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FORESIGHT Brief

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034

Early Warning, Emerging Issues and Futures

Vehicle tyre particles in the environment

Background

The Foresight Briefs are published by the United Nations Environment Programme (UNEP) to, among others, highlight a hotspot of environmental change, feature an emerging science topic, or discuss a contemporary environmental issue. The public is thus provided with the opportunity to find out what is happening to their changing environment and the consequences of everyday choices, and to think about future directions for policy. The thirty-fourth edition of UNEP's Foresight Briefs looks at the negative effects of tyre abrasion particles and how they can be regulated.

Abstract

Tyre-wear particles are one of the most abundant types of primary microplastics discharged into the environment. During their degradation in the environment, various tyre components are released, including some chemicals with harmful effects to organisms. There are various prevention and mitigation methods that can alleviate the problems, but effectively designed and enforced policies are needed to support these strategies.

Introduction

Driving a vehicle causes abrasion of the tyres, generating very large amounts of small particles, known as tyre-abrasion or tyre-wear particles. These particles are emitted into and spread throughout the environment (Giechaskiel *et al.* 2024; Gieré and Dietze 2022). Due to their chemical composition, typical size, and mode of formation and release, these particles are classified as primary microplastics (Boucher and Friot 2017;

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Hartmann *et al.* 2019; Järlskog *et al.* 2022). Once in the environment, the tyre-wear particles interact with light, air, ozone, and water, as well as with soil, sediments, and biota. These interactions trigger particle degradation, which in turn leads to the release of tyre constituents, including zinc and various organic chemicals (Halsband *et al.* 2020; Gieré and Dietze 2022; Zhang *et al.* 2023). There is increasing evidence that some of these released compounds are highly toxic to various organisms (Brinkmann *et al.* 2022; Chen *et al.* 2023; Bohara *et al.* 2024). It is therefore essential that appropriate measures are taken by both the tyre industry and governments around the world to curtail emission of tyre-wear particles in order to minimize their distribution and concentration in the environment.

Why is this an important issue?

Tyre-wear particles constitute one of the most abundant types of primary microplastics discharged into the environment (Kole *et al.* 2017; Sommer *et al.* 2018; Kole *et al.* 2019; Furuseth and Rødland 2020; Vogelsang *et al.* 2020). It has been estimated, for example, that of the 1.5 million tonnes of primary microplastics reaching the oceans every year, 28 per cent, or 400,000 tonnes, are tyre-wear particles (Boucher and Friot 2017). According to another study, the annual accumulation of tyre-wear particles in the oceans may be as high as 1.0±0.2 million tonnes (PEW Charitable Trusts, 2020). Tyre-wear particles have also been observed within the intestines of fish and other aquatic species (Leads *et al.* 2019; Parker *et al.* 2020), some of which are consumed by humans.

Tyre-wear particles originate from a tyre's outermost layer, known as the tread (Figure 1).

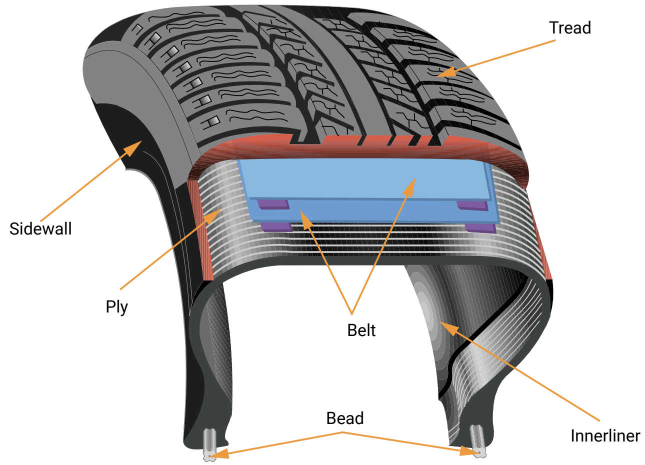

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Figure 1: Basic structure of a passenger car tyre. Belts provide stiffness to the tread, overall tyre strength, and protection from puncture; body ply maintains tyre shape and prevents it from tearing; beads enable the tyre to firmly grip to the wheel.

