has become less prevalent with the growth of the budget tyre market. However, there has been new interest retreading recently, such the retreading facility[56] at a former Bridgestone plant in France, where the tyres produced are marketed through the manufacturer's own distribution channels. For retreading of cars tyres, the BTMA mentioned that it will be more economical to collect a range of premium tyres collectively among different third-party retailers.

5.2.4. Tyre specifications for EVs

While there are no fundamental differences between EV tyres and regular tyres, one stakeholder noted that there can be specific tyre options for EVs due to their greater weight, and high starting torque that affects tyre wear. The main differences are the architecture of the tyre and the compounds used. There have been manufacturers that have launched new tyre products specifically for EVs to account for the increased weight and torque, but recently many have said that all their available tyres are EV compatible. The BTMA observed that for these reasons, tyre wear and road wear increase for EVs compared to conventional vehicles, and while regulators and the tyre industry may push for reducing tyre particle emissions, an increased number of EVs could cancel this out.

The BTMA mentioned that there was a potential reduction in frequency of visiting maintenance garages for EV owners compared to ICEV owners, providing less opportunity for vehicle technicians to check tyre pressure and wear. It is possible that in some cases such as fleet services, tyres may be changed earlier than they need to be because they are expected to reach the legal limit before the next service checks are due. These concerns are based on the understanding that many drivers do not carry out regular safety checks of the tyres themselves.

5.3. Stakeholder feedback – Brakes

As outlined in Section 1.3.2, a selection of stakeholders across the brake industry and research were contacted with interviews carried out, and written submissions provided. The questions discussed (listed in Appendix 1) built on the findings of the literature review and explored the environmental impacts of brakes, future legislation and other drivers for reducing impacts, and the potential technologies being used and developed to minimise environmental impacts from brakes and brake component manufacture.

5.3.1. Drivers for minimising environmental impacts

Stakeholders identified that the introduction of Euro 7 regulations in Europe will lead to a reduction in brake emissions, aligning with the broader environmental goals of emission control, although the details of implementation were not clear. While there is currently no plan for Euro 7 to be adopted in the UK, the Euro 7 regulations for brake emissions rely on UNECE's work to develop standardised measurement methods for brake emissions which is supported by the UK. Stakeholders expected similar limits be implemented in the UK in due course and felt that vehicles sold in the UK may be produced to similar specification to those for Europe in any case. As well as promoting the adoption of technologies to reduce tyre abrasion, Euro 7 regulations were thought likely to incentivise the use of hybrid technology in internal combustion engine vehicles, enabling greater use of regenerative brakes and a diminished use of friction brakes. The choice of the regulatory testing procedure was highlighted as crucial for effective product development, emphasising the importance of a well-regulated testing framework. Some stakeholders also foresee a potential reduction in the market size of replacement brake components due to the adoption of technologies that reduce brake abrasion rates.

However, concerns were raised around Euro 7 such as regarding the vagueness of the current proposals, particularly in relation to brake testing procedures, with stakeholders, such as TMD Friction, highlighting issues of repeatability and variance in measurements. Emissions limits for heavy duty vehicle brakes have not yet been proposed. Practical challenges, such as the current lack of dynamometer capacity meeting Euro 7 testing requirements, have also been pointed out, indicating potential hurdles in the effective implementation of these regulations.

[56] See https://www.tyrepress.com/2021/11/retreading-at-former-bridgestone-plant/

5.3.2. Minimising use-phase environmental impacts

Stakeholders highlighted the various strategies and new technologies that are being explored in the automotive industry to address brake emissions, with coated discs emerging as a promising solution. Stakeholders, such as Roulunds, highlight the benefits of coated discs, including excellent corrosion resistance, high hardness, and similar friction coefficients. However, there is acknowledgment that the adoption of coated discs comes with higher costs, potentially marginalising their feasibility to more expensive vehicles, as noted by a research expert and TMD Friction. Despite the advantages in reducing particulate emissions, the significantly elevated costs of up to 10-15 times more than traditional discs raises doubts about their widespread adoption. However, the research expert noted that when coated discs become a mass production solution, the cost is expected to be significantly reduced, rendering this solution as both cost-effective and environmentally friendly.

Non-asbestos organics (NAO) present another avenue, with emission reductions and greater prevalence in the United States and Japan, yet stakeholders have noted the reluctance to implement this technology in Europe. Stakeholders express reservations despite the 2-5 times lower mass emissions, pointing to a complex landscape of factors influencing technology adoption. TMD Friction noted that NAO materials generally have a lower friction coefficient and are not normally considered suitable by EU drivers, such as in ‘Autobahn’ conditions (as an example, Ford Mustang US specification vehicles have friction pad materials changed on import into the EU).

Filtering and vacuum systems, while recognised as new technologies, have not gained prevalence, with TMD Friction noting their proprietary nature and current lack of readiness and proven robustness. Brake drums which emit fewer particles as emissions are enclosed within the drum are discussed as a solution, although challenges including reduced heat rejection, more complex maintenance, and braking capacity compared to disc brakes limit their application, typically to the rear axle of smaller vehicles.

Resized brakes, especially for electric vehicles (EVs), are proposed as a solution by a research expert and TMD Friction. The idea is to downsize brakes due to the retardation provided by electric motors, resulting in smaller and lighter brake systems and less material use. Nevertheless, safety constraints impose limits on the extent to which brakes can be downsized, since the vehicle must be able to achieve a safe emergency stop even without regeneration, and heavy braking with smaller a brake friction pad area will increase temperatures, particulate emissions and wear.

As a general statement, stakeholders, such as Roulunds, emphasise the complexity of finding an optimal material to be used in pads and brakes, and no obvious new material is better. This is due to the operating conditions (temperature, pressure, speed) of different brake systems varying greatly, and thus testing the emissions generated in a specific condition may not be representative of real-world conditions. TMD Friction suggests that a holistic approach, considering a complete redesign of the brake system rather than just the disc and pad material, should also be considered, albeit acknowledging the associated expenses.

5.3.3. Production and EoL/circularity aspects

Roulunds highlighted the efficiency of current brake manufacturing processes, with minimal waste production amounting to less than 1% of emissions in the industry. However, there is some waste generated from test work, showing potential areas for improvement. TMD Friction emphasised their commitment to sustainability by actively engaging in recycling initiatives such as utilising a potential government grant to develop the incorporation of recycled materials into their friction mix. This includes grinding waste from their factories and reintegrating it into the production process, showcasing a dedication to minimising environmental impact.

Concerning end-of-life (EoL) disposal of brakes, stakeholders confirmed that discs are typically melted down for metal recovery, and the steel backplate in brake pads can also undergo a similar melting process for recycling. However, the friction material is often unlikely to be re-used and may end up in landfills or be incinerated. Although there is a life-cycle benefit for brake pads to be used to their maximum life, it was recognised that they may be replaced earlier for safety reasons aligned to servicing or inspection routines, indicating a nuanced perspective on the balance between environmental impact and safety considerations in the industry.

5.3.4. Brake specifications for EVs

Stakeholders noted that manufacturers customise brake designs to cater to the unique characteristics of electric vehicles. The increased weight, instantaneous torque and rapid acceleration of EVs necessitate brake systems tailored to these specific demands, and the use of regenerative braking, a key feature in electric and hybrid vehicles.

Attributes of EV brake systems may include slightly larger brake discs for the increased weight, and slightly reduced pad thickness reflecting the lower wear rate compared to ICEVs, which reduces resource use. Lower wear rates may potentially resulting in a smaller aftermarket segment. Additionally, stakeholders have noted the potential of drum brakes due to their corrosion resistance, minimal wheel dust, and lower emissions, when housed inside the drum. However, there are reservations about the feasibility of certain drum brake configurations in the front brakes of EVs, citing concerns related to stability. A shared concern among stakeholders revolves around the potential for increased corrosion in less-utilised friction brakes, posing challenges that may need to be addressed in the future. Mention was made of strategies to mitigate this which could include occasional use of the friction brakes to ensure discs are kept clean and free from corrosion, or the use of (more costly) coated discs which are protected from corrosion and offer reduced wear.

5.4. Evaluation and expert input

5.4.1. Tyres

The stakeholder feedback confirmed that regulations are most significant driver for minimising the environmental impacts of tyres, followed by customers. The key regulations identified as relevant to tyre manufacturers include:

- **Production phase:** EU Deforestation Free Products Regulation and UK's Environment Act 2021 to limit the use of deforestation linked to rubber use.
- **Use phase:** Euro 7 to limit abrasion (although limit values have yet to be proposed); and UN Regulation No 117 to limit rolling resistance.
- **End-of-life phase:** EU Eco-design for Sustainable Products Regulation to improve product circularity, energy performance and other environmental sustainability aspects.

The timing and limits of these regulations will be critical to the extent of impact they could have on environmental performance of tyres. The extent to which EU regulations affect the products sold in the UK is unclear, unless similar regulations are adopted for GB[57], although European manufactured and OEM-fitment tyres are likely to be common between UK and EU markets.

The literature review and stakeholder feedback have provided an overview of the various strategies and technologies to improve the environmental performance of tyres, and their associated trade-offs and conflicts. While there are well known trade-offs between rolling resistance (fuel efficiency), wet grip (safety), abrasion/wear resistance (tyre life and emissions), and noise, some manufacturers have been able to produce tyres that perform well in all these areas. This suggests there is scope to improve the environmental performance during the use phase for many tyres without jeopardising safety. However, achieving this optimal performance is still challenging considering these trade-offs, where any significant improvement in one attribute is likely to have a negative impact on others.

Some key technologies/processes that are likely to be **near-term** solutions for tyres include:

- The use of HD silica to improve rolling resistance and abrasion resistance.
- Tread design and depth can be optimised for noise or wet or dry grip.
- The elimination of tyre vent spews either during or after the manufacture process to reduce the unnecessary emission of coarse particles.
- Increased use of renewable energy and improvement in the efficiency of manufacturing processes to reduce energy and resource usage.

Some technologies that are currently being researched and may have potential to play more of a role in the **medium** to **long term** include:

- Alternative rubber matrix materials such as Russian dandelion and guayule to reduce reliance on natural rubber.
- The use of green silica and other natural reinforcing fillers that make use of agricultural waste and reduce the amount of carbon black needed.

[57] EU regulations will apply in Northern Ireland but not in GB following Brexit.

- Increased use of recycled content in tyres such as pyrolytic carbon black, devulcanised rubber granules, and PET from waste tyres.
- Porous tread tyres to reduce noise emissions and rolling resistance.
- Non-pneumatic (airless) tyres to reduce rolling resistance, material consumption, and improve recyclability.
- Self-healing materials to increase tyre life by sealing damage that could otherwise render the tyre unsafe or require early replacement.

While particle emissions from tyres may be minimised through the use of some of these technologies, The Tyre Collective has developed a technology which enables tyre particles to be collected as they are emitted. Having discovered tyre particles are charged by friction with the road, the award-winning device uses a combination of electrostatics and airflow to collect the particles, preventing them from entering the environment[58]. At present, it is not clear how practical the device is for widespread deployment or how it may be commercialised, a process which will require partnership with vehicle manufacturers and suppliers, but it is generating a lot of interest.

The life cycle impacts of a tyre are minimised when its life is maximised, meaning the tread is worn to the legal minimum limit. This benefit is magnified as the BTMA reported that tyres wear approximately 50% more slowly when nearing minimum tread depth and can have up to 30% lower rolling resistance than when new, so both particulate emissions and CO_2 emissions are reduced in the use phase. However, tyres are often replaced prematurely due to service and inspection routines, and a lack of confidence in consumers carrying out their own checks of tyres (which can also lead to the negative environmental impacts from incorrect tyre pressures – see Section 8.4.1). Tyres do have minimum tread depth indicators, but they require active checking and unlike an audible warning of minimum brake pad depth, it is easy for the consumer to miss these. The market for part-worn tyres facilitates making the maximum use of tyres with consequential environmental benefits, although there are risks that potentially unsafe tyres are sold[59], suggesting reinforced regulation of the part-worn market may be beneficial to consumer confidence. Retreading worn tyres with new tread is another process for extending the life cycle benefits of tyres, a process that is common for truck tyres, although for light-duty vehicles the availability of budget tyres has reduced demand and their increased use of synthetic rubber means they are less suitable. However, some manufacturers are considering tagging their tyres to enable targeted collection which could facilitate high-quality retreaded tyres.

The transition to EVs is currently under way, and stakeholders noted that some manufacturers are designing tyres specifically for EVs to suit their higher weight and torque, and possibly with low rolling resistance to maximise range, but recently more tyre ranges are being advertised as EV compatible. Note that the impact of rolling resistance on vehicle use CO_2 emissions is likely to be lower for EVs than fossil-fuelled vehicles and reduce further (ultimately to zero) as the carbon intensity of grid electricity reduces, although the benefit to range and running costs may be just as important to consumers. The higher weight and torque of EVs leads to increased wear rate (abrasion) compared to a similar conventional vehicle, a point that is explored in Section 8.2.2. An important point to note is that tyre abrasion produces mainly coarse and fine particles, and airborne emissions of ultrafine particles are a small fraction of the mass lost (see Section 6.4.1), although may still comprise a large number of particles. A couple of conclusions may therefore be drawn:

- A transition to EVs may increase tyre abrasion and particularly the emissions of microplastics, and if that increased abrasion results in shorter tyre life, an increase in production and end-of-life impacts.
- For understanding the health impacts of tyre emissions, measurement of airborne particle number (the total number of particles emitted) is likely to be more relevant than mass lost from the tyre.

5.4.2. Brakes

There is wide acknowledgement of the issue of brake particle emissions which international actions are starting to address, with standards for measurement adopted at UN ECE level and proposals for mass-based emission limits to be introduced with Euro 7 in the EU. However, further research is needed to develop a deeper understanding of the particles formed, their size and composition, and reduce the uncertainties associated with the different types of brake wear emission factors. Evaluations of brake emissions have traditionally focused on mass, and concerns have been

[58] See https://thetyrecollective.com/
[59] See DVSA's Vehicle Market Surveillance Unit: results of the 2023 programme: https://www.gov.uk/government/publications/vehicle-market-surveillance-unit-programme-results-2023/vehicle-market-surveillance-unit-results-of-the-2023-programme#part-worn-tyres

related to visible dust (e.g. on wheels) or known toxins (such as asbestos or copper). It is increasingly clear that it is the fine and ultrafine particles that pose the greatest danger to humans, and it is unclear whether technologies which reduce mass emissions also reduce fine and ultrafine particles, so in the future the measurement of particle number (the total number of particles emitted) may become more important than mass alone.

The emergence of hybrid and electric vehicles that can use regenerative braking systems (RBS) provides the opportunity to reduce the use of conventional friction brakes, minimising their emissions. Literature suggests the use of RBS can reduce brake wear emissions by 69-95% in full electric vehicles and 65-87% for hybrid-electric vehicles, since friction brakes are used less and typically for lower braking power at lower temperatures. However, braking power is influenced by a complex interaction between vehicle mass, speed, deceleration rate and powertrain technology, and thus the extent of mitigation and the driving cycles employed to measure brake emissions must be considered holistically.

There is thought to be some potential for EVs to be able to use smaller brakes with reduced emissions, thinner friction materials reducing resource use, brake-by-wire or even drum brakes which have the benefit of reduced corrosion as well as containing particulate emissions. Brake-by-wire systems enables shorter braking distances, and reduces the residual drag torques that occur in conventional braking systems to almost zero. This results in even fewer particulate emissions due to brake abrasion. Some EVs are noted to have adopted rear drum brakes, while others are reported to be using strategies or technologies to control disc corrosion, which can become an issue where friction brakes are rarely used due to regenerative braking. However, the requirement to maintain primary braking performance in an emergency in the event of regenerative assistance being unavailable, when considering the increased weight of EVs, is thought to limit the potential to down-size EV brakes. The potential emissions from hard braking of a heavy vehicle with downsized brakes should also be considered.

From both literature and stakeholder feedback, coating technologies show promise in reducing brake wear emissions through enhanced wear resistance and friction coefficient reduction. Nickel-based and iron-based coatings, along with solid lubricant additives, demonstrate significant improvements. However, their current high costs remain a barrier to widespread adoption. Alternative materials for brake pads and discs, such as those with zinc additives and molybdenum disulphide, also show varying degrees of success in wear reduction, although trade-offs between environmental impact, braking efficiency, and feasibility for large-scale adoption must be considered. Examples of the use of low particulate NAO pads in other regions show potential but stakeholders thought their overall attributes made them less suitable for UK drivers and conditions at the current time. Other friction material technologies such as alternative binders and resins are not as far along their development and commercial readiness trajectory, and further development and optimisation are required to reach market readiness, which stakeholders identified as a complex process considering the brake system (pads and rotor) and the wider vehicle requirements.

As well as technologies to reduce brake emissions at source, solutions for capturing brake particles on-board the vehicle are emerging. Automotive supplier MANN+HUMMEL are developing a passive filter that fits around the brake calliper and part of the disc, and an active filter system that draws particles into a remote filter by vacuum[60]. Another active vacuum filter system is offered by Tellano which extracts particles at source through a groove in the pad, claimed to remove up to 90% of fine particles with filter replacements at services up to 30,000km interval[61]. Other brake particle solutions are seen in technical papers and patents, although at present no such systems are known to be in commercial use. Their feasibility is likely to depend on their cost and effectiveness compared to low emission brake components, and their practicality, durability, and service burden in use. Ultimately, their adoption will depend on regulatory limits on brake emissions, and the options vehicle manufacturers choose to adopt to meet them.

The exploration of technologies to mitigate the environmental impact of brakes extends beyond the use-phase emissions to encompass cleaner production and waste recycling strategies. While end-of-life activities has a relatively low impact on emissions and recycling is commonly applied to brake callipers and discs due to their manufacturing materials, there are considerations over new recycling procedures for friction pad materials which are non-degradable. Disposal via landfill or combustion raise environmental concerns, emphasising the need for sustainable recycling solutions. Innovative approaches to separating and recycling the friction materials and incorporating the waste into new brake components contributes to a circular economy. Refurbishing brake discs through laser metal melting deposition yields a higher friction coefficient and low abrasion surface, with reduced energy consumption compared to new manufacturer. However, these recycling and remanufacturing technologies may be some time away from commercial deployment.