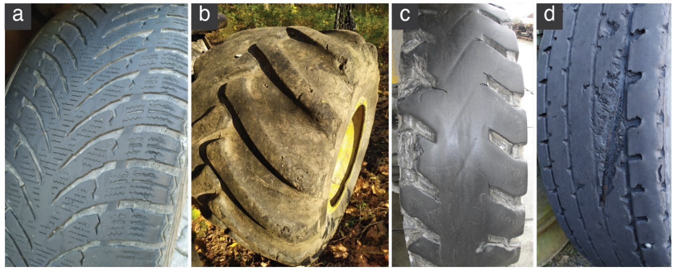

Photo credits (a) - (d): Radek Stoček

Figure 2: Images of vehicle tyres that exhibit visible wear of the tread

(a) tyre from passenger car;
(b) tyre from forestry vehicle;
(c) a multi-purpose radial tyre, commonly used for construction vehicles and forklifts; and
(d) commercial tyre, used by vans and heavy-duty vehicles.

Tyre damage caused by fatigue (smooth tread surface – smallest tyre particles generated), abrasion (rougher surface – medium-sized tyre particles generated), and cutting (visible breakage of a large piece from the tread – largest tyre debris generated).

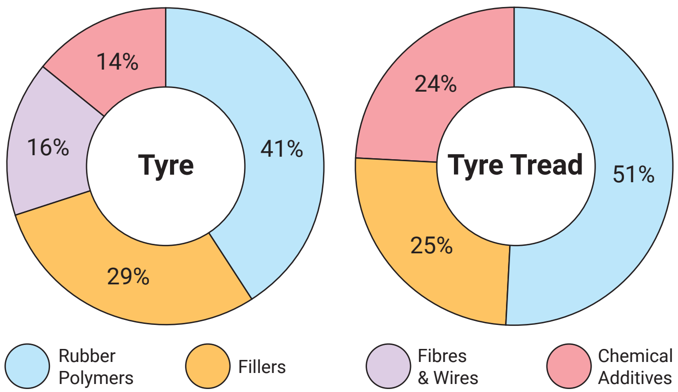

Figure 3: Examples of compositions of a reference passenger car tyre in the European Union (OECD 2014) and of a tyre tread (Winther and Slentø 2010). Colour scheme is identical to that used in Table 1, which provides some details for each of the components shown here. All values given in per cent by mass.

The tread is in direct contact with the road surface and, due to slippage and friction between the two materials, is abraded during driving (Figure 2), especially through acceleration, braking, and cornering (Luhana *et al.* 2004). These particles therefore reflect the chemical composition of the tread rather than that of an entire tyre. Both compositions vary among different manufacturers and tyre types (Gieré *et al.* 2004; Rauert *et al.* 2021). The tyre tread is rich in both natural and synthetic polymers as well as chemical additives, comprises various types of fillers, primarily carbon black and amorphous silica, and does not contain steel or textiles (Figure 3, Table 1) (Gent 2006; Broekhuizen 2024). During tyre manufacturing, certain chemical components, including polycyclic aromatic hydrocarbons (PAHs), are added as unintentional byproducts, because they are associated with carbon black and some chemical additives (e.g., plasticizers) (Boonyatumanond *et al.* 2007; Aatmeeyata and Sharma 2010).

Global release rates of tyre-wear particles have been estimated at approximately 6 million tonnes per year (Kole *et al.* 2017; Kole *et al.* 2019), equivalent to an overall average of 0.8 kilograms (kg) per capita per year. The release rate, however, varies widely among individual countries, reaching values up to about 5 kg/capita/year (Figure 4). Loading the 6 million tonnes of tyre-wear particles onto cargo railroad cars with a capacity of 60 tonnes and a length of 15 metres would create a freight train with a length of 1500 kilometres.