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[60] See https://oem.mann-hummel.com/en/oem-products/fine-dust-filters/brake-dust-particle-filter.html

[61] See https://www.tallano-technologies.com/en/solutions/automotive/

5.4.3. Road surfaces

While this study is focused on the environmental characteristics of tyres and brakes, it has become clear through literature and consultation with experts that the road surface itself plays a significant role in the way that particles are generated from tyre abrasion, the rolling resistance of the tyre, the grip under wet and dry conditions, and the noise generated by the tyre rolling over it. Since the particles emitted are known to comprise both tyre material and road dust (being termed tyre and road wear particles, TRWP), the road surface also contributes to the composition of the particles emitted. Since through its specifications, National Highways has direct control over the way road surface characteristics are managed across the Strategic Road Network, there is an opportunity to consider the effects of road surface characteristics in the overall equation of optimising the environmental impacts of tyre use.

At present, road surface characteristics are optimised to consider the way they influence skidding, tyre/road noise, ride quality and durability, all of which depend on aspects of the tyre/road interaction [274]. Considering the road together with the vehicle (i.e. tyre, suspension and brakes) can therefore enable a ‘global’ rather than a ‘local’ optimum to be achieved and help to ensure that, where trade-offs are necessary, the effect on each property (particularly those affecting safety) is fully understood. Analysis of the literature has highlighted that considerable research exists in some areas to inform this optimisation. For example, National Highways’ extensive previous research on skidding resistance, international projects such as ROSE (Roads Saving Energy) [275] and ROSANNE [276], and ETRma initiatives [277] have produced really interesting results, supporting engineers in keeping current standards and specifications updated.

To date, aggregates used in road surfacing materials are specified to provide grip and resist polishing under traffic, and the shape of the surface texture is chosen to provide drainage pathways in wet conditions. Research has shown how these choices impact on how much tyre and brake wear is generated, as they affect the hardness and the sharpness of the tyre/road interface, and the level of vibrations transferred from the tyre/road interface to the vehicle suspensions, brakes and the rest of the vehicle [278]. In 2020, a briefing paper produced for National Highways [279] showed how existing equipment could be used to better understand how road surface characteristics influence the production of tyre and road wear particles and a detailed test plan was developed to respond to the following research question:

> *Is there any material, construction technique or maintenance strategy that road authorities could specify to ensure their supply chain delivers environmentally optimal roads to:*
>
> - *minimise tyre and brake particles,*
> - *produce as little noise as possible,*
> - *reduce road rolling resistance (and thus vehicle fuel consumption and emissions, or increase vehicle range of electric vehicles), and*
> - *provide adequate skidding resistance (are safe to stop in case of emergency)?*

Or in other words, to investigate what road authorities can do to minimise the amount of microplastics and brake wear that is produced due to vehicle/road interaction. Research to address this question within the realms of pavement engineering and road asset management could support National Highways in making their contribution towards minimising the negative impacts of tyres and delivering environmentally optimal roads.

6. Performance of tyres and brakes currently on sale and in use

6.1. Overview of the literature

Limited information was found in literature on the performance of tyres and especially brakes currently on sale and in use. While tyres have a standardised rating and labelling for key attributes in the EU (fuel economy, wet grip, and noise) and treadwear ratings in the US, there are no equivalents for brake performance.

Research found that **tyres** of the same US treadwear rating but of different brands showed different behaviour in terms of material loss, PM, and PN emissions under the selected testing conditions. Therefore, the treadwear ratings could not be used to categorise tyres of different brands in terms of their emissions. Other key research that involved testing of different types and brands of tyres found that there were tyre models in all sizes that had low abrasion and good driving safety, showing that it was possible for tyre manufacturers to achieve good performance in both parameters. The research also found that only a small proportion of tyre abrasion particles by mass had a diameter of below 10μm, emphasising that there is a fundamental disconnection between tyre wear rates and non-exhaust (tyre) emission rates to the air.

Very limited research was available for the performance of **brakes** currently on sale and in use. Further market research into the brakes fitted by vehicle OEMs and the different dominant brake manufacturers will be undertaken and reported in this project's final report.

6.2. Market research and stakeholder feedback – Tyres

6.2.1. Performance of tyres currently on sale

Considering the Original Equipment Manufacturer (OEM) fitment. Table 6-1 shows the tyre performances of the tyres fitted from new to, and recommended for, the top 10 best-selling passenger car models in the UK[62]. None score A in all three categories, the best are rated BBA, BBB, or CAB.

[62] Year-to-date best-selling cars up to August 2023 data sourced from SMMT: https://media.smmt.co.uk/august-2023-new-car-registrations/ . Rating and pricing data collated in September 2023 from www.oponeo.co.uk.

Table 6-1: Top 10 selling vehicles and the tyre brand/models recommended[62, 63]

Rank	Vehicle model	Tyre brand/model fitted	Size	Efficiency	Grip	Noise	Price
1	Ford Puma (2023)	Bridgestone Weather Control A005 EVO	R17	C	A	B - 70dB	£85.00
2	Vauxhall Corsa (2023)	Bridgestone Weather Control A005 EVO	R16	C	A	B - 70dB	£85.00
3	Tesla Model Y (2023)	Continental AllSeasonContact	R19	B	B	B - 72dB	£188.00
4	Nissan Qashqai (2023)	Yokohama BluEarth-4S AW21	R17	C	B	B - 72dB	£105.00
5	Hyundai Tucson (2023)	Yokohama BluEarth-Winter V906	R17	D	B	B - 71dB	£123.00
6	Kia Sportage (2023)	Yokohama BluEarth-4S AW21	R17	C	B	B - 72dB	£105.00
7	Nissan Juke (2023)	Vredestein Quatrac	R16	C	B	B - 71dB	-
8	Vauxhall Mokka (2023)	Goodyear Vector 4Seasons Gen-3	R16	C	B	B - 72dB	£122.00
9	Ford Fiesta (2023)	Michelin CrossClimate2	R15	B	B	A - 69dB	£104.00
10	Mini (2023)	Yokohama V903	R15	E	C	B - 70dB	£73.00

For the secondary tyre market (replacement fit), the data in Table 6-2 is for the top 15 tyre brands/models in 2023.[64] Although the range of prices is similar to those of the OEM fitment, seven out of the top 15 best-selling tyres are under £100 each, compared to just two of the top ten by vehicle sales. The median value of the replacement tyres is £99.99, whilst the arithmetic mean price is £112.20, while for OEM fitment tyres these values are £105.00 and £110.00 respectively. This suggests cost is an influence on the choice of tyres for many consumers, although others will pay more, perhaps for recognised brands or perceived performance (e.g., dry grip).

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[63] Note that vehicle models may be available with multiple wheel and tyre options and the data in the table represents the assumed standard fitment

[64] List of top 10 selling tyres for September 2023 taken from https://www.mytyres.co.uk/bestselling-tyres.html. Rating and pricing data collated in September 2023 from www.oponeo.co.uk.

Table 6-2: Top 15 best-selling tyres[64]

Rank	Tyre Brand/Model	Size	Efficiency	Grip	Noise	Price
1	Maxxis AP2 All Season	195/65 R14	E	B	A - 69dB	£85.69
2	Uniroyal Rainsport 3	205/55 R16	D	A	B - 71dB	£96.99
3	Pirelli PZERO	205/40 R18	D	B	B - 72dB	£174.79
4	Bridgestone Blizzak LM001	205/65/ R16	C	B	B - 72dB	£149.75
5	Pirelli Cinturato P7	205/45 R17	A	B	A - 69dB	£135.99
6	Nexen Winguard Sport	225/55 R17	C	C	B - 71dB	£109.50
7	Bridgestone Potenza S001	225/40 R18	D	A	B - 71dB	£96.99
8	Star Performer STPS AS	205/55 R16	D	C	B - 71dB	£74.40
9	Nankang AS-1	195/40 R17	F	C	B - 71dB	£69.04
10	Nexen N Fera SU1	195/65 R15	C	B	A - 69dB	£84.80
11	Toyo Nanoenergy 3	205/55 R16	C	C	B - 69dB	£76.09
12	Toyo Snowprox S943	225/60 R16	C	C	B - 70dB	£102.99
13	Pirelli Scorpion Winter	235/55 R18	C	C	B - 72dB	£182.99
14	Hankook RW06	205/70 R15	E	D	B - 73dB	£120.89
15	Uniroyal Rainsport 3	205/60 R16	C	A	B - 72dB	£107.10

The data in these tables is analysed in terms of the frequency for each possible label score for efficiency, grip or noise in Figure 6-1 (for original fitment) and Figure 6-2 (for replacement market).

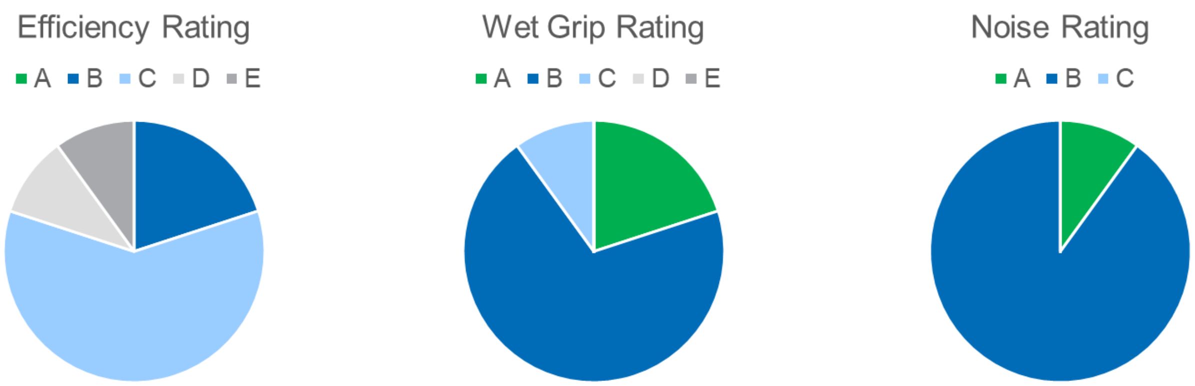


Figure 6-1: Characteristics of the tyres fitted by OEMs to the 10 top selling passenger car models

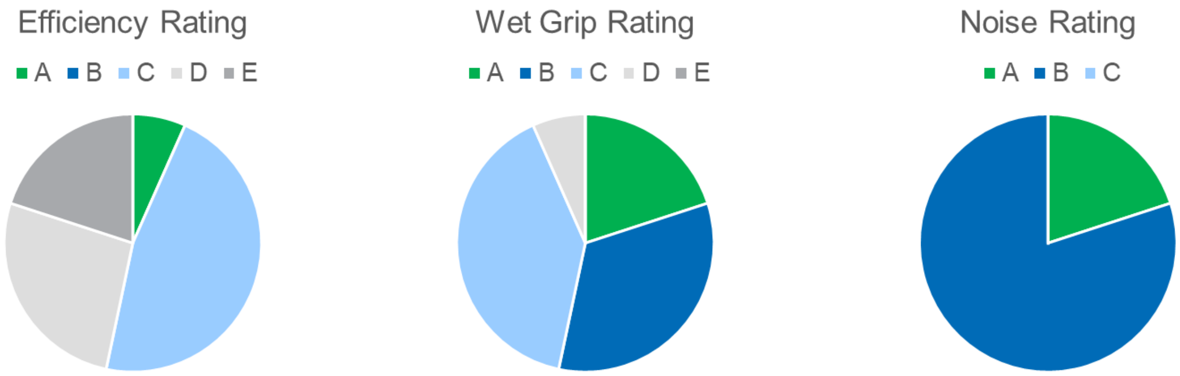


Figure 6-2: Characteristics of the top 15 selling tyres

Overall, for efficiency and grip, the average characteristics are seen to be less optimal for replacement tyres than for original equipment manufacturer (OEM) fitment. This combined with the wider range of tyre brands represented may reflect price being the priority for many consumers. Of the OEM fitment tyres 90% are rated A or B for wet grip, of the top 15 replacement tyres this reduces to just over half. Most OEM-fitted tyres are rated C or B for efficiency, whereas most of the top-selling replacement tyres are rated C or D. Just one of the top 15 replacement tyres score A for efficiency, which suggests some consumers and/or fleet operators value that attribute, either through environmental concern or for potential fuel savings. The difference between tyres with fuel efficiency class B and D is that the rolling resistance of the latter is 40% higher than for the former. For tyres with fuel efficiency class E (rolling resistance >10.6N/kN), and class A (rolling resistance <6.5N/kN) this difference is 63%. If doubling a vehicle's tyres rolling resistance leads to a roughly 10% increased fuel consumption, these comparisons lead to approximately 4% and 6.3% increased fuel consumption, and so consumer choice on tyre replacement may be negatively affecting the fuel consumption and so the CO_2 impact of their vehicles.

The noise rating provides limited distinction between tyres, with only three possible ratings. None of the OEM tyre fitments or the top 15 replacement tyre options were rated C, and only a small proportion rated A. Furthermore, the maintenance facilities studied did not offer any tyres with a noise rating of C (>72dB).

There may be many different tyre options on the market, but the choice to the consumer may be limited. Tyres differ by wheel size, tyre width, profile, and speed and load rating, but the fitting garage may only stock a limited selection in any given size and rating suitable for the vehicle. Consumer choice may be greater for common wheel sizes but more limited for unusual sizes or vehicle models, while larger specialist tyre fitters may be able to hold more stock than smaller fitters or general garages. In recent years, online tyre sales have become available, which may use local tyre fitters for distribution and fitment, and these outlets may be able to offer a greater range of tyres displayed with their labelled attributes and manufacturer claims suitable for the consumer's vehicle. This provides consumers the choice to select tyres that meet their environmental or performance requirements, or simply their budget.

6.2.2. Stakeholder feedback

Stakeholders highlighted that OEM 'off-the-shelf' tyres ranges produced for the replacement market have very small or non-existent differences in specifications and performance to the same OEM brand and range of tyres produced specifically for vehicle manufacturers to fit on their vehicles. Vehicle manufacturers and tyre manufacturers are both consulted and involved in the design and testing process of tyres, after which parameters are chosen to be included in the final tyre design. These tyre designs may differ slightly between specifications of the same tyre model as they are tailored for different car dimensions, weights and other characteristics. However, general performance characteristics such as wet grip and rolling resistance are generally the same across different tyres of the same model, and a similar trend is also seen in the replacement market. Stakeholders noted that the specifications and performance of different tyre models and brands can differ quite substantially, especially when comparing between premium and budget tyre brands. The BTMA noted that California is pursuing a regulation[65] to require replacement tyres to have the same rolling resistance performance as the OE specification.

Stakeholders have also noted the influence of consumers and their tyre preferences in the after-market industry. While the range of tyre choices available in the after-market industry is considerable, the cost is a major driving factor, and some consumers will just select the cheapest set available. There are also consumers that prefer to have replacement

[65] See https://www.energy.ca.gov/programs-and-topics/programs/replacement-tire-efficiency-program

tyres that are identical to their pre-existing OEM-specification set, which are relatively more expensive at point of purchase in the aftermarket. Michelin noted that for small truck fleets, the motivation for buying budget vs premium tyres is transactional; the cheapest tyre at the point of sale is often selected, with no consideration given to total cost of ownership, which takes into account longevity, susceptibility to damage and fuel savings.

6.3. Market research and stakeholder feedback – Brakes

6.3.1. Characteristics of brake systems currently on sale

As discussed in the literature review, there is currently no legislation that requires a standard ranking or labelling system for brakes sold in the UK or EU. Therefore, manufacturers use different ranking systems, if any, thus making comparisons between products from different manufactures/suppliers difficult. There is a lack of research and literature on the environmental impact of brakes, and limited details about the attributes of brakes on sale, and consequently a lack of public awareness of the issue. Without a standardised ranking/labelling or emissions measurement process, manufacturers are not required to publish the emissions or environmental performance of their products, or indeed any other attribute. Without this information, customers are unable to consider environmental factors when purchasing brakes.

Whilst there is little research/literature on the environmental impact of brakes, some brake component manufacturers offer products that claim to have environmentally optimal attributes. A specific example is EBC Brakes, who advertise themselves as being at the vanguard of technology, quality, product performance and customer service, and offer an ECO friendly brake system, the characteristics of which are shown below in Figure 6-3.

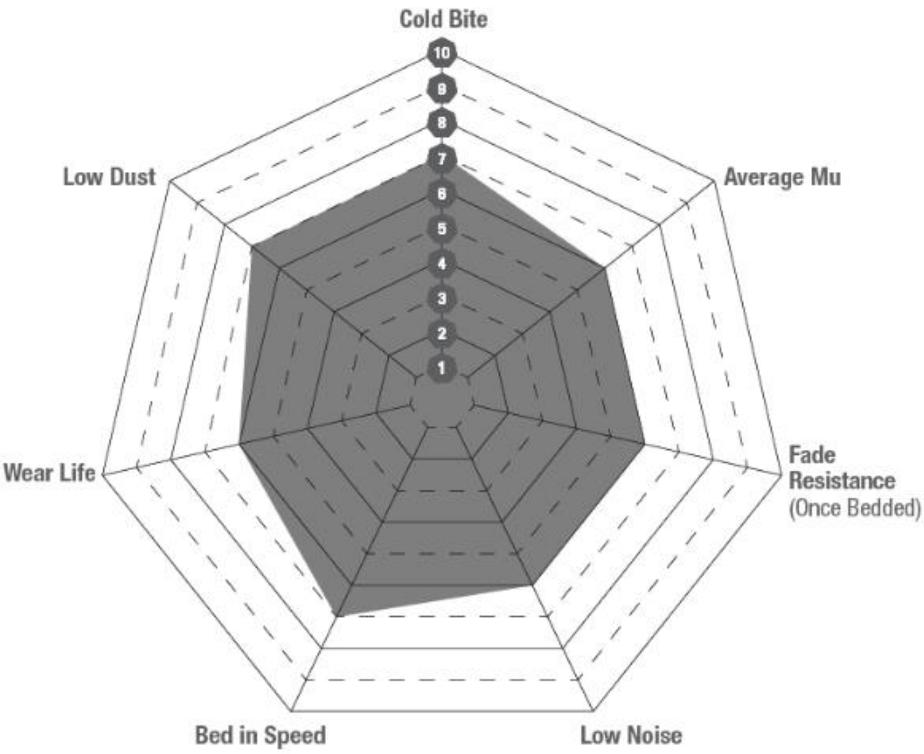


Figure 6-3: EBC's description of its ECO-friendly brake system characteristics[66]

EBC Brakes recently launched a new material with their "ECO friendly Ultimax 2 ™ brake friction material that completely eliminated all heavy metals and sulphides". EBC Brakes include the production of dust in all their product ratings. The aim of this, however, is not to make the user aware of the particulate emissions produced by the components, but simply the effects on the visual appearance of dust on their vehicle.

[66] Figure sourced from EBC Ultimax2™ Brake Pads - EBC Brakes

Research into the brake manufacturers whose products are fitted by the passenger car OEMs are summarised in Table 6-3.

Table 6-3: Brake suppliers for 12 vehicle OEMs

Vehicle OEM (in alphabetical order)	Vehicle model	Brake supplier
Alpha Romeo	Tonale	Ferodo
Audi	Q7, A3, A4	Ferodo
BMW	X3	Jurid
Honda	CR-V	Ferodo
Iveco	Daily 4.2	Ferodo
Lexus	F models	Brembo
Maserati	Levante	Jurid
Mazda	CX5	Ferodo
Mercedes-Benz	EQA, GLC	Ferodo
Smart	Fortwo	Ferodo
Volkswagen	Golf VIII, Crafter	Ferodo
Volvo	XC60, XC90	Jurid

In terms of leading brake system manufacturers, and the types of vehicles their brakes are fitted to, our research shows the following breakdown in Table 6-4.

Table 6-4: Brake manufacturers and vehicle types their brakes are fitted to

Brake manufacturer	Passenger cars	Commercial and heavy goods vehicles
ATE	YES	-
Brembo	YES	YES
EBC Brakes	YES	-
FEBI-Bilstein	-	YES
Ferodo	YES	YES
Jurid	YES	YES
Knorr-Bremse	-	YES
Textar	YES	YES

Three quarters of the passenger car brake systems offered by EBC Brakes have been designed to reduce their environmental impact. This has been done by removing harmful materials or by designing the product so that the dust production is reduced. In addition to the innovative product, and its associated information, offered by EBC, some other brake manufacturer specific details are:

- ATE offer brakes pads which do produce less dust, although this is aimed at keeping the customers' vehicles cleaner for longer. There is no mention of any environmental benefits.
- Brembo have released a new braking system range that reduces PM_{10} and $PM_{2.5}$ emissions, and increased durability. Currently available for a select few vehicle models (light commercial vehicles).
- Ferodo offer a 'green' option which is said to reduce particle emissions.
- Jurid advertise Low/No copper in their brake pads for everyday vehicle use and brake pads designed for electric vehicles designed to produce less particle emissions.

Some overall observations regarding trends from brake manufacturers are:

- Manufacturers are showing interest in reducing the impact that brake components have on the environment.

- The most common method of reducing the environmental impact is by replacing potentially toxic materials, such as copper and sulphides, with “green” and “eco-friendly” materials.
- Low dust production is a relatively common design feature, however the manufacturers market this as a method of keeping the users’ cars cleaner for longer, rather than for the health impacts of particle emissions.
- Components that are claimed to reduce particle emissions are beginning to appear on the market in preparation for the expected Euro 7 emission standards. The manufacturers do not release the details about how this is achieved.
- Braking power, durability, noise and service life remain the driving design requirements.
- Excluding Brembo, there are no aftermarket suppliers who have designed any braking components for commercial / heavy goods vehicles that are designed to reduce PM emissions.
- The priority for these products is for durable, long lasting, quiet brake components that make the driving experience as safe and easy as possible.
- Brembo, typically an aftermarket component manufacturer for performance vehicles, is leading the way with low PM emitting braking components in the commercial vehicle market.

In terms of the **vehicle OEMs,** generally they do not release technical information about the brakes used on their vehicles. These are referred to as their original manufactured parts and come as standard on their vehicles. The OEM’s customers aren’t provided with any brake system options to choose from when purchasing a new vehicle. They therefore do not release any specifications besides what type of braking system is used.

In addition, OEM’s do not share any form of performance/efficiency ratings or mention a target of reducing non-exhaust emissions through brake system design. The brake components fitted are often design specifically for each vehicle model.

Some OEM trends are significantly impacting PM emissions. These are principally focussed on regenerative braking because this does significantly reduce the PM_{10} and $PM_{2.5}$ emissions compared to standard disc brakes. Therefore, the increase in EV and hybrid vehicle productions by OEMs introducing these powertrain product lines, is increasing the number of vehicles with regenerative braking into the fleet.

6.3.2. Brake system maintenance, and the aftermarket services for brake maintenance

For passenger cars, and vans, the requirement to replace brake pads and discs arises during routine servicing, during the periodic technical inspection (PTI, or MOT test), or because a warning light becomes illuminated, or because of the warning noise emitted by pads nearing their minimum thickness. These activities are usually undertaken by a repair garage. Garages can be categorised broadly as:

- Main dealer, or OEM franchised garages – where replacement components are those recommended by the vehicle’s original manufacturer, and;
- Independent garages – who undertake repairs on a wide variety of vehicle makes – where replacement components need not be those recommended by the vehicle’s original manufacturer (which can be ordered but often with a time lag), or the general components they hold a limited stock of.

Repair garages will generally offer a narrow range of product and may not provide the customer a choice of component specification, unlike for tyres where there may be a range of products on offer that would be appropriate replacements. The consumers rarely know the name of brake system manufacturers, the maker of the original brake system fitted to the car or have information to differentiate between options if they were offered some. The one variable they might be made aware of is the price of various options.

For HDV, many operators of these vehicles have servicing packages, often with the vehicles’ main dealer, or a franchised HDV workshop. For these vehicles, replacement components for the braking system are likely to be those used by the vehicle’s OEM during manufacture.

6.3.3. Stakeholder feedback

Stakeholders highlighted that similarly to tyres, the overall difference in specifications of brake products supplied to the after-market compared to the original OEM specification is quite small and mostly come down to cost.

There is a range of brake products that are currently supplied in the market. Products available to be sold in after-market dealerships are likely different to those originally fitted to the vehicle on the production line. This is a result of many factors including different compliance sign off processes, and different components available at motor factors.

While they vary greatly in price partly due to cost differential between the product cost vs selling price, fundamentally the after-market and OEM specification brakes offer the same braking performance. Roulunds Braking noted that from an environmental perspective, cheaper brake pads are likely to wear faster and produce more emissions whilst more expensive products may include more functionalities (e.g. brake pad shims to reduce noise). After-market brake products have also been free of polluting materials such as copper and antimony for over 20 years, mirroring that of OEM products. However, in the current market, as long as ECE regulation and other market surveillance standards are met, any brake pad or disc product can be sold (including third party manufacturers.

Finally, similarly to tyres, the choice of brake products is dictated by that of consumer preference. TMD Friction noted that given consumer knowledge over brakes is generally lower than tyres due to lower transparency over specifications and a lower prioritisation compared to tyres, many of the brake products that are supplied in the aftermarket depend on what is available to be sold to the consumer at motor factors.

6.4. Evaluation

6.4.1. Tyres

This section delves into the performance of tyres currently on sale and in use, revealing a notable gap in the existing research, particularly regarding brakes. In the European Union, tyres are subject to standardised ratings encompassing fuel economy, wet grip, and noise, with the United States adding further treadwear ratings. The research underscores a significant disconnect between tyre wear rates and their emission rates into the air, with the treadwear ratings in the US failing to provide a consistent categorisation of tyres from different brands in terms of their emissions.

The research conducted by ADAC on tyre abrasion and emission rates in Europe found that tyre models of all sizes can achieve low abrasion while ensuring good driving safety. The research further reveals that only a small fraction of tyre abrasion particles are sizes below 10µm, which indicates a fundamental discrepancy between tyre wear rates and non-exhaust (tyre) emission rates to the air.

A quantification of tyre wear to the airborne emissions from tyres can be estimated from comparing the ADAC figure of average tyre wear, given in the literature review, with the EMEP EEA non-exhaust emission factors, used to generate air emissions inventories. The ADAC figure gives an average tyre wear of 120 g/1000km per tyre. This would be equivalent to 480 mg per vehicle km if all tyres wear at this rate. The 2023 EMEP/EEA “Air pollutant emission inventory guidebook”[67] gives an average tyre wear emission factor **to the air,** for a medium sized ICE passenger car, of 10.7 mg/vehicle-km total suspended particulate (TSP). It reports 60% of this is PM_{10}, and 42% $PM_{2.5}$. Comparison of the average tyre wear emission factor to the average abrasion rate measured in the ADAC tests suggests the total airborne particulate emissions represents just 2.2% of the tyre abraded material.

6.4.2. Brakes

In terms of brakes, there is currently no standardised measurement, ranking or labelling system in the UK or elsewhere, other than for the assessment of braking power and so suitability of replacement. Therefore, comparing products from different manufacturers and even assessing their basic contributions to environmental impacts and especially emissions is currently not possible in a meaningful way.

The topic of brakes and their environmental impact has received limited attention in academic and corporate research. It has been highlighted in this section that there is a low albeit increasing level of public awareness of the environmental impact of brake choices, reinforced by the scarcity of data on the environmental attributes of brakes currently on sale. Despite this, there have been innovations and trends in new braking technology, as discussed in the literature review, highlight ongoing advancements in this space.

[67] See 1.A.3.b.vi-vii Road tyre and brake wear 2023 — European Environment Agency (europa.eu)

7. Understanding consumer awareness of the environmental impacts of tyre and brake choice

7.1. Overview of the literature

The main findings for **tyres** were:

- Price was the main factor in the decision-making process for tyres, and there was a potential willingness to pay slightly more for an environmentally friendly tyre from some respondents.
- Influencers played an important role in the decision-making process, particularly parents, with friends and family and online reviews also influencing.
- Fleet operators are likely to have different priorities to private buyers.

Many of the tyre studies reviewed were from the United States and these consumers may have different priorities when choosing a tyre, particularly in places where winter tyres are necessary. A YouGov survey [169] demonstrates differences between the priorities of residents of the US and GB.

There was no literature for consumer research about choosing **brakes**. This suggests there are less options for choosing brakes for consumers compared to tyres in that the servicing garage may not provide the consumer a choice. It is likely therefore that decision-making for brake fitment is with the servicing garage, and possibly fleet operators, and consumers may have little understanding of the environmental impacts of brakes.

Analysis of this literature with input from experts and stakeholders will be used to develop a methodology to understand consumer awareness of the environmental impacts of tyre and brake choice, with the intention of applying the methodology during Phase 2 of this study.

7.2. Stakeholder feedback (workshop)

A workshop took place on Wednesday 29 November 2023 with attendees from National Highways, the British Tyre Manufacturers' Association (BTMA), Department for Environment, Food and Rural Affairs (DEFRA), the Environment Agency, TyreSafe, AECOM and Ricardo.

Headline findings from the consumer literature review for tyres were presented, as described in section 6.1 of this report. Attendees were advised there was no published consumer literature for brakes found and it was generally agreed that end-users were unlikely to make a choice for brakes in the same way they possibly could for tyres.

7.2.1. Tyres

The current method of tyre labelling using the European Product Registry Energy Label was introduced to attendees, specifically the environmentally specific information such as fuel efficiency and noise levels. It was mentioned that in a previous National Highways survey 45% of respondents were aware of tyre labels and 44% were not.

Three stages of the product life cycle of a tyre were introduced, which were production, usage and end-of-life use, to gather intelligence of what may, or may not be important and these are listed below.

- The presence of hazardous or other substances such as microplastics which would impact the environment.
- The use of a 'Star' rating or similar style of rating to communicate the environmental factors applied during production and / or a rating scale to communicate the potential longevity of the tyre.
- Whether end users believe the tyre would not be sold if it didn't meet minimum standards.
- Methods to educate end users about correct tyre pressures and driving style and how these can help meet the predicted longevity of the tyre life, as well as impact on safety.
- Whether consumers are aware of, and have an interested in, what happens to a tyre at the end of use, or whether there is there an assumption (or trust) that the tyre fitting garage will pass on the tyres for recycling or reuse. Possibly asking direct question 'Have you ever thought what happens to the tyres that you leave behind?'

- Whether customers are aware of a disposal charge and if so, what they believe they are paying for.
- Whether individual consumers have different considerations to fleet managers.

A list of suggested topics to discuss and types of consumers to be approached for research were presented and were generally agreed with.

Possible topics for discussion

Customer decision making process including:

- When and where is the decision made.
- What are the end user priorities.
- Who influences the decision and the impact they have.

Purchase decisions for an environmentally friendly tyre:

- What could encourage this choice.
- Willingness to pay / pay a premium.

Type of messages to inform the decision:

- Importance of messaging and / or labelling
- Which messages are impactful.
- How to communicate messages and information.

Possible types of respondents

- Car and van owner / drivers.
- Motorcycle owner / riders.
- Professional drivers: e.g. taxi, bus/coach, HGVs.
- Fleet managers.
- Tyre manufacturers.
- Tyre wholesalers/suppliers.
- Tyre fitters.
- Subject experts and influencers such as consumer organisations, trade associations and journalists.

7.2.2. Brakes

As described previously, it was agreed it was unlikely the end user made a purchase decision for brakes and it was likely many decisions were made higher up the chain, such as decision made by the brake fitter (garage) to offer to the end-user and the decisions made by the brake supplier about which brakes they will stock to sell to the fitter. For this reason, there was limited time spent and detail discussed for brakes in the workshop. An additional point was raised about car manufacturers implementing regenerative brakes reducing friction brake use which could mean that, over time, brake pads would be in less demand and therefore may be less of a priority.

It was agreed there was value in confirming there was little or no decision making made by the end-user using an Omnibus style survey and to focus any primary research on other decision makers such as fitters, wholesalers, and manufacturers. The initial evaluation needed to be the amount of choice the end users have and believes they have when choosing brakes. A list of possible discussion topics and types of respondents to contact about brakes was shown to attendees, however, as described earlier, less time was spent on this topic.

Possible topics for discussion

- Who is making the decision.
- How is this presented to the end user.
- Impact of influencers.
- Importance of messaging (labelling).
- What types of messages could be impactful.

Possible types of respondents

- Professional drivers: e.g. bus/coach, HGVs.
- Fleet managers.
- Brake manufacturers.
- Brake suppliers (motor factors).
- Brake fitters (garages).
- Subject experts and influencers such as consumer organisations, trade associations and journalists.

7.3. Evaluation: Methodology for consumer engagement

The aim of the consumer research would be to deliver the following objectives for each of tyres and brakes;

- Who makes the purchase decision.
- Factors and influencers of the purchase decision.
- The messaging and types of communication to influence behaviour change.

7.3.1. Determining the demographic profile of respondents

Car and van owners

An initial online survey, expected to be no more than 5 minutes (approximately 15 questions) or an Omnibus survey should be considered to clarify the profile of drivers, and from this, the profile of drivers who make purchase decisions for tyres and brakes. The questions should include:

- Frequency of purchasing tyres/brakes.
- Where the decision is made, such as online, at the tyre/brake fitters, over the telephone following an MOT or service.
- Where the fitting takes place, such as at a garage or by a mobile fitter at work/home, or fit their own.
- Level and type of research made ahead of the decision-making process.
- Age and gender of respondent.

The survey would be nationally representative to allow for a representative fall-out of drivers by age, gender, government region and social economic grade or similar measure to ensure a spread of the most and least affluent members of the population.

An Omnibus[68] sample size of 2,000 from a previous National Highways survey with adults who own or have continual use of a private or leased car or van had an outcome of 1,599 drivers. Statistical analysis with a sample size of 1,599 will deliver findings with a level of confidence under +/-2.5% using 95% confidence limits for a view shared by 50% of the population. Therefore, we would recommend a sample size of 2,000 for this evaluation stage.

*If possible, we would use the outcomes of the National Highways Tyre Noise survey in November 2022 for the initial measure of tyre decision making.

Motorcyclists, Taxis and HGV drivers

There would be a requirement to interview these types of respondents separately to an Omnibus survey. If possible, the questionnaire used for the National Highways Tyre Noise survey would be replicated for these types of respondents. We would assume a sample size of 400 for each type of respondent using the following methodology and locations for interviewing, shown in Table 7-1. HGV and taxi drivers would be asked to self-complete a survey to maintain consistency of data collection. Statistical analysis with a sample size of 400 will deliver findings with a level of confidence under +/-4.9% using 95% confidence limits for a view shared by 50% of the population.

Table 7-1: Summary of interview locations for motorcyclists, taxis and HGV drivers

Type of respondent	Interview location	Further information
Motorcycle owners	Online survey	Feasible to complete using an online panel
HGV owner/drivers	HGV truck stops Motorway service areas	Previous experience has shown this to be a successful method for interviewing
Taxi drivers	Taxi ranks / private hire operators	Previous experience has shown this to be a successful method for interviewing

[68] An omnibus survey covers a variety of topics (often for different organisations).

7.3.2. Tyres: suggested methodologies

A series of qualitative focus groups (between 90 and 120 minutes) and in-depth interviews (between 30 and 60 minutes) would be used to understand the depth of the decision-making process, the importance of messaging and the type of messaging required to influence behaviour change.

Table 7-2: Summary of suggested methodologies for different tyre respondents

<table>
<tr><th>Type of respondent</th><th>Method</th><th>Topics</th></tr>
<tr><td>Car and van owners</td><td>Focus Groups</td><td rowspan="7">• Awareness of different features of tyres and importance, or not, of the current labelling
• Understanding the decision-making process
• What is considered an environmental factor?
• What is the best terminology for environmental factors and each individual factor?
• Where do environmental factors rank as a priority? Why?
• How driver behaviour relates to environmental factors and the impact of driver behaviour on tyre longevity
• What needs to be known to make environmental factors more of a priority?
• Willingness to pay</td></tr>
<tr><td>Motorcycle owners</td><td>Focus Groups</td></tr>
<tr><td>Professional drivers
HGV and taxi</td><td>Focus Groups: separate for each type of driver</td></tr>
<tr><td>Tyre fitters</td><td>In-depth interviews</td></tr>
<tr><td>Fleet managers;
Company cars and vans
Bus/coach operators</td><td>In-depth interviews</td></tr>
<tr><td>Tyre suppliers</td><td>In-depth interviews</td></tr>
<tr><td>Subject experts (journalists; consumer organisations and trade associations)</td><td>In-depth interviews</td></tr>
</table>

An extra discussion group or series of in-depth interviews is recommended with tyre manufacturers to validate that any proposed mechanisms are feasible, as well as to establish their perception of selling to tyre suppliers.