Degradation, or weathering, of tyre-wear particles in the environment or the intestines of wildlife facilitates the release of various chemical compounds, including fillers as well as intentional and non-intentional additives (Evans 1997; Wik and Dave 2009; Wagner *et al.* 2018; Müller *et al.* 2022). Numerous ecotoxicological studies have demonstrated that some of the released chemicals (for example zinc, butadiene, benzothiazoles, PAHs

Table 1. Material classes employed for the fabrication of tyres. For each material class, select compounds are listed as examples with their specific function during production or subsequent use of a tyre (Broekhuizen 2024; Chen *et al.* 2024; Gent 2006; Wan *et al.* 2020)

Material	Type	Examples	Function
Rubber polymers	Natural polymers	Natural rubber (NR)	Provide elastic properties and increase resistance to fatigue and tear; control rolling resistance an traction performance
	Synthetic polymers	Styrene-butadiene rubber (SBR), butadiene rubber (BR), isoprene rubber (IR)	
Fillers	Nanostructured agglomerates	Amorphous silica	Strengthen the rubber to achieve maximum performance and lifespan
		Carbon black	
Fibres and wires	Textile fibre	Nylon, polyester, rayon	Reinforcing the body ply
	Wire cords	Steel	Providing strength to belts and beads
Chemical additives	Zinc oxide and various organic chemicals	Activators and accelerators (e.g. various benzothiazole* compounds	Activate and accelerate chemical reactions during production
		Vulcanizers	Transform rubber into a solid material during production
		Plasticizers	Enhance processability of materials during production
		Antioxidants and antiozonants (e.g. 6PPD**)	Reduce susceptibility to degradation due to exposure to temperature, oxygen and ozone
		Flame retardants	Reduce flammability of rubber

* Benzothiazole: organic chemical compound with the formula C_7H_5NS
** 6PPD: organic chemical compound named N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine, and with the formula $C_{18}H_{24}N_2$

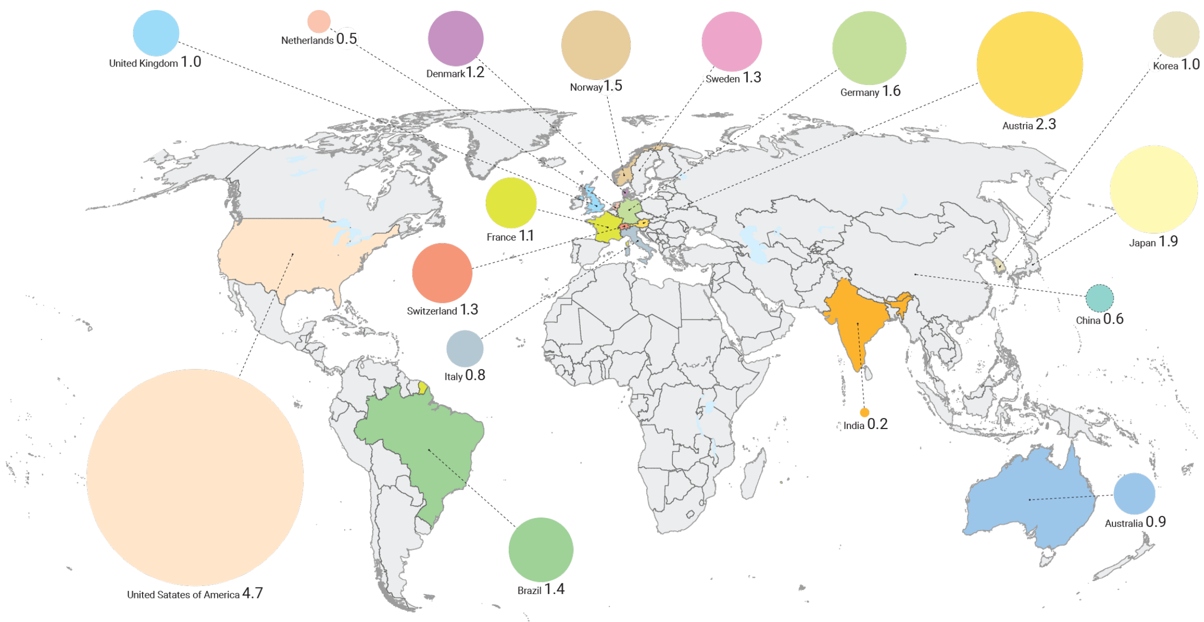

Figure 4: Estimated emissions of tyre-wear particles in countries for which data are available. Data given in kilograms per capita per year. Data from Kole *et al*. (2019); Lee *et al*. (2020); Sieber *et al*. (2020); and Prenner *et al*. (2021).