Further research

Once a short-list of possible mechanisms and messaging has been developed, further consumer research would evaluate these mechanisms.

Firstly, using qualitative research as outlined above

Secondly, through a series of surveys to quantify the possible impact of the:

- Mechanism;
- Messaging; and
- Willingness to pay, using a series of trade-off questions

Sample sizes for the further research would match those in the early engagement phase. 2,000 for car or van owners, 400 each for motorcycle, taxi, and HGV owner/drivers.

7.3.3. Brakes

As described in section 6.2, it is believed the end-user has very little influence over the decision-making process for brakes and section 6.3 explained how an initial, short survey to verify this with 2,000 respondents would be used to verify this belief.

7.3.4. Brakes: suggested methodologies

A series of in-depth interviews (between 30 and 60 minutes) would be used to understand the depth of the decision-making process, the importance of messaging and the type of messaging required to influence behaviour change. Where the types of respondents overlap with the proposed tyre methodologies, we would aim to discuss tyres and brakes in the same discussion.

Table 7-3: Summary of suggested methodologies for different brake respondents

<table>
<tr><th>Type of respondent</th><th>Method</th><th>Topics</th></tr>
<tr><td>HGV drivers</td><td>Focus Groups:</td><td rowspan="5">• Awareness of different features of brakes and importance, or not, of labelling
• Understanding the decision-making process
• What is considered an environmental factor?
• Where do environmental factors rank as a priority? Why?
• How driver behaviour relates to environmental factors and the impact of driver behaviour on brake longevity
• What needs to be known to make environmental factors more of a priority?
• Future of brakes and regenerative brakes</td></tr>
<tr><td>Fleet managers;
Company cars and vans
Bus/coach operators</td><td>In-depth interviews</td></tr>
<tr><td>Brake suppliers</td><td>In-depth interviews</td></tr>
<tr><td>Brake fitters</td><td>In-depth interviews</td></tr>
<tr><td>Subject experts (journalists; consumer organisations and trade associations)</td><td>In-depth interviews</td></tr>
</table>

An extra discussion group or series of in-depth interviews is recommended with brake manufacturers to validate that any proposed mechanisms are feasible, to establish their perception of selling to brake suppliers and their thoughts on the future of brakes and regenerative brakes.

8. Influence of driver behaviour on environmental performance

The influence of driver behaviour in tyre and brake environmental impacts is generally studied from the perspective of how driving style and driving actions may lead to increased emissions of particulates and volatiles. The impacts of these actions have been researched and documented in literature in Section 2.6. In this section following an overview of the literature findings, the analysis of driver influences takes a consumer journey approach in which potential driver influence is assessed starting from the time of vehicle selection, through driving actions, and maintenance routines. We will present an analysis of how every choice in this journey could lead to potential increased environmental impacts from tyre and brake wear based on expert analysis of evidence collected in studies and research of the impacts of not only a particular driving style, but also the vehicle size, powertrain selection, and maintenance routines.

8.1. Overview of the literature

Research related to driver behaviour is generally linked to particular driving styles and actions, and consistently demonstrates that higher deceleration rates from harder braking seen in “aggressive” driving results in higher wear of an emissions from both brakes and tyres. Higher braking forces from harder braking and in braking from higher speeds increase the power absorbed by the brakes leading to higher temperatures in the friction materials, and particulate emissions are seen to step up at higher temperatures. Similarly, the friction heat generated by the tyre against the road surface increases tyre abrasion. Increased wear is also observed for tyres during rapid accelerations and high-speed cornering for the same reasons. Tyre wear is also increased with speed due to the amplified rotational forces and temperatures at the tyre surface.

Some studies do mention that even when not driving, driver actions through checks and maintenance of tyres can influence their environmental impact. For example, incorrect tyre pressure can lead to uneven wear and require premature replacement of the tyre, as well as affecting rolling resistance and CO_2 emissions, and even noise. The influence of such maintenance actions will be explored further in section 8.4.

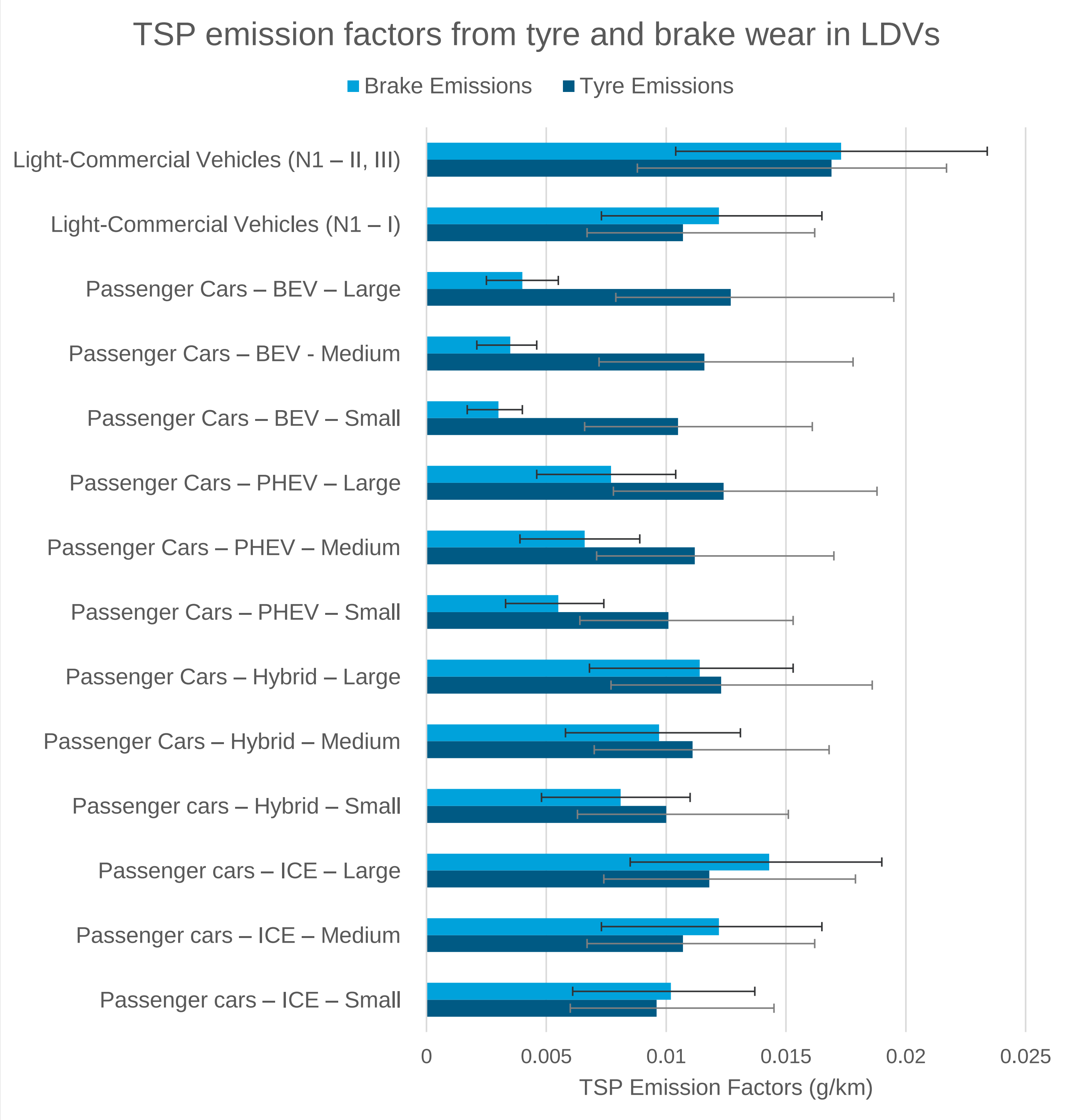
Literature does not link vehicle weight and powertrain differences, which have varied impacts on tyre and brake wear, to a driver decision or behaviour, and so this aspect is explored below.

8.2. Vehicle selection

8.2.1. Vehicle size and weight selection

Consumers have a choice of vehicle types and sizes, and vehicle size and weight are known to affect brake and tyre wear rates. This is reflected in the non-exhaust emission factors given in the EMEP EEA Air Pollutant Emission inventory guidebook published in September 2023 [280]. The technical chapter 1.A.3.b.vi-vii (Road vehicle tyre and brake wear, road surface wear) gives the average emission factors for different vehicles in units of mass emitted per vehicle-km. The data for tyre and brake wear from light duty vehicles are presented in Table 7-1 below.

Figure 8-1 Total suspended particulate (TSP) emission factors from tyre and brake wear for LDVs



Source: Ricardo analysis using information from: European Environment Agency [280]
NOTE: the emission factors are specified for total suspended (airborne) particulates, in grams per vehicle-km.

The data clearly indicates that that choice of vehicle size and powertrain has a clear influence in emissions from tyres and brakes. This implies that the driver's choice of vehicle purchase has a direct implication in the emissions from tyre and brake in all trips.

For tyre emissions, non-exhaust emissions increase with the increasing vehicle size and mass. The data presented in Table 7-1 suggests that choosing a large vehicle over a small one may increase the rate of tyre emissions by around

22%, given the same powertrain. Brake emissions also increase with increasing vehicle size, and mass, typically increasing by 40% for a large car compared to a small car.

Light commercial vehicles follow similar trends with an N1 Class I van being the same as a medium car, and the average emissions from N1 Class II and III (i.e., up to 3.5 tonnes GVW) being higher in comparison; 58% more for tyres and 42% more for brake emissions.

This analysis of widely recognised emissions factors confirms that vehicle mass and powertrain have a significant influence on tyre and brake wear. Extreme duty cycles such as carrying heavy loads or towing trailers will also increase wear by adding pressure to tyres and braking components. Modifying the power, mass, or duty cycles of a vehicles will also affect tyre and brake wear. Increased power or mass leads to higher friction and stress on tyres and brakes. As noted in Section 8.4.1, other vehicle modifications such as changing wheel sizes or suspension geometry may also increase tyre wear. Drivers who modify their vehicles may therefore experience higher tyre and brake wear.

8.2.2. Powertrain selection

Powertrain choice has also a large impact in the emissions from tyre and brake wear. As illustrated in Table 7-1, there are notable differences between Internal Combustion Engine (ICE), hybrid, Plug-in Hybrid Electric Vehicle (PHEV), and Battery Electric Vehicle (BEV) configurations. By using regenerative braking, BEVs exhibit reduced brake emissions, as do PHEVs albeit to a lesser degree. A transition from a standard ICE vehicle to a BEV enables a reduction of brake emissions of over 70%.

Conversely, moving from a conventional ICE vehicle, through a hybrid, to a BEV shows an approximately 8% increase in tyre emissions, attributed to the greater average mass of the vehicle. According to these emissions factors, the increased tyre emissions of a BEV relative to an ICE should be mitigated by the 70% reduction in brake emissions. Furthermore, a BEV has no tailpipe emissions, and as the electricity grid decarbonises the impact of tyre rolling resistance on GHG emissions decreases (albeit still affects range and efficiency). Overall, a driver choice for a BEV is expected to reduce total non-exhaust emissions as well as GHG and other tailpipe emissions, but the emissions of microplastics from tyres to water may be expected to increase.

8.3. Driving style

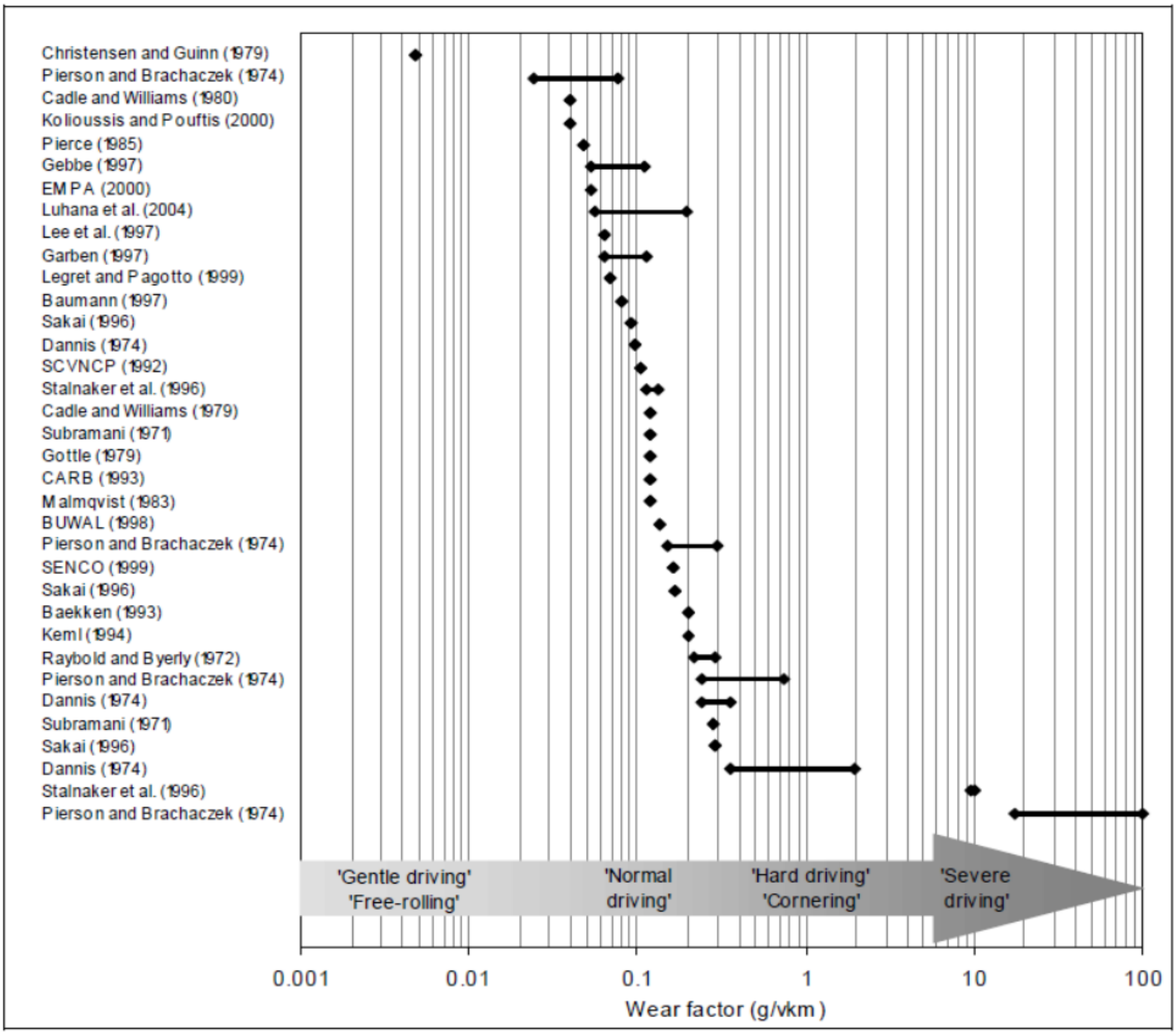
8.3.1. Characterisation of driving styles and their influence in tyre and brake wear

As described in section 2.6, the relationship of driver behaviour and the environmental impacts of tyre and brake wear is heavily determined by driving style. Some of the studies reviewed establish that driver behaviour can even account for as much as 30% of tyre wear, while also influencing drastically in the lifespan reduction of brakes[69]. Aggressive driving behaviour characterised by harsh and drastic acceleration and braking has been described in Figure 2-23.

Research consistently demonstrates that higher deceleration rates from harder braking seen in “aggressive” driving results in higher wear of an emissions from both brakes and tyres. A review of studies performed in 2004 shows the ranges of emission factors for a light duty vehicle finding that the typical tyre **wear** factor for passenger cars is around 100mg per vehicle-km as presented in Figure 8-2. Aggressive driving, noted as hard or severe acceleration, braking, and cornering, can lead to higher tyre wear factors than ‘normal’ driving by several orders of magnitude. Note that Figure 8-2 shows emissions to air, total tyre wear is observed to be at least a factor of 10 greater than the airborne component of tyre wear which is what Figure 8-2 refers to.

[69] According to the Royal Automobile Club (RAC) (2022) [] brake pads can last anywhere between 30,000 and 70,000 miles, and even more, depending on the way the vehicle is driven

Figure 8-2: Wide spread of tyre wear factors with 4 wheels. The range covers five orders of magnitude indicating the strong influence of driver behaviour.



Source: Scientific Report on Tyre and Road Wear Particles, TRWP, in the aquatic environment, ETRMA, 2019 [281] *from Boulter 2005* [282]

Tyre abrasion is due to the contact with the road surface leads to the release of large quantities of small rubber particles. The wear process is dominated by both heat generation in the tread cap and shear forces between the tread and the road pavement. Mechanical shear is responsible for the generation of coarse particles, whereas the high temperature reached in the tyre surfaces causes the volatilisation of organic materials, leading to the formation of small particles in the ultrafine and fine regime. The number and size of wear particles released depend on, amongst other factors, speed, driving behaviour, climate, composition of the tyre, road surface and conditions. Increased wear is observed for tyres during rapid accelerations, braking, and high-speed cornering since these both create larger shear forces and increase tyre temperature. Tyre wear is also increased with road speed due to the amplified rotational forces and temperatures at the tyre surface.

Higher braking forces from harder braking and in braking from higher speeds increase the power absorbed by the brakes leading to higher temperatures in the friction materials, and particulate emissions are seen to increase non-linearly rising markedly when the brake system components are at higher temperatures. This effect occurs much less for vehicles with regenerative braking because much of the vehicle's kinetic energy is converted into electrical energy, which is stored in the battery, rather than degraded to heat in the friction braking components.