and a substance known as “6PPD”; see Table 1) or their transformation products can cause various biological responses in diverse organisms, including acute toxicity and lethality in some species (Wik and Dave 2006; Wik *et al.* 2009; Halle *et al.* 2020; Halsband *et al.* 2020; Honda and Suzuki 2020; Lu *et al.* 2021; Brinkmann *et al.* 2022; Bohara *et al.* 2024). The potential impact of tyre-wear particles on human health is not well studied, but it can be gender-specific, influenced by social roles, responsibilities, and exposures. For example, women in certain occupations (e.g., street vendors, food-stall cooks, outdoor workers) and children in some school yards may be particularly exposed to pollution from tyres due to prolonged periods spent near busy roads or intersections.

The presence of tyre debris in the environment and biota, and the toxicity of tyre particles and some of their chemical constituents, therefore, remain a major concern, which needs to be addressed by the global community. Exposure differences, health vulnerabilities and socio-economic factors are general gender-related aspects of microplastics pollution (UNEP 2023) and, where possible, should be taken into consideration when developing policies that aim at lowering the emissions of tyre particles.

What are the main findings?

Characteristics of tyre-wear particles

Tyre-wear particles deposited on or near a road typically range in size between a few micrometres (µm) and about 1500 µm, or 0.15 centimetres (Figure 5). They have an elongated shape and are partially covered by even smaller particles (Figure 6), derived primarily from the road surface but also from vehicle-brake pads and soils (Adachi and Tainosho 2004). Therefore, they are commonly referred to as *tyre- and road-wear particles* in the scientific literature (Baensch-Baltruschat *et al.* 2020). These particles occur most abundantly in road dust that accumulates in curves of roads and roundabouts and at traffic lights (Venghaus *et al.* 2023).

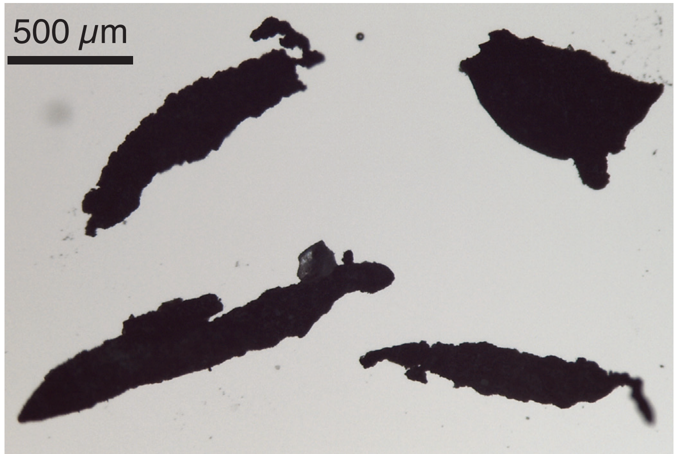

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Figure 5: Tyre-wear particles viewed under a light microscope. Scale bar shows 500 micrometres.

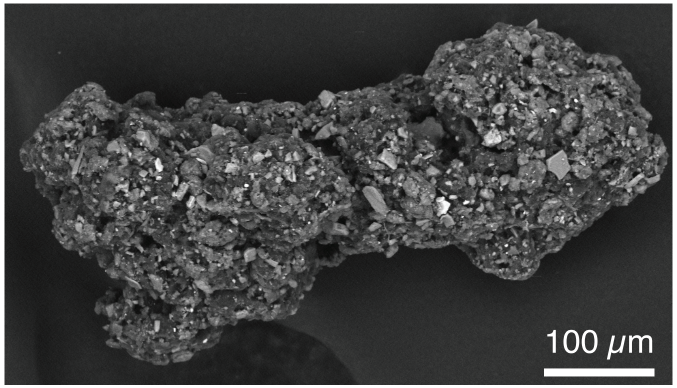

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Figure 6: Tyre-wear particle viewed under a scanning electron microscope, demonstrating that its surface is partially covered with small particles derived from vehicle brakes, the road surface, and local soils. Scale bar shows 100 micrometres.

Emission estimates

On average, passenger cars emit approximately 100 milligrams (mg) of tyre-wear particles per kilometre (km), implying that about 1 gram of tyre debris is released for every 10 km driven (Gieré and Dietze 2022). Emissions are considerably higher for heavier vehicles, such as vans, buses, and trucks (Figure 7), independent of the type of road travelled (Figure 8). On rural roads, however, all vehicle categories emit smaller amounts of tyre-wear particles than on urban roads (Figure 8).

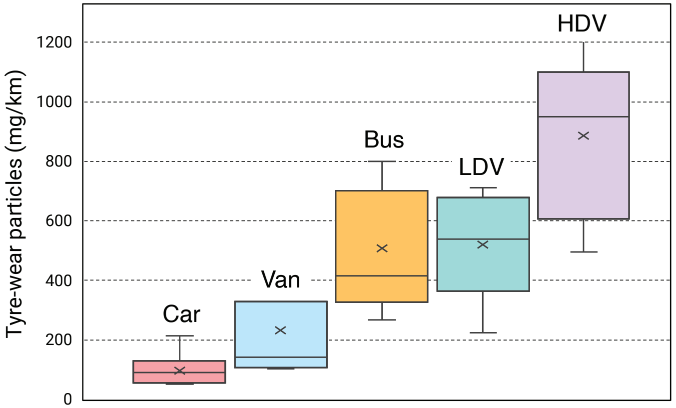

Figure 7: Emissions of tyre-wear particles (in milligrams per kilometre for various types of vehicles. Data compiled from multiple sources (Gebbe *et al.* 1997; Gustafsson 2002; Luhana *et al.* 2004; Hillenbrand *et al.* 2005; United Nations Economic Commission for Europe (UNECE) 2013; Verschoor *et al.* 2016; Kole *et al.* 2017; Grigoratos *et al.* 2018; Allgemeiner Deutscher Automobil-Club (ADAC) 2019; Lee *et al.* 2020). Symbols: x = mean value; horizontal line = median. Abbreviations: LDV = light-duty vehicle; HDV = heavy-duty vehicle (for example, a truck).

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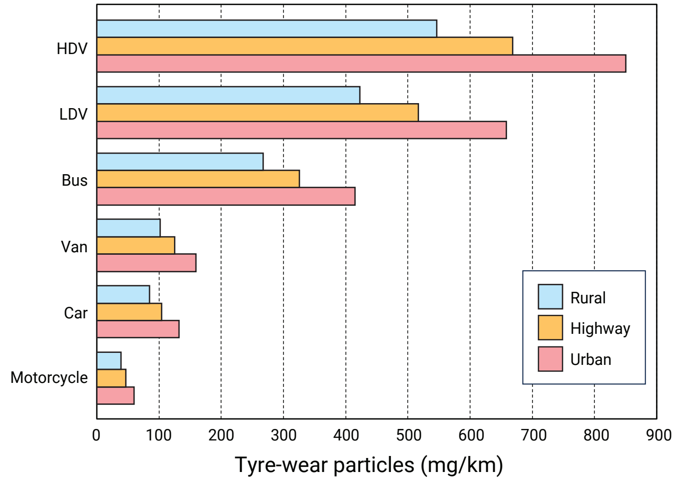

Figure 8: Emissions of tyre-wear particles (in milligrams per kilometre) for various types of vehicles on rural roads, highways, and urban roads. Data compiled from Verschoor *et al.* (2016). Abbreviations: LDV = light-duty vehicle; HDV = heavy-duty vehicle.