8.3.2. Routine behaviours

As shown previously in Table 7-1, weight does have an influence in the emission factor of tyre and brakes in vehicles. The loads carried in a vehicle can influence tyre and brake wear. This study has remarked already how the increased load on the vehicle places additional strain on the tyres, causing them to wear out more rapidly. Extra weight amplifies the friction between the tyres and the road surface leading to accelerated tread wear and a diminished lifespan for the tyres, imposes greater stress on the braking system, and will result in more frequent maintenance and replacement of tyres and brakes. Therefore, it is advisable to be mindful of unnecessary loads carried in a vehicle to mitigate the adverse effects on tyre and brake longevity.

As with any emissions from vehicle use, tyre and brake emissions can also be reduced by using vehicles less, such as avoiding unnecessary journeys, using public transport or rail freight. The type of routes taken may also affect brake and tyre emissions while needed increased start-stop patterns. For example, urban driving has lots of stop-start accelerations adding to brake and tyre wear, whereas high-speed driving, as noted above, can increase tyre emissions. Also driving in hilly or mountainous regions with steep downhill slopes may increase brake and tyre wear.

8.4. Maintenance

Even when not driving, driver actions through checks and maintenance of tyres can influence their environmental impact. Following Vehicle manufacturer guidance with respect to maintenance routines and vehicle care can affect environmental impact, cost of ownership and vehicle performance and safety.

8.4.1. Tyre maintenance influence

In tyre maintenance, various factors can impact tyre wear, consequently influencing tyre emissions. One crucial factor is **tyre inflation pressure**. Incorrect or inconsistent inflation pressure can result in abnormal or excessive tyre wear. Underinflation increases the contact patch area, causing higher deformation in the tyre carcass. This, in turn, raises the tyre temperature compared to a properly inflated tyre. During cornering, lateral forces aren't correctly distributed, creating localised hotspots that accelerate the degradation of the tyre structure and tread blocks. On the other hand, overinflation reduces the contact patch, affecting traction, ride comfort, and road noise. Tyre wear becomes concentrated at the centre of the tread, with forces improperly distributed through the tyre construction. Reduced traction can lead to increased tyre slip during braking and acceleration, causing higher abrasion wear and mechanical damage to the tread blocks. In both instances of incorrect inflation, tread wear becomes uneven with increased wear rate over limited portions of the tyre leading to premature need for replacement, and the full potential of the tyre's lifespan remains unrealised.

Another aspect of tyre maintenance that influences environmental behaviour of tyres is **tyre age** regardless of tread wear. The materials used within the tyre construction react with the environment causing it to age and break down. Rubber compounds typically reduce in elasticity when exposed to oxygen. The “hardening” of the tyre reduces performance (grip), increases noise transmission, and can lead to visible cracking of the tyre surface posing a risk of sudden failure. The tyre industry recommends that tyres greater than five to seven years old should be replaced for safety reasons regardless of their wear condition. Tyres sold in the UK must display a manufacturing date code allowing their age to be understood for replacement.

Proper alignment, balancing and suspension geometry also affect tyre wear and performance. Suspension geometry anomalies such as tracking, or camber alignment can induce abnormal or increased tyre wear due to the tyre contact patch not being correctly presented to the road surface. The effect of incorrect suspension geometry can be exacerbated during cornering where the contact patch is working harder in shear and its area is typically reduced. Regular inspection for wear of suspension components or after impacts likely to deform the suspension such as kerb strikes, potholes, or accident damage should be made to ensure steering geometry remains true minimising the risk of abnormal tyre wear. Likewise, **modifications** such as lowering the vehicle’s suspension (which changes its geometry) or fitting different size wheels (including the offset relative to the hub) may result in increased tyre wear.

Balancing the wheel and tyre correctly will reduce the risk of vibration into the steering and suspension system. In extreme cases tyre imbalance and radial force variation[70] can lead to the uneven wear on the tread blocks and associated reduction in ride comfort. On vehicles where tyre wear imbalance between axles is great, some sources recommend periodically rotating the position of the tyres between axles to optimise tyre wear. The use of directional tyres can make this practice impractical.

[70] Radial force variation refers to a difference in the stiffness of a tyre sidewall as it rotates and contacts the road.

Finally, a good practice for drivers is to **check the tyre labelling** when purchasing a new set of tyres. The tyre labelling regulation ensures consumers are provided with some indication of the tyre performance with respect to traction, noise and wear to help them make informed decisions when replacing tyres. The detail of the regulation is given in section 2.3.1. However, the choice of tyres in the correct size for the vehicle may be limited by the stock at the tyre fitter or garage.

8.4.2. Brake maintenance influence

Regular **brake wear inspection** is fundamental to vehicle safety, but less easily performed by the vehicle operators than inspecting tyres. Consequently, legislative and customer expectations have led to vehicle manufacturers providing alternative means to ensure brake pad condition is provided to the operator. One regulation sanctioned for this purpose is UN Regulation ECE 13-H-01 “Uniform provisions concerning the approval of passenger cars with regard to Braking” section 5.2.11.2. This regulation, relating to checking brake friction components wear, states that “It shall be possible to easily assess this wear on service brake linings from the outside or underside of the vehicle, without the removal of the wheels, by the provision of appropriate inspection holes or by some other means.” Complying to the regulation, this is typically achieved by the vehicle manufacturer either by utilising standard workshop tools or common inspection equipment for vehicles. The vehicle user is unlikely to routinely inspect the condition of the brake pads and discs due to obscuration of the outboard pads due to wheel style and the practicality of viewing the underside of the vehicle. To warn drivers about pads nearing minimal thickness, vehicle manufacturers typically install a pad wear sensing device which will warn the driver when lining replacement is necessary. This warning is either optical, via a warning lamp or message in the dashboard instruments, or an audible pad wear warning device which, once wear allows contact of the device with the brake disc, generates a graunching or squealing noise to alert the driver to the wear condition. For safety reasons, drivers should not ignore such warnings and perform brake wear inspections as soon as possible.

Brake pads and discs are normally **inspected and replaced** by a repairing garage or fitter rather than a consumer**.** It becomes the responsibility of the garage to advise the consumer regarding the necessity to replace components based on their likelihood to remain functional until the next scheduled service. This can lead to premature replacement of pads, consequently increasing waste and unnecessary production energy consumption as well as increased cost of ownership. When brake pads and rotors are replaced, customer choice may be limited and is typically dictated by the repairing garage or their supplier, and so selection is likely to be based on cost, existing service suppliers, or availability. In any case, there are no standards or regulations on labelling of any attributes, and little if any information on environmental performance may be provided. For replacement pads in the aftermarket, performance characteristics are regulated by UN Regulation ECE 90-02 “Uniform provisions concerning the approval of replacement brake lining assemblies, drum brake linings and discs and drums for power-driven vehicles and their trailers” which ensures braking force is a close match to the original OEM part. Other friction material attributes such as refinement, dust generation and corrosion resistance are not typically significant customer considerations. As a conclusion, drivers have less influence in brake maintenance and replacement choice than when performing tyre changes.

8.4.3. Disposal of used brakes and tyres

Since the significant majority of consumers will purchase tyres and brakes along with fitting services rather than fit them themselves, the disposal of used tyres and brake components is the responsibility of the fitting garage or service provider for whom disposal routes are established. The end-of-life treatment of tyres and brakes with their environmental impact is covered in Sections 3.2.3 and 3.3.3 respectively, and the optimisation of tyre and brake products for end-of-life in Sections 5.2.3 and 5.3.3 respectively.

9. Impact of road surface and design on environmental performance

9.1. Overview of the literature

The literature review identified limited research that investigate the effects of road surface characteristics on the production of tyre and road wear particles (TRWP), for which open questions remain around the detailed mechanics of tyre and road abrasion, although attributes such as skid resistance, drainage, and noise have received more attention. The literature does reveal that TRWP formation is found to increase for harder and more irregular road surfaces, which are more abrasive to the tyre rubber. Harder and more irregular road surfaces also serve to increase the rolling resistance of the tyre since there is more deflection of the tyre and therefore more energy dissipated, this increases heat in the tyre which may also contribute to particle formation. However, road surface texture and hardness are important for improving skid resistance while drainage improves with a more irregular road surface, indicating a conflict between the safety requirements for the road surface and its impact on the environmental performance of the tyre and vehicle using it.

The significant properties of the road surface and their influence on rolling resistance, TRWP, noise, and safety considerations and potential for optimisation for environmental benefit are:

- Road surface unevenness is detrimental to rolling resistance and increases TRWP formation and road noise but requires deep intervention making it expensive to address.
- The macrotexture is detrimental to rolling resistance, and increases TRWP formation and road noise, but is beneficial for skid resistance and drainage. However, it can be influenced with lower-cost treatments.
- The microtextural properties of the aggregates used in the road surface increases TRWP formation, but are important for skid resistance, so may be challenging to optimise.
- The hardness properties of the aggregates used in the road surface affects TRWP formation and road noise, and also benefit skid resistance.
- Porosity improves resistance, drainage and road noise but is not seen to have any real impact on rolling resistance or TRWP formation.

The literature also indicated that colder (road and tyre) temperatures generally benefit TRWP and rolling resistance as well as skid resistance but increase noise. Higher average temperatures could therefore be detrimental to rolling resistance and TRWP formation.

9.2. Discussion: balancing the impossible equation

Historically, national specifications have always put safety and ride quality first. However, as environmental challenges have become more and more prominent, optimisation of the environmental performance of road surfaces in use becomes key. Figure 9-19.1 exemplifies the relationship between road surface characteristics, tyre interaction and impacts that road surface properties have on safety, functional and environmental performance of road pavements.

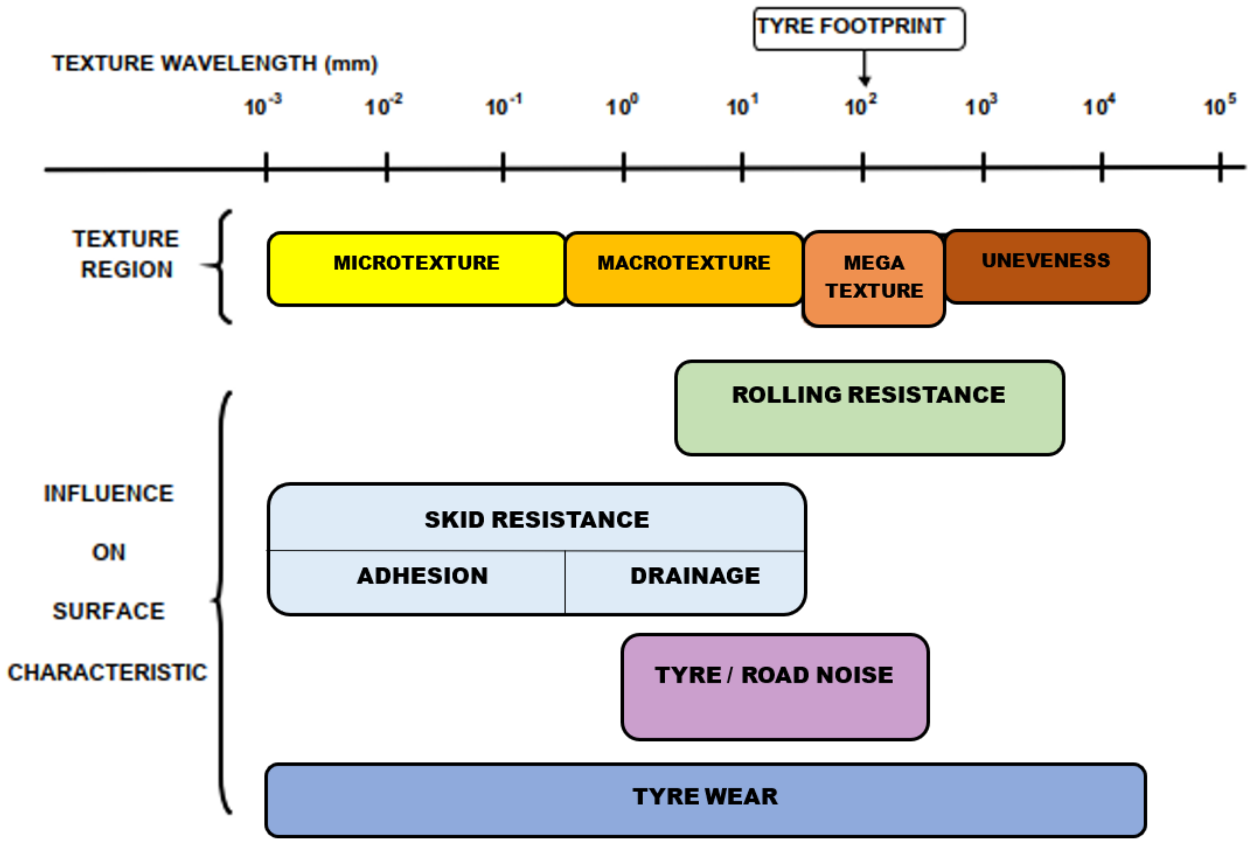


Figure 9-1. Relationship between road surface characteristics, tyre interaction and impacts (adapted from [240]).

The figure highlights how a key characteristic of road surfaces, which influences both safety and environmental performance, is the macrotexture. This is important as this characteristic of road surfaces can be adjusted relatively easily, even via very thin types of treatments. On the other hand, it is clear how there are opportunities to optimise tyre wear, rolling resistance and road noise independently from safety aspects. However, these seem to be linked more with the unevenness of the road which, although controllable through adequate construction and quality assurance techniques, it is often determined by geological characteristics of pavement subgrade, difficult to change on existing pavements, if not via deep sort of interventions or full reconstruction.

In addition, deterioration of road characteristics can change the way certain road properties affect the performance of the road. As mentioned, this can depend on traffic loads, environmental factors (such as temperatures), and other variables, which introduces significant uncertainty around the estimates made in experimental set ups. Road surface deterioration including increasing roughness, unevenness, and the presence of discontinuities and potholes can all lead to excessive road noise, rolling resistance, tyre abrasion, and in some cases, tyre damage resulting in early replacement. Where these cause drivers to take avoiding action, both increased tyre wear and brake wear are possible.

Ultimately, as both tyres and asphalt roads (96% of total in the UK) are made of viscoelastic materials, respectively rubber and asphalt concrete, their characteristics can change, affecting the way the two respond to the loads applied and consequently wear under mutual interaction. In this regard, current specifications try to reduce the effect of climate and other variables on road performance, e.g. setting a specific range of temperatures that tests need to be carried out at, or introducing adjusting factors to reconduct measurements taken at non-standard temperatures to the reference values. For this reason, going forward it would be beneficial if research in the area of TRWP, road noise and rolling resistance, could make testing reflect local condition, to be able to update local specifications, appropriately.

9.3. Potential for further research

In consideration of the findings from the literature review and the limited existing research, it is identified that further research into the interaction of road surface and tyre could investigate:

The mechanism of TRWP production and the role of road surface characteristics in the process, both from the qualitative and quantitative perspective.

A more precise range of road surface properties to enable optimal environmental outcomes, in terms of TRWP, road noise and rolling resistance perspective, keeping road users safe, for conditions typical of the SRN.

The correlation between road surface characteristics and TRWP, road noise and rolling resistance, for condition typical of the SRN.

Methods to initially estimate and possibly measure the effect of road surface properties on TRWP, road noise and rolling resistance, to enhance the way environmental performance are evaluated for roads, beyond carbon.

The effects of climate change (e.g. high temperature, heavy rainfalls, etc.) on road surface deterioration rates, and impact of that on environmental performance, for materials typical of the SRN.

Such research could be used to define priorities in terms of updates to national specifications (mainly MCHW and DMRB) to account for the effects of road surface characteristics on TRWP, road noise and rolling resistance, without that affecting safety. This further research building on the findings from the initial research carried out by National Highways, in regard to TRWP [208], road noise [247] and rolling resistance [248] could provide a solid base to reduce existing uncertainty and support continuous improvement of national specifications, to keep road users safe and enable environmentally optimal roads.

10. Conclusions

10.1. Key findings for tyres

This study has analysed the key factors that contribute to tyre emissions across the different phases of tyre life cycle covering manufacturer, use, and disposal (end-of-life).

Tyre manufacture requires materials such as natural rubber (especially for tyres that require higher load-bearing capacity, such as HDV tyres) which has potential land-use impacts, and the use of carbon black and fossil oil which have a high carbon footprint. Bio-based alternatives are in development, such as alternative rubber matrix materials (for example, guayule and Russian dandelions), “green” silica and other natural fillers, but have potentially high feedstock costs. Recycled PET and tyre crumb, and pyrolysis residue (pyrolysis oil and carbon black) also offer alternative material sources. Recycled content reduces resource use, while increasing tyre life reduces waste – such as through additives to improve aging resistance or even add self-healing properties. European manufacturers are already incentivised to reduce energy use and waste, regulations will encourage sustainable supply chains and reduce deforestation while increasing the use of renewable or recyclable and recycled materials.

The tyre-use phase of a tyre’s lifecycle creates the greatest environmental impact through vehicle CO_2 impacts from rolling resistance and particle emissions though abrasion of the tyre against the road surface. Tyre and road wear particles (TRWP) consist of coarse, fine and ultrafine microplastic particles, a large proportion of which go into watercourses where their impact is uncertain but the subject of increasing concern, and a small fraction become airborne with risks to human respiratory health. An average passenger car releases PM_{10} emission of between 5.8-8.8 mg/vehicle km and $PM_{2.5}$ emission of about 4.1-6.1 mg/vehicle km, however, since the airborne particles are the smallest particles which contribute limited mass, they may be best quantified through particle number measurement. Tyre wear rate, and hence particulate emissions rate, can be exacerbated by the vehicle’s characteristics such as age, segment/size and mass, while improper tyre pressures and wheel alignment can increase wear rates. Driver behaviour is reported to influence tyre wear by up to 30%; rapid accelerations, hard braking, and high-speed cornering create large sheer forces at the contact patch and in the tyre tread, increasing tyre temperature and surface abrasion. Tyre wear is also increased with speed due to the amplified rotational forces and temperatures at the tyre surface. Although not the focus of this study, the road surface was also found to be a significant factor in tyre abrasion and noise as well as grip: in dry conditions, concrete roads appear to wear tyres more than asphalt roads.