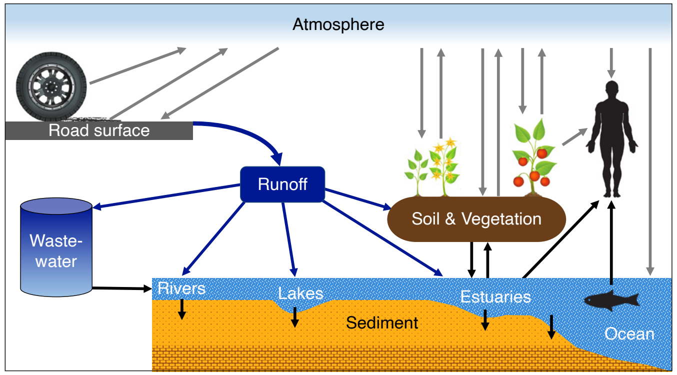

Figure 9: Schematic diagram illustrating the transport of tyre-wear particles from the source to various environmental compartments, whereby road runoff represents the main pathway into soils, surface waters and sediments.

It is predicted that releases of vehicle tyre particles, along with those of other non-exhaust materials, such as brake-wear particles, will increase both in absolute terms and relative to the emissions from fuel combustion. This rise results from a continuing increase in traffic as well as from the growing number of electric vehicles in circulation, which – due to the battery weight – are generally heavier than similarly-sized vehicles with internal combustion engines and thus impart a considerably higher twisting force, known as torque, on the tyre tread (Amato *et al.* 2012; Timmers and Achten 2016; Jekel 2019; Organisation for Economic Co-operation and Development (OECD) 2020; Vanherle *et al.* 2021; Gehrke *et al.* 2023).

Release into the environment

Small amounts of tyre-wear particles are initially released directly into the atmosphere, whereas the majority first settles on the road surface (Baensch-Baltruschat *et al.* 2021). From these temporary sinks, they are then redistributed through wind or water and deposited in various environmental compartments (Figure 9) (Jekel 2019; Sieber *et al.* 2020; Cho *et al.* 2021; Prenner *et al.* 2021; Giechaskiel *et al.* 2024). Because road runoff in many settings is not collected by a sewer system and thus, not delivered to wastewater-treatment facilities, it plays a central role in transporting tyre-wear particles and associated pollutants to soils and surface waters (Maltby *et al.* 1995a; Maltby *et al.* 1995b; Boxall and Maltby 1997; Kumata *et al.* 2002; Sundt *et al.* 2016; Parker-Jurd *et al.* 2021; Chen *et al.* 2024).

Toxicity

During manufacturing of a tyre, various chemicals and fillers are added to the rubber polymers to enhance materials processability and to maximize performance and lifetime of the final product (Table 1, Figure 3). Yet, upon physical, chemical, and microbial degradation of tyre particles, some of these chemical components can be leached from the particles into the environment or into the intestines of organisms that have ingested the tyre debris (Spies *et al.* 1987; Reddy and Quinn 1997; Kumata *et al.* 2000; Johannessen *et al.* 2021). Recent studies have documented a hazardous potential of several leached tyre-derived chemicals (Cao *et al.* 2022; Gieré and Dietze 2022; Jiang *et al.* 2023; Roubeau Dumont *et al.*

2023). For example, zinc as well as organic chemical additives (Table 1), such as benzothiazole compounds (accelerators) and 6PPD (antioxidant and antiozonant) and/or their derivatives can cause acute and chronic toxicity to aquatic wildlife, including salmon (Capolupo *et al.* 2020; Honda and Suzuki 2020; Cuajungco *et al.* 2021; Tian *et al.* 2021; Brinkmann *et al.* 2022; Foldvik *et al.* 2022; Hussain *et al.* 2022; Page *et al.* 2022; Peng *et al.* 2022; Tian *et al.* 2022; Yang *et al.* 2022; Chen *et al.* 2023; Lo *et al.* 2023; Bohara *et al.* 2024).

Some of these problematic tyre-derived chemical additives and their transformation products have also been found in lettuce leaves, where they are metabolized and accumulated (Castan *et al.* 2023).

Tyre-wear particles that become airborne are typically smaller (less than 10 µm across) than those settling on the road surface (Giechaskiel *et al.* 2024), and thus are inhalable (Gustafsson *et al.* 2008). Because the smallest particles are produced through thermochemical processes rather than friction between tyres and road surface, this size fraction is chemically different as well. It consists primarily of carbon compounds and polymers (Dahl *et al.* 2006; Park *et al.* 2017; Johannessen *et al.* 2022; Chae *et al.* 2024), and thus has a different hazardous potential (Vallabani *et al.* 2023).

What has been done?

Measures to alleviate the problems of abundance and hazardous potential of tyre particles in the environment are focused on both prevention and mitigation (Piscitello *et al.* 2021; Gehrke *et al.* 2023).

Prevention

Prevention methods to minimize tyre-particle emissions at their source include: advanced design of tyre materials, such as modification of rubber into a self-healing material, capable of repairing damage and delaying tyre aging (Mandal *et al.* 2023a; Mandal *et al.* 2023b); innovation in developing new road pavements (Miera-Dominguez *et al.* 2023); optimizing the automotive axle systems (Schütte and Sextro 2021); investing in road maintenance to preserve a smooth surface (Gehrke *et al.* 2023); installing devices behind the wheels that capture tyre-wear particles (Dong *et al.* 2021); substituting problematic tyre components with more environmentally friendly chemicals to reduce the release of toxic compounds (Ayar *et al.* 2021; Böruban Bingöl *et al.* 2024); implementing stronger policies, which promote using public transport to reduce the number of vehicles on the road and stimulate transporting cargo by rail (Sundt *et al.* 2016); reducing traffic density and speed (Tian *et al.* 2017; Querol *et al.* 2018; Sommer *et al.* 2018); changing fleet composition to smaller and lighter vehicles (Andersson-Sköld *et al.* 2020); enhancing on-board driver-assistance and traffic-management systems to facilitate traffic flow with fewer brake maneuvers (Gieré and Dietze 2022); and consumer education on driving behavior, tyre choice, maintaining correct tyre-inflation pressure, vehicle maintenance (e.g., wheel alignment) and environmental impacts of driving (Fussell *et al.* 2022). The current efforts by the tyre industry to substitute some major components, such as carbon black and silica, with more sustainably-sourced materials (Lolage *et al.* 2020; Scott 2023) are a promising way forward, but the issue of the toxic chemical tyre additives must also be addressed, requiring swift action.

Mitigation

The transport of tyre-wear particles to locations far from the source of release can be reduced by various measures, including: applying porous asphalt to trap tyre particles on the road surface (Kole *et al.* 2017; Miera-Dominguez *et al.* 2023; Svensson *et al.* 2023); sweeping and rinsing of the road surface in high-traffic areas (Querol *et al.* 2018; Piscitello *et al.* 2021); spraying water or hygroscopic solutions onto the road surface to keep it moist, thus preventing resuspension and dispersion of road dust (Fussell *et al.* 2022; Gehrke *et al.* 2023); improving stormwater management to reduce road runoff into soils and surface waters by installing roadside settling ponds and gullies (Furuseth and Rødland 2020; Gehrke *et al.* 2023); connecting road-drainage systems to wastewater-treatment infrastructure while, at the same time, banning the use of the resulting sewage sludge as fertilizer (Gieré and Dietze 2022); and by planting suitable vegetation which, depending on geometrical features and surface roughness of the leaves, can trap tyre-wear particles along roadsides (Cho *et al.* 2021). Once the tyre-wear particles are in the soil or surface waters, it is almost impossible to recover them.