While the use phase of tyres has the greatest environmental impact, there is little regulation targeting these impacts. The rolling resistance, wet grip, and noise attributes of tyres are rated in the UK and Europe according to standard tests and labelling. The rolling resistance rating is directly related to the tyre’s use-phase GHG impact, although there is no minimum standard, nor a requirement that replacement tyres match the rolling resistance of the original fitment tyres (as there is planned for California). There is no standard assessment of tyre wear rate or abrasion as there is in the US. Standards for measuring tyre abrasion have been developed at UN ECE level and adopted (including by the UK), which provide a basis for future labelling or regulation. Europe is proposing a limit on vehicle tyre emissions (by mass wear rate) using the UN ECE standard as part of Euro 7, possibly from 2026, although introduction date and limit threshold are not yet clear. There is no announcement on whether Euro 7 or this measure will be introduced into GB[71]. REACH restricts the use of certain chemicals toxic to the environment and human health. While there is little regulation specifically targeting the environmental impacts of tyre manufacture, general industry regulation covers energy use, pollutant emissions, waste, and noise. Natural rubber is recognised as a critical raw material at risk of causing deforestation, although legislation to ensure sustainable supply is still in development. Disposal and storage of end-of-life tyres is regulated with the aim of maximising recycling and minimise emissions.

The tyre labelling provides consumers with an informed choice on some attributes of tyres, and although some buyers are prepared to pay more for improved environmental performance (especially fleets due to fuel cost savings), surveys of consumer awareness have found price is the main factor in replacement tyre choice, and choice may be limited by the stock of the fitting garage. Market research indicated that vehicle manufacturer initial fitment favours grip and noise (usually A or B rated) over efficiency (typically C rated) despite the pressure of vehicle CO_2 standards, but many popular replacement tyres have lower efficiency ratings which could increase in-use CO_2 emissions by up to 6%. US surveys showed consumers valued tread wear more than UK buyers, possibly due to a standard rating/label for wear rate being available in the US.

Improving environmental performance often involves trade-offs. A ‘magic triangle’ is typically observed trading between rolling resistance (fuel efficiency), wet grip (safety), and abrasion/wear resistance (tyre life and particle

[71] European regulations will continue to apply in Northern Ireland

emissions). While these trade-offs are challenging, some tyres achieve good performance in all areas suggesting there is scope for optimisation of many tyres. Environmental and other attributes of tyres can be improved using nanomaterials (HD/HD-HS silica and nanoclay) which can reduce both rolling resistance and wear rate. Tread design and depth can be optimised for noise or wet or dry grip, with novel tread designs and manufacturing techniques, including porous tread, enabling improved optimisation. Also, eliminating tyre vent spews either during or after the manufacture process reduces the unnecessary emission of coarse particles.

Although end-of-life is regulated, concerns are identified about the robustness of export control enabling burning of tyres. Vulcanised tyres are not easy to recycle, although research is exploring chemical recycling. Energy-from-waste is a better use of old tyres than burning or landfill but only recovers half the potential energy, and pyrolysis may become useful in the future. Maximising the use of a tyre (to its minimum tread depth) achieves the best life cycle benefits since resource use and end-of-life impacts are minimised on a vehicle mileage basis. Tyre replacement poses a trade-off since low tread-depth can decrease wet grip and risks safety, but the low tread block depth reduces rolling resistance, abrasion, and particle emission rates. There are also safety risks associated with the market for part worn tyres if regulation is not effective. Re-treading of old tyres is common for HDV, but rare for LDV due to the use of synthetic rubbers and the availability of budget tyres, although novel techniques for “tagging” tyre carcasses could be developed to help increase effective reuse or appropriate disposal of old tyres.

The use of electric vehicles (EVs) is expected to increase until petrol and diesel vehicles are phased out from 2035. EVs tend to be heavier than conventional vehicles due to their batteries, and electric motors produce high torque from rest. As already noted, these attributes will lead to increased tyre wear. Some tyres have been promoted as being tailored to greater EV weights, and while these may have lower rolling resistances to optimise range, stakeholders said there were no fundamental differences. Of course, CO_2 impacts with EV are reduced, especially as electricity decarbonises. Increasing EV use is therefore expected to increase tyre abrasion which could become the dominant environmental impact of tyres, with microplastic emissions to water the main environmental concern and airborne ultrafine particulates a human health concern.

10.2. Key findings for brakes

In the case of brakes, the manufacturing phase of brake pads and discs has the highest potential environmental impact due to the use of energy, and materials including tungsten carbide and brass. European manufacturers are incentivised to reduce energy use, adopt use of renewable power and alternatives to fossil heat sources, and reduce waste. Rotors typically use 90% recycled metal while waste from pad manufacture can be reintegrated into their manufacturing process.

The use-phase of brakes is the second most polluting life cycle stage overall, largely because vehicle CO_2 emissions related to brakes are negligible. However, the release of particulate emissions is a significant air quality, human health, and environmental toxicity concern. The composition of the emissions is influenced by the material formulation of brake pads and discs. Iron, brass, copper, chromium, and synthetic silica are some of the most common components in the composition of brake wear dusts. These materials, in varying particle sizes, particularly the fine and ultrafine fractions, have reportedly been found to penetrate through tissues into blood streams eventually depositing and accumulating in vital organs. Brake emissions increase with braking force, and so larger vehicles tend to have higher emissions, but emissions are found to increase non-linearly with brake temperature with an increase of just 15°C over a critical temperature (typically in the range 150-250°C) found to increase particle emissions by about 5000 times. Brake particle emissions therefore increase with higher deceleration rates, braking from higher speeds, and repeated braking, since these increase temperatures in the friction materials and so these critical temperatures can be reached even in normal driving, and more aggressive driving increases peak and average temperatures further increasing emissions. Effective brake system cooling is a key design consideration to mitigate emissions.

Brake pad materials with lower emissions are available, but the choice of brake pad material involves various trade-offs and is closely connected to rotor design and materials. Non-asbestos organic (NAO) pads which have low particulate mass emissions (compared to metallic and semi-metallic types) are favoured in the US and Japan as wheels remain clean, but don’t provide the brake response or performance demanded by European drivers and roads. It isn’t clear whether being low in visible dust emissions means the number of ultrafine airborne particles are also reduced. Alternative pad materials are being explored to reduce emissions while improving the sustainability of the materials used. These include composites with clay, aluminium, titanium, zinc additives, and molybdenum disulphide, which exhibit strong coefficient of friction values and wear resistance. Additionally, alternative binders like lignin and geopolymers could replace traditional phenolic resins. Industrial by-products and waste materials, such as waste tyre rubber and fly ash from coal combustion, have also been explored as additives to brake friction materials. These technologies are at different development stages but are not yet commercialised. Another promising technology is disc coatings which use Nickel-based alloy, High Velocity Oxygen Fuel (HVOF), or laser cladding that can improve wear resistance and reduce particle emissions, but these techniques have a high cost and are not yet in volume production.

Regenerative braking used by hybrids and especially electric vehicles reduces friction brake use and so emissions. While there is a risk of increased emissions from corrosion of underutilised discs, vehicles are now designed to occasionally deploy brakes to keep discs corrosion free, or to use coated discs to eliminate corrosion on more expensive vehicles. There is some discussion of EVs being able to use smaller brakes with less emissions, thinner friction materials reducing resource use, or even drum brakes which have the benefit of reduced corrosion as well as containing particulate emissions. However, the requirement to maintain primary braking performance in an emergency in the event of regenerative assistance being unavailable, when considering the increased weight of EVs, is thought to limit the potential to down-size EV brakes. Overall, the increasing adoption of EVs will reduce emissions from friction brakes, and may reduce the frequency of their replacement, reducing their manufacturing and disposal impact too.

Brake system components are tested for braking force and regulations limit certain toxic materials from being used in their manufacture including asbestos. Copper is also specifically limited in the US along with some other heavy metals. However, there are currently no tests, standards, or ratings for any other brake attributes including emissions or wear rate. The UN ECE is developing new standards to measure brake PM_{10} emissions which the UK has supported. The European Commission has proposed a limit on vehicle brake PM_{10} as part of Euro 7 emissions regulation using this standard, although the introduction date is not yet clear and the limit for heavy duty vehicles is not yet proposed. Limits for particle number are also possible at Euro 7, though levels have not yet been discussed. There is no announcement on whether Euro 7 or these measures will be introduced into the UK. The Euro 7 brake PM_{10} emission limit is expected to be met through a mixture of regenerative braking (hybrids and EVs), alternative pad materials, and coated discs, depending on the vehicle size, cost, and powertrain. These technologies may increase vehicle costs but could reduce demand for replacement brake pads and rotors due to reduced wear rates. Brake manufacturing has no specific environmental regulation beyond those applying to industries in general, and the steel, iron, and aluminium used will fall under the UK emissions trading system and proposed Carbon Border Adjustment Mechanism.

Brake disposal comes under vehicle end-of-life regulation in the UK and EU which seeks to improve recycling and limit the risks of toxic emissions. The end-of-life impact for brake components is relatively low overall, but landfill disposal poses risks of toxic heavy metal contamination. Brake rotors, being primarily iron, are easily recyclable. Brake pads are often incinerated with up to 90% metal parts recycled, and energy recovery is possible. Experimental methods include high-temperature thermal decomposition, embrittlement using liquid nitrogen for pad separation, and refurbishing worn brake rotors through laser melting for energy efficiency.

The major brake suppliers claim to be reducing emissions of particles or dust, or specific substances such as copper, but braking power, durability, noise, and service life remain the primary design requirements driven by vehicle manufacturers. Consumers have little choice in replacement brake parts, the fitting garage or their supplier making the choice. While main dealers may fit similar parts to those present on the vehicle when new, other garages are likely to fit cheaper compatible parts. However, since there are no standards for brake attributes, and manufacturers publish little in the way of detail of their brake systems, it is difficult to evaluate the relative environmental impacts of different vehicles or brake systems, and a purchase choice based on environmental characteristics is impossible. Where a choice is available, brand, manufacturer claims, and price are the only indicators. This is reinforced by a total lack of survey or consumer awareness studies into brake choice.

10.3. Key findings for road surface impacts

Tyre abrasion and rolling resistance as well as grip and noise were found to be highly dependent on road surface, and so additional research was carried out into road surface characteristics and their impact on the safety, functional and environmental performance of tyres in use. Although limited research was identified investigating the effects of road surface characteristics on the production of TRWP, findings indicate that the effects of road unevenness, macro- and microtexture can be significant. In conclusion:

Although road unevenness may not have a huge impact on TRWP, if minimised, this characteristic of the road surface could help improving ride quality and rolling resistance, without compromising the safety or functional properties of the road. However, this may require deep interventions which can be costly.

Macrotexture is a characteristic of road surfaces which helps achieving adequate levels of skid resistance and drainage properties but that, if minimised, could help delivering reductions in TRWP as well as road noise and rolling resistance. Despite this conflict, as macrotexture can be influenced with relatively shallow and cost-effective treatments, research in this area could help to deliver safe and environmentally optimal roads.

Although research to optimise the microtextural properties of the aggregates used in pavement materials could enable TRWP reduction with minimal impact to the other themes considered, the importance of this property to guarantee adequate levels of skid resistance at low speed could be a challenge difficult to overcome.

Hardness of aggregates is a characteristic of road materials which can help achieving higher levels of skid resistance, but that it can also increase the production of microplastics from tyre-road interaction at the surface. For this reason, research in this area could also help to deliver safe and environmentally optimal roads.

Porous surfaces can help solve road noise and drainage related issues without unduly compromising skid resistance, rolling resistance nor TRWP. For this reason, although high porosity could affect the overall longevity of the road surface, there are circumstances where high porosity can constitute a solution to consider, especially in proximity of areas where achieving adequate levels of road noise and/or appropriate drainage have been challenging.

The findings from the literature have highlighted how temperatures affect road surface characteristics and their deterioration rates, with colder temperatures generally benefitting both safety and environmental factors (other than noise). This means that as higher average temperatures may be expected in the future [223], issues related to the environmental performance of road pavement could become more challenging to solve.

Table 10-1 summarises findings of the literature review on the impacts of road surface properties. Minimising surface unevenness, macro and microtexture, and aggregate hardness are beneficial for minimising TRWP, while minimising surface unevenness and macrotexture also benefit rolling resistance, but there may be a trade-off to maintain adequate skid resistance and drainage.

Table 10-1: High-level summary of the impacts of road surface attributes

Road surface property	TRWP	Skid resistance	Drainage	Road noise	Rolling resistance
Unevenness	Minimise	Not critical	Minimise	Minimise	Minimise
Macrotexture	Minimise	Beneficial	Beneficial	Minimise	Minimise
Microtexture	Minimise	Beneficial	Not critical	Not critical	Not critical
Hardness	Minimise	Beneficial	Not critical	Minimise	Not critical
Porosity	Not critical	Beneficial	Beneficial	Beneficial	Not critical
Temperature	Minimise	Minimise	Not critical	Beneficial	Minimise

A need for further research has been identified into the interaction of road surface and tyre, and how road surface properties could be developed for environmentally optimum performance of tyres. An improved understanding of optimising road surfaces may provide opportunities to update current national specifications, to preserve the safety-related and functional properties of pavements, improve the environmental performance of the asset in use while at the same time minimising TRWP, road noise, and rolling resistance.

10.4. Quantifying tyre and brake abrasion

The emission of particles into the environment as both tyres and brakes wear in use has been identified as a major environmental impact, although the literature review reveals relatively little is understood about the mechanisms and pathways of these emissions. Figure 10-1 summarises the range of estimations of the particle emission pathways from literature. Around half of brake emissions are thought to become airborne (PM_{10}), while most tyre particles end up in soil or waterways with only a small proportion small enough to become airborne. Most road transport PM_{10} emissions now originates from non-exhaust emissions, while some literature suggests that up to 70% of microplastics found in oceans originate from tyres and road transport.

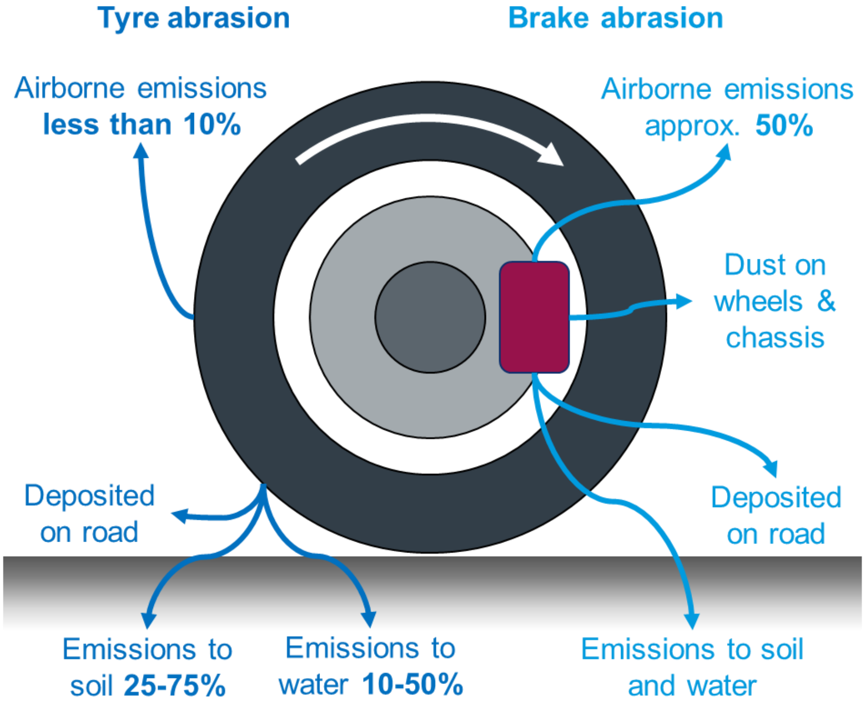


Figure 10-1: Tyre and brake abrasion and particle emission pathways from literature

An approximate quantification of the abrasion emissions is illustrated in Figure 10-2. This shows the average and range of tyre and brake mass lost on the Strategic Road Network (SRN) in 2022 from literature estimates of abrasion rates, and the total PM_{10} airborne emissions from non-exhaust sources using the SRN in 2022 from NAEI emission factors., Both plots use traffic and freight data from DfT[72]. The high degree of uncertainty is clear from the range of literature estimates of abrasion rate which suggests abrasion could be double or half the indicated average.

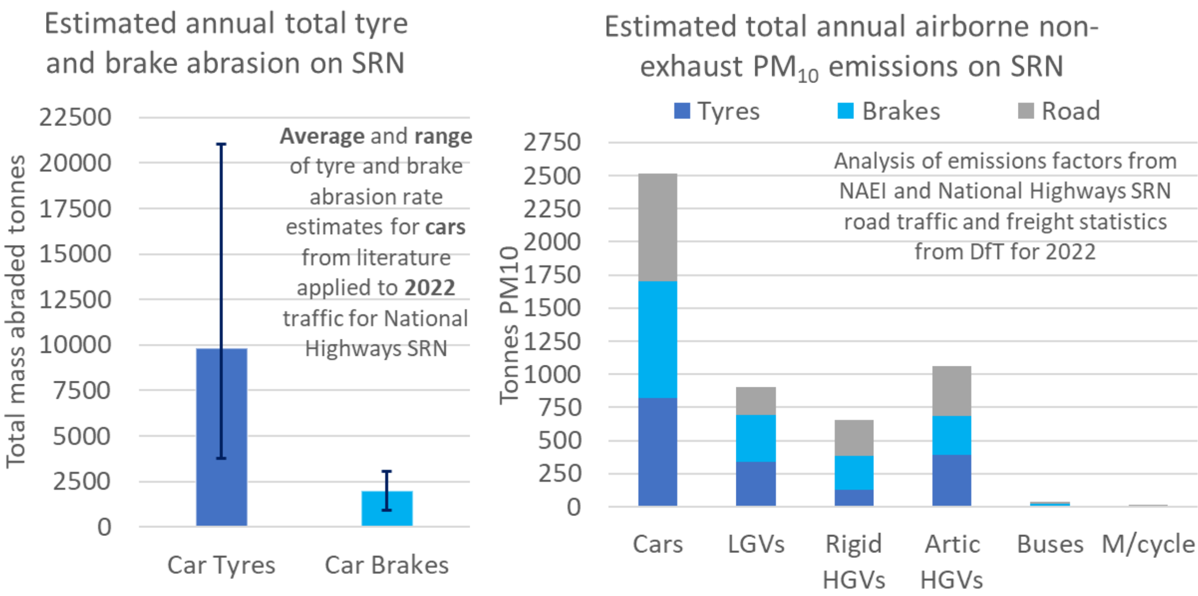


Figure 10-2: Estimated tyre and brake abrasion and PM10 emissions on Strategic Road Network (SRN) in 2022

[72] Abrasion rate estimates from https://www.eng.auth.gr/mech0/lat/PM10/, NAEI emission factors from https://naei.beis.gov.uk/data/ef-transport, traffic data for 2022 from https://www.gov.uk/government/statistical-data-sets/road-traffic-statistics-tra Table TRA4115

Despite this uncertainty, as vehicle tailpipe emissions reduce and more zero-tailpipe-emission vehicles are adopted, it is clear that PM_{10} from tyres, brakes, and road wear will remain a significant source of air pollution unless mechanisms to reduce these emissions are implemented. As well as enabling a reduction in their GHG emissions, a benefit of the electrification of vehicles is that regenerative braking is expected to reduce brake particulate emissions However, electrification is also associated with increased vehicle weight (e.g. due to batteries) and torque (from electric motors) which is likely to increase the abrasion of tyres. The resulting impact on air pollution is unclear but at least a benefit in urban areas (where vehicles brake frequently) is likely, however tyre abrasion is a major contributor to microplastics in soil, freshwater and oceans, and consequently finding their way into humans.