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Table 2: Roles of various stakeholders in addressing tyre-particle emissions and reducing the environmental impact of tyre manufacturing and usage

Stakeholder	Action
Governments (national, regional, and local)	• Invest in research on environmentally friendly tyre design • Policies to regulate tyre-particle emissions and to reduce the number of vehicle-kilometres travelled • Certain chemical components added during the tyre manufacturing process should be regulated or banned to reduce their documented toxic effects • Information related to chemical additives used for tyre manufacturing should be disclosed • Strong public policies must be developed and implemented to target non-exhaust traffic emissions
Businesses (e.g., tyre and car manufacturer, maintenance, service provider, recyclers)	• Advanced design of tyre materials, such as modification of rubber into a self-healing material, capable of repairing damage and delaying tyre aging • Substituting problematic tyre components with more environmentally friendly chemicals to reduce the release of toxic compounds • Substitute components, such as carbon black and silica, with more sustainably-sourced materials • Enhance on-board driver-assistance systems
Municipalities	• Invest in road maintenance to safeguard a smooth surface • Install traffic-management systems to facilitate traffic flow with fewer brake maneuvers • Direct road drainage to wastewater-treatment facilities
Consumers and users	• Reduce overall speed • Avoid rapid acceleration and braking • Drive with correctly inflated tyres • Use smaller and lighter vehicles • Choose public transport

What are the policy implications?

To reduce emission of tyre-wear particles and to minimize their dispersion into various environmental compartments, measures must be taken by a variety of stakeholders (Table 2), including tyre manufacturers, the automotive industry, road-construction companies, the wastewater sector, governments, research institutions, and environmental organizations, as well as educators and the media (European Tyre & Rubber Manufacturers Association (ETRMA) 2019; Gehrke *et al.* 2023). These stakeholders must be brought together in a joint effort to raise awareness in the society at large and to find suitable solutions to the ever-increasing accumulation of small tyre-wear particles in the environment and the associated release of hazardous chemicals during their degradation.

Unlike in the case of vehicle exhaust emissions, there are only a few policy instruments targeting non-exhaust traffic emissions. For example, in the European Union, various efforts exist to regulate tyre-particle emissions and to reduce the number of vehicle-kilometres travelled; measures include economic disincentives and/or potentially actual emission limits for heavier vehicles, as well as various incentives to increase the use of public transportation (OECD 2020). Elsewhere, the Road Traffic Regulations, issued by the government of Ghana, for example, prohibit the use of under- and overinflated tyres (Driver and Vehicle Licensing Agency (DVLA) 2012), which helps in reducing tyre-particle emissions (for example Fisher 2017).

On the material side, while essential tyre properties and safety requirements must be maintained, certain chemical components added during the tyre manufacturing process (e.g., 6PPD, PAHs, benzothiazoles) should be regulated or banned to reduce their documented toxic effects. An example of such a measure is a European Commission Regulation that has prohibited the placing on the market of extender oils or using them for the manufacturing of tyres or parts of tyres, if they contain certain PAHs in concentrations above a given limit (European Commission (EC) 2009). Elsewhere, new legislation implemented by California's Department of Toxic Substances Control (DTSC) 2023a, DTSC 2023b) mandates that tyre manufacturers search for alternatives to one of the main chemical additives of concern (6PPD). Similar initiatives should be pursued by governments around the world. In addition, effective policies must also be developed and implemented to improve transparency regarding the various chemicals used during tyre manufacturing (Trudsø *et al.* 2022).

In urban areas, road drainage systems should be connected to wastewater-treatment facilities, which have been documented to retain a major part of the tyre-wear particles (Baensch-Baltruschat *et al.* 2021; Parker-Jurd *et al.* 2021). The treatment of road runoff should also include procedures for the abatement of various organic chemicals contained in tyre-derived particles, and more generally, in road dust. Limited budgets or other priorities of policymakers (for example in low- and middle-income countries), however, may delay implementation of these recommendations, especially where the transport infrastructure is older.

Conclusions

Additional research as well as innovation and effective policies are urgently needed to lower the emissions of tyre-wear particles into the environment. Information related to chemical additives used for tyre manufacturing should be disclosed, and regulations should ensure the use of safer and more sustainable alternatives. Other important measures include improvement of traffic-management and road-drainage systems, strictly enforced regulations on speed limits, and enhanced driver education.

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