10.5. Environmentally Optimum Tyres and Brakes

The objective of this study is to gain a more comprehensive understanding of the environmental impact associated with the manufacturing, use and disposal of tyres and brakes. Based on the findings from the literature, engagement with stakeholders, market research, and past consumer engagement, the significant environmental impacts of tyres and brakes and the potential to reduce them over the manufacture, use, and disposal are, for tyres:

- **Tyre manufacture** use of energy, carbon-intensive fossil-based materials, and scarce resources such as natural rubber which risks land use change. Product development needs to move towards sustainably sourced, low GHG impact materials and low-carbon energy.
- **Tyre use** rolling resistance impact on GHG emissions, and abrasion leading to tyre and road wear microplastic particles entering watercourses and airborne particulate pollution. Reducing both involves optimising tyre materials composition and tread design while considering any trade-off against wet grip (for safety) and noise. Emerging technologies may enable further optimisation. Eliminating vent spews removes unnecessary microplastic particles.
- **Tyre end-of-life** carbon release and pollution. Circular economy strategies for tyres should minimise unwanted environmental impacts and exploit emerging technologies, including maximising the use of tyres through safe part worn and re-treaded tyres, recycling of tyre carcases and materials, and maximising the energy extracted with minimal environmental impact at disposal.

And for brakes:

- **Brake component manufacture** use of energy and carbon-intensive fossil-based materials. Product development needs to move towards sustainable production through minimising the use of scarce resources and energy, and developing products that use sustainably sourced, low GHG impact materials.
- **Brake use** causing particulate emissions, with airborne pollution a threat to human health and the risk of particles poisoning water courses. Particulate emissions reduction can use a range of technologies including alternate pad materials, disc coatings, and regenerative braking, while meeting safety requirements and driver demands for braking performance and minimising the use of toxic substances of concern. Emerging technologies may enable lower emission and more sustainable friction materials.
- **Brake end-of-life emissions**. While a high proportion of brake components by mass are already recycled, further circular economy strategies for brakes could utilise emerging technologies including remanufacture of discs, pad material extraction and recycling, and maximising the energy extracted with minimal environmental impact at disposal.

As well as the attributes of the tyres and brake components themselves, achieving optimum environmental impact from their use relies on other factors including:

- Consumer and understanding and choice to make informed buying decisions. While there is good information provided for tyres covering rolling resistance, wet grip, and noise, abrasion or manufacture are not covered and there is no standard information for brakes. Consumer choice may also be limited by garage stock.
- Correct use and maintenance. Incorrect tyre pressure or wheel alignment (camber and tracking) can increase GHG emissions and abrasion rate. Maximising the life of tyres and brakes requires regular checks so they can be changed at the optimum time.
- Driving style. Hard braking events increase brake and tyre temperatures and abrasion rates, while harsh acceleration and cornering and even high speeds increase tyre abrasion. Road layout and traffic management may also affect tyre, road, and brake wear by introducing additional braking and cornering.

- Road surface. Tyre abrasion and rolling resistance as well as grip and noise were found to be highly dependent on road surface, and optimum use of tyres will be dependent on suitable surfaces.
    - Minimising surface unevenness, macro and microtexture, and aggregate hardness are beneficial for minimising TRWP while minimising surface unevenness and macrotexture also benefit rolling resistance, but there may be a trade-off to maintain adequate skid resistance and drainage, or reduced tyre noise for roads in built-up areas.
    - However, optimising the properties of the road surface to minimise TRWP and rolling resistance is a topic with limited existing research, and further work would be required to establish how this could be achieved.
    - Both TRWP and rolling resistance are generally seen to increase with higher road temperature.

It is also worth considering the impact of the transition to use of electric vehicles as the phase-out of petrol and diesel vehicles from 2035 approaches. Their use of regenerative braking is expected to significantly reduce the emissions from brakes, and potentially reduce manufacturing and disposal impact through fewer replacement parts. However, their greater weight and high torque from rest is likely to increase tyre abrasion compared to conventional vehicles. A shift from air pollution to water pollution is possible since a large proportion of tyre particles enter water courses compared to a small proportion (by mass) becoming airborne, whereas brake particles are more likely to be airborne.

Tyre and brake use regulations currently focus on safety of performance and limiting toxic material use, and for tyres, standard labelling covering rolling resistance, wet grip, and noise. UN ECE standards are being established for brake emissions (PM_{10}) measurement and are in development for measuring tyre wear. This will facilitate the implementation of labelling and/or limiting regulations, and the proposed Euro 7 regulations are expected to limit both tyre wear and brake emissions. It is noted that the UN standards and Euro 7 proposals use measurements of mass emissions, but it is the ultrafine particles that pose the largest threat to human health, and it is not well understood how these relate to total mass lost. Therefore, a deeper understanding of the number and size distribution of the particles is needed. However, regulating tyres by mass loss will be effective at minimising microplastic emissions to soil and water. Specific regulations apply to the disposal of vehicle components including tyres and brakes although manufacturing is covered only by general industrial regulation, and regulation to ensure sustainable use of materials is not yet mature.

It is expected that Phase 2 of this work will identify and investigate mechanisms which can build on these findings to promote the development of environmentally optimum tyres and brakes, their deployment by vehicle manufacturers, and their purchase by consumers and fleet operators.

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Appendix 1 – Stakeholder interview questions

Questions relevant for tyre manufacturers/associations

1. What does your organisation see as the significant environmental impacts of tyres?
2. What work/developments is your organisation doing to reduce environmental impacts of tyres?
    a. What impact does your organisation foresee from the proposed Euro 7 regulations?
    b. Does your organisation have any targets or objectives to improve the environmental performance of their products?
    c. What are the main drivers for improvements in environmental performance and do customers value these benefits, or do they provide a competitive advantage?
3. What are the potential improvements to tyre materials, design, and production methods to reduce particle emissions, rolling resistance and toxicity?
    a. How can improvements be made to environmental impact without compromising safety or performance and are there any other trade-offs (like cost)?
    b. How does your organisation currently measure these improvements or impacts?
4. What are the environmental impacts of the waste from manufacturing and/or end-of-life tyres and how can they be mitigated?
5. Does your organisation have strategies to reduce their manufacturing raw material and energy use?
6. Are there different specifications of products supplied to the after-market compared to OEMs?
7. Are there different specifications used for EVs?

Questions relevant for brake manufacturers/associations:

1. What does your organisation see as the significant environmental impacts of brakes?
2. What work/developments is your organisation doing to reduce environmental impacts of brakes?
    a. What impact does your organisation foresee from the proposed Euro 7 regulations?
    b. Does your organisation have any targets or objectives to improve the environmental performance of your products?
    c. What are the main drivers for improvements in environmental performance and do customers value these benefits, or do they provide a competitive advantage?
3. What are the potential improvements to pad and disc materials, design, and production methods to reduce particle emissions or their toxicity?
    a. How can improvements be made to environmental impacts without compromising safety or performance, are there any other trade-offs (like cost)?
    b. How does your organisation currently measure these improvements or impacts?
4. What are the environmental impacts of the waste from manufacturing and/or end-of-life brake pads and how can they be mitigated?
5. Does your organisation have strategies to reduce your manufacturing raw material and energy use?
6. Are there different specifications of products supplied to the after-market compared to OEMs?
7. Are brake systems supplied for electric and hybrid vehicles different to those used on conventional vehicles?

Questions relevant for research organisations:

1. What does your research indicate to be the significant environmental impacts of brakes and tyres?
2. What do you see as the likely impacts of Euro 7 on the specification of brakes and tyres (based on current draft standards/limits and your research)?
    a. How might the industry address these standards?
    b. Are other standards likely to be needed too?
3. From your research, what do you see as the key potential improvements to brake pad and disc materials, design, and production methods to reduce particle emissions or their toxicity?
    a. How can improvements be made to environmental impacts without compromising safety, noise, or performance, are there any other trade-offs (like cost)?
    b. How can these improvements or impacts be measured? (Will the proposed Euro 7 standards suffice?)

4. From your research, what do you see as the key potential improvements to tyre materials, design, and production methods to reduce particle emissions, rolling resistance and toxicity?
    a. How can improvements be made to environmental impact without compromising safety, noise or performance and are there any other trade-offs (like cost)?
    b. How can these improvements or impacts be measured? (Will the proposed Euro 7 standards suffice?)
5. Has your research looked at how brakes and tyres used in aftermarket replacement compare to those fitted by OEMs?
6. Has your research looked at if/how brakes and tyres used for electric vehicles differ to those fitted by conventional ICE vehicles?
7. Have you identified areas of brake and tyre environmental impact and optimisation that need more research?

Appendix 2 – Regulations and standards index

As described in Section 2.2, index tables were developed listing each of the identified legislation, policies and standards relevant to the UK (see Table 0-1 below) and other regions (see Table 0-2 below). For ease of navigating the index tables, the regulations and standards have been grouped and ordered as follows:

1) By **relevance**, in the following order:
   a) Tyres [73]
   b) Brakes [74]
   c) Tyres & Brakes
2) Followed by **life cycle phase**, in the following order:
   a) Production phase ✓
   b) Use phase ✓
   c) End-of-Life phase ✓

Table 0-1: Regulations and standards applicable in UK

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
1	**Environment Act (2021)**	UK Parliament	Regulation - Published/current	UK	The natural environment	"The Environment Act ("the Act") comprises two thematic halves. The first provides a legal framework for environmental governance. The second makes provision for specific improvement of the environment, including measures on waste and resource efficiency, air quality and environmental recall, water, nature and biodiversity, and conservation covenants." Includes provision to amend or modify legislation for which chemicals are taken into account and their quantities in assessing ground and surface water quality. Establishes setting a limit on PM2.5 in "ambient air".		✓	✓	
2	**The Environmental Permitting (England and Wales) Regulations 2010 (2010)**	UK Parliament	Regulation - Published/current	England & Wales	Potentially damaging/polluting processes from industries and businesses	Set's out the requirement of obtaining an environmental permit for activities deemed potentially damaging. widen the existing streamlined environmental permitting and compliance system in England and Wales by integrating existing permitting regimes covering water discharge consenting (DC), groundwater authorisations (GW) and radioactive substances regulation authorisations (RSR) and the outcomes of the Waste Exemptions Order Review into the Environmental Permitting system.		✓		✓
3	**Communication from the Commission on the 2017 list of Critical Raw Materials for the EU (2017)**	European Commission	Policy - Published/current	EU & GB	Producers, importers and suppliers of raw materials	Given the continued strategic importance of raw materials for the EU manufacturing industry, the Commission is implementing a wide range of actions under the EU Raw Materials Initiative to help ensure their secure,		✓		✓

[73] Tyre icon source: Icons8

[74] Brake icon source: Icons8

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
						sustainable and affordable supply. The list of critical raw materials for the EU is a central element of this Initiative.				
4	**Labelling of tyres for fuel efficiency and other essential parameters Regulation (EC) No 1222/2009 (2009)**	European Commission	Regulation - Published/current	EU & GB	Tyre manufacturers	This Regulation establishes a framework for the provision of harmonised information on tyre parameters through labelling to allow end-users to make an informed choice when purchasing tyres, for the purpose of increasing safety, the protection of health, and the economic and environmental efficiency of road transport. In the EU, this regulation was repealed in 2021 by the new Regulation (EU) 2020/740.			✓	
5	**Regulation 30: "Pneumatic tyres for motor vehicles and their trailers (Class C1)" (2007)**	UNECE	Regulation - Published/current	EU & GB	Manufacturers of tyres	Requirements for the approval of tyres fitted to vehicles. Includes load and speed durability testing requirements.			✓	
6	**Regulation 54: "Pneumatic tyres for commercial motor vehicles and their trailers (Classes C2 & C3)" (2013)**	UNECE	Regulation - Published/current	EU & GB	Manufacturers of tyres	Requirements for the approval of tyres fitted to vehicles. Includes load and speed durability testing requirements.			✓	
7	**Regulation 64: "Temporary-use spare unit, run-flat tyres/system (and tyre pressure monitoring system)" (2018)**	UNECE	Regulation - Published/current	EU & GB	Manufacturers of temporary-use spare tyres and run-flat tyres	Requirements for the approval of temporary-use spare tyres and run-flat tyres for vehicles. Includes load capacity, speed limits and braking test requirements.			✓	
8	**Regulation 117: "Uniform provisions concerning the approval of tyres with regard to rolling sound emissions and/or to adhesion on wet surfaces and/or to rolling resistance" (2016)**	UNECE	Regulation - Published/current	EU & GB	Tyre manufacturers obligations for Labelling of tyres	Technical description of how to undertake testing, to obtain the (semi)quantitative measurements of energy efficiency of tyres, their wet road grip and noise. To be used to label tyres according to Regulation (EU) 2020/740			✓	
9	**Regulation 141: "Uniform provisions concerning the approval of vehicles with regard to their Tyre Pressure Monitoring Systems (TPMS)" (2017)**	UNECE	Regulation - Published/current	EU & GB	Tyre pressure monitoring systems fitted to vehicles	Requirements for the approval of tyre pressure monitoring systems (TPMS) fitted to vehicles.			✓	
10	**Regulation 142: "Tyre installation" (2017)**	UNECE	Regulation - Published/current	EU & GB	Tyres fitted to vehicles	Requirements for the approval of tyres fitted to vehicles. Includes load and speed capacity requirements.			✓	
11	**Polymers of Low Concern (2009)**	OECD	Guideline - Published/current	OECD countries (incl. UK)	Products/materials containing polymeric material	Initial analysis by an OECD Expert Group supported the contention that polymers meeting low concern criteria (PLC) have insignificant human health or environmental impacts, which in turn, supports reduced regulatory requirements for these polymers. However, gaps in data to support the analysis were also noted.			✓	
12	**Directive 2005/69/EC relating to restrictions on the marketing and use of certain dangerous substances and preparations (polycyclic aromatic hydrocarbons in extender oils and tyres) (2005)**	European Parliament	Directive - Published/current	EU & GB	Extender oil and tyre manufacturers	This directive imposes limits on the amount of PAHs allowed in extender oils, tyres and treads used for retreaded tyres.			✓	✓
13	**Regulation 108 & 109: "Retreaded pneumatic tyres for passenger cars and their trailers" (108) for Commercial vehicles and their trailers (109) (1998)**	UNECE	Regulation - Published/current	EU & GB	Manufacturers of retreaded tyres.	Requirements for the approval of retreaded tyres for passenger and commercial vehicles.			✓	✓
14	**SR2021 No 13: storage and mechanical treatment of end-of-life tyres for recovery (2022)**	UK Environment Agency (EA)	Guideline - Published/current	UK	Operators involved with the "scrapping" and disposal of tyres - who would receive end-of-life tyres from public, garages, recycling centres etc	Statutory guidance on The Environmental Permitting (England & Wales) Regulations 2016 - Chapter 4 Standard rule. Includes description of the facilities, and processes that can be used in the recycling of tyres, ranging from location of facilities, to permitted activities.				✓
15	**The Road Vehicles (Brake Linings Safety) Regulations 1999 (1999)**	UK Parliament	Regulation - Published/current	UK	Manufacturers, suppliers and fitters of brake linings for road vehicles	Provides safety standards for brake linings including a ban on the use of asbestos in brakes linings.			✓	
16	**Regulation 13: "Braking of vehicles and trailers (& of passenger cars, Reg 13-H)" (2023)**	UNECE	Regulation - Published/current	EU & GB	Braking systems fitted to vehicles and trailers.	Requirements for the approval of braking systems fitted on vehicles. Includes requirements of braking tests and performance of braking systems (including regenerative braking systems). Includes requirement that brake linings shall not contain asbestos.			✓	

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
17	**Regulation 90: "Replacement brake lining assemblies, drum-brake linings and discs and drums for power-driven vehicles and their trailers" (2012)**	UNECE	Regulation - Published/current	EU & GB	Replacement brakes going into vehicles and trailers.	This regulation applies to replacement brake and drum brake lining assemblies intended for use in friction brakes forming part of a braking system of vehicles.			✓	
18	**UN Global Technical Regulation No. 24: Laboratory Measurement of Brake Emissions for Light-Duty Vehicles (2023)**	UNECE	Regulation - Published/current	Worldwide	This UN GTR applies to category 1-1 and category 2 vehicles with a fully laden mass below 3500 kg.	This Global Technical Regulation (UN GTR) provides a worldwide harmonised methodology for the measurement of brake wear particulate matter and particle number emissions from brakes used on Light-Duty vehicles. This UN GTR defines the test cycle, minimum system requirements, test conditions, and equipment preparation to execute the WLTP-Brake cycle using brake dynamometers. This UN GTR also provides requirements for the design and set up of test systems to measure brake emissions, including requirements on calibration and validation of test equipment.			✓	
19	**UK Emissions Trading Scheme (UK ETS) / Greenhouse Gas Emissions Trading Scheme Order (2021/2020)**	UK Government	Regulation - Published/current	UK	Energy intensive industries, the power generation sector and aviation.	The UK Emissions Trading Scheme (UK ETS) replaced the UK's participation in the European Union Emissions Trading Scheme (EU ETS) on 1 January 2021. The UK, Scottish and Welsh Governments and Northern Ireland Department of Agriculture, Environment and Rural Affairs – collectively making up the UK ETS Authority – established the scheme to increase the climate ambition of the UK's carbon pricing policy, while protecting the competitiveness of UK businesses. Emissions trading schemes usually work on the 'cap and trade' principle, where a cap is set on the total amount of certain greenhouse gases that can be emitted by sectors covered by the scheme. This limits the total amount of carbon that can be emitted and, as it decreases over time, will make a significant contribution to how we meet the UK's Net Zero 2050 target and other legally binding carbon reduction commitments.		✓		✓
20	**UK Carbon Border Adjustment Mechanism (CBAM) (Implementation in 2027)**	UK Government	Proposed Reg/Std - Proposed/draft	UK	The UK CBAM will place a carbon price on some of the most emissions intensive industrial goods imported to the UK from the aluminium, cement, ceramics, fertiliser, glass, hydrogen, iron and steel sectors. Further detail, including the precise list of products in scope, will be the subject of consultation in 2024.	The liability applied by the CBAM will depend on the greenhouse gas emissions intensity of the imported good and the gap between the carbon price applied in the country of origin (if any) and the carbon price that would have been applied had the good been produced in the UK. CBAM liability will lie directly with the importer of imported products within scope of the UK CBAM on the basis of emissions embodied in imported goods. This system will not involve the purchase or trading of emissions certificates. Further details on the design and delivery of a UK CBAM will be subject to consultation in 2024.		✓		
21	**Industrial Emissions Directive (IED) 2010/75/EU (2010)**	European Commission	Directive - Published/current	EU & GB	The Legislation covers industrial activities in the following sectors: Energy, Metal Production and Processing, Minerals, Chemicals, Waste Management	The Directive aims to address the entire environmental impacts of the installation, including emissions to air, water and land, generation of waste and noise, use of energy and raw materials, prevention of accidents, and site closure. Installations can only occur if they possess a permit and comply with the specified conditions. The IED is based on several pillars, in particular (1) an integrated approach, taking the whole environmental performance of a plant into consideration (2) use of best available techniques (BAT), BAT conclusions are used to set permit conditions (3) flexibility around emissions limit values linked to disproportionally higher costs (4) inspections are a mandatory requirement (5) public participation, by having access to permit applications, permits and the results of the monitoring of releases		✓		
22	**Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability (2005)**	European Commission	Regulation - Published/current	EU & GB	Cars and LCVs	This legislation applies to new models and models already being produced of cars, station wagons, people carriers and light commercial vehicles (e.g. vans). New vehicles may only be sold in the EU if they may be reused and/or recycled to a minimum of 85 % by mass or reused and/or recovered to a minimum of 95 % by mass.		✓		✓

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
						Manufacturers must have strategies in place to properly manage the reusability, recyclability and recoverability requirements of the legislation.				
23	**Clean Air Strategy (2019)**	UK Government	Policy - Published/current	UK	Multiple sectors including transport	The final strategy sets out these proposals in detail and also indicates how devolved administrations intend to make their share of emissions reductions. It complements three other UK government strategies: the Industrial Strategy, the Clean Growth Strategy and the 25 Year Environment Plan.			✓	
24	**The road vehicles (Construction and use) regulations (1986)**	UK Parliament	Regulation - Published/current	UK	Road vehicles	Requirements for the approval of road vehicles, including their tyres and braking systems fitted.			✓	
25	**MOT inspection manual: cars and passenger vehicles / heavy duty manuals (2018)**	UK Government (DfT)	Regulation - Published/current	GB	Vehicle owners/users	UK interpretation/requirements of Directive 2014/45/EU – Road worthiness directive. Contains further details/ guidance for tyre and brake testing.			✓	
26	**UK Registration, Evaluation, Authorisation and Restriction of Chemicals (UK REACH) (2021)**	UK Government (DEFRA)	Regulation - Published/current	UK	Manufacturers, importers and suppliers of chemical substances or products containing chemicals	UK version of EU REACH regulations implemented after BREXIT. It corrects deficiencies to ensure that the legislation operates effectively in the domestic context.			✓	✓
27	**Directive 2014/45/EU – Road worthiness directive (2014)**	European Commission	Directive - Published/current	EU & GB	Vehicle owners/users	Over-arching (minimum) requirements for MSs to have in their legislation regarding the in-use testing of the roadworthiness of road vehicles. Article 6 is entitled: "Contents and methods of testing" and refers to Annex 1 of the Directive. This covers brakes (1) and axles, wheels tyres, suspension (5)			✓	
28	**Directive 2000/60/EC Water Framework Directive (2000)**	European Parliament	Directive - Published/current	EU & GB	Inland surface waters, transitional waters, coastal waters and groundwater	The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which: (a) prevents further deterioration and protects and enhances the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems; (b) promotes sustainable water use based on a long-term protection of available water resources; (c) aims at enhanced protection and improvement of the aquatic environment, inter alia, through specific measures for the progressive reduction of discharges, emissions and losses of priority substances and the cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances; (d) ensures the progressive reduction of pollution of groundwater and prevents its further pollution, and (e) contributes to mitigating the effects of floods and droughts			✓	
29	**Directive 2004/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (2004)**	European Parliament	Directive - Published/current	EU & GB	PAHs in ambient air	The objectives of this Directive shall be to: (a) establish a target value for the concentration of these PAHs in ambient air so as to avoid, prevent or reduce harmful effects on human health and the environment as a whole; (b) ensure, with respect to these PAHs, that ambient air quality is maintained where it is good and that it is improved in other cases; (c) determine common methods and criteria for the assessment of concentrations of these chemicals in ambient air as well as their deposition; (d) ensure that adequate information on concentrations of these chemicals in ambient air as well as their deposition is obtained and ensure that it is made available to the public.			✓	
30	**REACH Regulation EC 1907/2006 (2006)**	European Parliament	Regulation - Published/current	EU & GB	Manufacturers, importers and suppliers of chemical substances or products containing chemicals	The Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is the main EU law to protect human health and the environment from the risks that can be posed by chemicals. Companies are responsible for collecting information on the properties and uses of the substances they manufacture or import above one tonne a year.			✓	
31	**Regulation (EU) 2019/2144 on type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the**	European Parliament	Regulation - Published/current	EU & GB	Motor vehicle to be able to be sold in Europe or UK	Overarching legislation on the requirements for a motor vehicle to be able to be sold in Europe or UK. Annex 1 lists over 100 UN ECE regulations that have to be complied with. Key UNECE regulations listed in this index.			✓	

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
	protection of vehicle occupants and vulnerable road users (2019)									
32	**End of Life Vehicles (ELV) Directive (Directive 2000/53/EC) (2000)**	European Commission	Directive - Published/current	EU & GB	End of life vehicles and their components	Prohibits the use of hazardous substances when manufacturing new vehicles, sets targets for vehicle component and material reuse, recycling and recovery and aims to prevent and limit waste and improve environmental performance the life-cycle of vehicles.			✓	✓
33	**Council Directive 1999/31/EC on the landfill of waste (1999)**	Council of the European Union	Directive - Published/current	EU & GB	Waste going into landfills.	Supporting the EUs transition to a circular economy and meeting the requirements of Directive 2008/98/EC of the European Parliament and of the Council, the aim of this Directive is to ensure a progressive reduction of landfilling of waste, in particular of waste that is suitable for recycling or other recovery, and, by way of stringent operational and technical requirements on the waste and landfills, to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill.				✓
34	**Waste Framework Directive 2008/98/EC (2008)**	European Parliament	Directive - Published/current	EU & GB	Producers and waste management	The Waste Framework Directive lays down some basic waste management principles. It requires that waste be managed without endangering human health and harming the environment without risk to water, air, soil, plants or animals without causing a nuisance through noise or odours and without adversely affecting the countryside or places of special interest. It explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. The Directive also introduces the "polluter pays principle" and the "extended producer responsibility".				✓

Table 0-2: Regulations and standards applicable in other regions

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
1	**Regulation (EU) 2023/1115 on deforestation-free products (2023)**	European Commission	Regulation - Published/current	EU	Importers and exporters to or from the EU market	Under the Regulation, any operator or trader who places these commodities on the EU market, or exports from it, must be able to prove that the products do not originate from recently deforested land or have contributed to forest degradation.		✓		
2	**GB/T 40718-2021 - Green product assessment - Tyres (2021)**	State Administration for Market Regulation; Standardization Administration of the People's Republic of China	Voluntary standard - Published/current	China	Tyre manufacturers that would like to label tyres sold in the Chinese market as 'green' as part of the China Green Product (CGP) scheme.	This standard specifies product classification and evaluation requirements for tyre green product assessment. In order to classify tyres as green products and label them with the China Green Product (CGP) label, the tyres must meet conditions across the entire lifecycle of the tyres set by various other standards which this standard refers to, including those relating to noise, energy management, environmental management, occupational health and safety, emissions limits for rubber production and chemical limits. If the tyres meet all requirements, they can receive the 'all-green products' CGP label, if they meet at least one of the requirements then they can receive the CGP label for 'green-related products'.		✓	✓	✓
3	**Labelling of tyres for fuel efficiency and other parameters Regulation (EU) 2020/740 (2020)**	European Commission	Regulation - Published/current	EU	Tyre manufacturers	This Regulation establishes a framework for the provision of harmonised information on tyre parameters through labelling to allow end-users to make an informed choice when purchasing tyres, for the purpose of increasing safety, the protection of health, and the economic and environmental efficiency of road transport			✓	

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
4	**§ 575.106 Tire fuel efficiency consumer information program. (2010)**	US Code of Federal Regulations (CFR)	Regulation - Published/current	US	Tyre manufacturers, tyre brand name owners, and tyre retailers to provide information indicating the relative performance of replacement passenger car tyres in the areas of fuel efficiency, safety, and durability	Similar to EU regulation. Proposes a broad new consumer information program for replacement tyres to inform consumers about the effect of tyres on fuel efficiency, safety, and durability. This consumer information program would implement a national tyre fuel efficiency rating system for replacement tyres, with the information provided to consumers at the point of sale and online. Fuel efficiency ratings are expected to inform consumers so that they will be better informed about replacement tyre performance. This consumer information program seeks to enhance energy security and reduce costs by improving fuel economy. Information would also be provided about safety and durability.			✓	
5	**49 US Code of Federal Regulations (CFR) § 575.104 - Uniform tire quality grading standards. (2010)**	US Code of Federal Regulations (CFR)	Regulation - Published/current	US	Tyre manufacturers (and brand name owners, obligations for Labelling of tyres to be used in the US	Somewhat like the EU Tyre labelling directive, but requiring relative information on the performance of tyres with regards to treadwear, traction and temperature resistance			✓	
6	**California Replacement Tyre Efficiency Program (2003)**	California Energy Commission (CEC)	Regulation Proposed/draft	California, US	Tyre suppliers of replacement tyres	Since 2003, California has been considering efficiency standards for replacement tires to ensure that replacement tyres for passenger cars and light-duty trucks are at least as energy efficient as the tires sold as original equipment on the vehicles. The CEC are directed to 1) Develop and maintain a database for tire efficiency information. 2) Establish a rating system, based on an adopted test procedure, for the energy efficiency of replacement tires sold in the state. 3) Set minimum performance efficiency standards for replacement tires. 4) Require manufacturers to report the energy efficiency of replacement tires.			✓	
7	**Japan Tyre Labelling System for Fuel-Efficiency Tyres (2010)**	Japan Automobile Tyre Manufacturers Association (JATMA)	Guideline - Published/current	Japan	Tyre manufacturers	A tyre grading system that is based on both the tyre rolling resistance (RR) and Wet Grip performance; a definition of the fuel efficient tyre that complies with a certain level of tyre RR and Wet Grip performance; and a labelling system that provides appropriate information on tyres to the consumer as an implementation program of the fuel efficient tyre use promotion which is framed by the Fuel-Efficient Tire Promotion Council.			✓	
8	**Commission Regulation (EU) 2021/1199 as regards polycyclic-aromatic hydrocarbons (PAHs) in granules or mulches used as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications. (2021)**	European Commission	Regulation - Published/current	EU	Producers/suppliers of granules/mulches used as infill materials for synthetic turf pitches or playgrounds.	Granules or mulches shall not be placed on the market for use as infill material in synthetic turf pitches or in loose form on playgrounds or in sport applications if they contain more than 20 mg/kg (0,002 % by weight) of the sum of all listed PAHs.				✓
9	**California (Senate Bill (SB) 346), Washington (Senate Bill (SB) 6557), Rhode Island State (Senate Bill (SB) H7997), and New York State (Senate Bill (SB) A10871) -Better Brakes Laws (2010)**	Californian Government	Regulation - Published/current	Specified US States	Manufacturers, suppliers and fitters of brake linings for road vehicles	These law prohibits the sale of automobile brake pads sold in the states containing more than trace amounts of copper, certain heavy metals, and asbestos. The purpose of this law is to reduce the amount of copper and other toxic substances released from brakes from entering streams, rivers, and marine environment. Manufacturers must certify and mark products to show compliance			✓	
10	**Copper-Free Brake Initiative (2015)**	United States Environmental Protection Agency (EPA)	Voluntary standard - Published/current	US	Brake pad manufacturers/suppliers.	On January 21, 2015, EPA, states, and the automotive industry signed an agreement to reduce the use of copper and other materials in motor vehicle brake pads. The agreement calls for reducing copper in brake pads to < 5 percent by weight in 2021 and 0.5 percent by 2025. In addition to copper, this voluntary initiative reduces mercury, lead, cadmium, asbestiform fibres, and chromium-six salts in motor vehicle brake pads. The Initiative will decrease runoff of these materials from roads into the nation's streams, rivers, and lakes. Copper from stormwater runoff can affect fish, amphibians, invertebrates, and plants.			✓	
11	**Copper-Free Brake Initiative - AASA Leafmark (2015)**	Automotive Aftermarket Suppliers Association (AASA)	Voluntary labelling - Published/current	US	Brake pad manufacturers/suppliers.	Compliance designations (A, B & N) for labelling of brake pads published by the Automotive Aftermarket Suppliers Association (AASA). These compliance codes correlate with the various phases of the implementation timeline of the 'Copper-Free Brake Initiative'. Note that compliance code A is not compliant with the 'Copper-Free Brake Initiative.'			✓	

#	Name of regulation, policy, or standard	Organisation or Authority	Type and status	Scope: Geographical	Scope: Organisation/industries/products, boundaries, applications	Overview	Relevance	Production phase	Use phase	End-of-Life phase
12	**Ecodesign for Sustainable Products Regulation (ESPR) (Proposed in 2022)**	European Commission	Regulation - Proposed/draft	EU	All products placed on the EU market, whether produced inside or outside the EU. Priority will be given to highly impactful products, including textiles (especially garments and footwear), furniture (including mattresses), iron and steel, aluminium, tyres, paints, lubricants and chemicals, as well as energy related products, ICT products and other electronics.	The new law will build on the existing Ecodesign Directive that has successfully driven the improved energy efficiency of products in the EU for almost 20 years. It will allow to progressively set performance and information requirements for key products placed on the EU market. The Commission will adopt and regularly update a list of products identified on the basis of a thorough analysis and criteria notably related to the EU's climate, environment and energy efficiency objectives. The new Ecodesign requirements will go beyond energy efficiency and aim to boost circularity, covering, among others: - product durability, reusability, upgradability, and repairability - presence of chemical substances that inhibit reuse and recycling of materials - energy and resource efficiency - recycled content - carbon and environmental footprints - available product information, in particular a Digital Product Passport		✓		✓
13	**EU Emissions Trading System (ETS) (2005)**	European Commission	Regulation - Published/current	EU	Covers general sectors	The objective of the ETS is to reduce GHG from energy intensive industries by 1.74% every year starting in 2013, 21% by 2020, compared to 2005 levels, then 2.2%/yr. The cap of total emissions (and level of allowances) is reduced over time. Companies are allocated emission allowances that can be traded to make them more efficient. Penalty of 100 euro per excess tonne vs carbon trading price of ~50 euro/tonne		✓		
14	**Carbon Border Adjustment Mechanism (CBAM) (Transition phase: 2023-2026, Full implementation: 2026)**	European Commission	Regulation - Proposed/draft	EU	The CBAM will initially apply to imports of certain goods and selected precursors whose production is carbon intensive and at most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.	Aimed to increase costs to import goods manufactured in high-carbon countries to make low-carbon manufacturing more competitive, through CBAM certificates aligned to ETS. Planned to be introduced in a transitional phase from 2023 until the end of 2024 and cover all sectors under ETS by 2030. From 2021 EU importers of goods covered by the CBAM need to register with national authorities where they can also buy CBAM certificates Price of certificates will be calculated depending on the weekly average auction price of EU ETS allowances expressed in € / tonne of CO_2 emitted		✓		
15	**Corporate Sustainability Reporting Directive (CSRD) 2022/2464/EU (2022)**	European Commission	Directive - Published/current	EU	All large companies and all listed companies (except listed micro-enterprises)	On 5 January 2023, the Corporate Sustainability Reporting Directive (CSRD) entered into force. It modernises and strengthens the rules concerning the social and environmental information that companies have to report. A broader set of large companies, as well as listed SMEs, will now be required to report on sustainability. Some non-EU companies will also have to report if they generate over EUR 150 million on the EU market. The new rules will ensure that investors and other stakeholders have access to the information they need to assess the impact of companies on people and the environment and for investors to assess financial risks and opportunities arising from climate change and other sustainability issues.		✓		
16	**EURO 7 (Pending, provisional agreement reached in 2023)**	European Commission	Regulation - Proposed/draft	EU	Covers passenger cars, vans, buses, trucks and trailers	For the first time in Europe potential limits on PM10 from brake wear and tyre wear for vehicles. BUT this lays down principles, NOT how the measurements are to be made. That is still being developed. So too are the limits/drive cycle and test procedure details			✓	

national highways