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Review

Contribution of Road Vehicle Tyre Wear to Microplastics and Ambient Air Pollution

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Abstract: Tyre particles are generated by shear forces between the tread and the road or by volatilisation. Tyre abrasion (wear) contributes from one-third to half of microplastics unintentionally released into the environment. The major part ends up in the soil, a considerable amount is released into the aquatic environment, and a small percentage becomes airborne. Nevertheless, tyre abrasion contributes to 5–30% of road transport particulate matter (PM) emissions. This corresponds to approximately 5% of total ambient PM emissions. The particle mass size distribution peak at around 20 to 100 µm, with a second peak in the 2–10 µm range. A nucleation mode has been reported in some studies. The absolute abrasion levels depend on the tyre, vehicle, and road characteristics, but also on environmental conditions and driving style. Most tyre particle emission factors in the literature are based on data prior to the year 2000. We aggregated recent studies and found a mean abrasion of 110 mg/km per vehicle or 68 mg/km/t for passenger cars (based on approximately 300 measurements). Based on a limited number of studies, the PM_{10} emissions were 1.4–2.2 mg/km per tyre. On the other hand, the particle number emissions were in the order of 10^{10} #/km per tyre. The ratio of PM_{10} to total abrasion was found to be 2.5% on average. Finally, the ratio of $PM_{2.5}$ to PM_{10} was calculated to be around 40%. Various mitigation measures for tyre particle pollution could be envisaged; the most direct is the limitation of the tyre abrasion rate, as proposed by the European Commission for the Euro 7 regulation. Other regulatory initiatives are also discussed.

Keywords: microplastics; air pollution; PM; tyres; abrasion rate; emission factors; chemical composition; tyre wear; TRWP; TWP

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1. Introduction

Plastics can be found everywhere, from packaging and clothing to construction materials, electronic products, medical devices, furniture, toys, and vehicles, with a global production of more than 390 million tonnes in 2021 [1]. A fraction of these plastics can be released to the environment, sometimes as small particles. Although a commonly agreed-upon definition for microplastics does not exist, it is widely accepted that these are small plastic particles smaller than 5 mm in size. Of these, primary microplastics are those directly released into the environment, while secondary microplastics originate mostly from the degradation [2] of large plastic waste into smaller plastic fragments once exposed to the environment. The global release of primary microplastics into the environment was estimated at 3.2 to 6 million tonnes in 2017 [3,4]. Microplastics are recognised as an emerging global threat because of their potential health impacts on aquatic and terrestrial organisms, including humans, via multiple exposure pathways such as the food chain, drinking water, and air [5–8]. Microplastics releases to the oceans are projected to increase further unless action is taken [9].

Tyre wear is a major source of the unintentional release of primary microplastics into the environment [4]. Tyre particles and tyre leachates can cause various biological responses in aquatic and terrestrial biota. However, the environmental and health impacts of this type of pollution are poorly understood [10–13]. There is no “damage cost” specifically for tyres or particles > 10 µm, as given for particulate matter < 2.5 µm ($PM_{2.5}$) or <10 µm (PM_{10}) and NO_X in the “Handbook on external costs of transport” [14]. In 2021, in its action plan “Towards zero pollution for air, water and soil” [15], the European Commission proposed that by 2030, the European Union (EU) should reduce both intentional (i.e., microplastics added intentionally to certain products such as cosmetics and detergents) and unintentional (i.e., due to abrasion during use or poor handling) releases of microplastics into the environment by 30% compared to 2016 levels. The latter covers microplastics emissions from tyres, pellets, and textiles. In November 2022, the European Commission included emissions from tyres (and brakes) in the proposal for a Euro 7 regulation on emissions from road vehicles [16]. In October 2023, the Commission proposed measures to prevent microplastics pollution from the unintentional release of plastic pellets [17].

Tyre particles are generated either by shear forces between the tread and the road pavement [18] or by volatilisation, which results in the generation of very small particles [19]. Due to their nanoscale size, particles generated by volatilisation do not significantly contribute to emissions in terms of mass, but they are highly relevant for human health [20]. Tyre particles generated through thermochemical processes usually fall in the nanoparticle size fraction and are assumed to be semi-volatile organic compounds from softeners and additives from the tyre tread [19]. Due to the interaction of vehicle tyres with the road surface, emitted particles have been reported to contain tread rubber, embedded road material, and constituents of the suspended dust [21]. Furthermore, particles from the road surface or from the vehicle brakes may be incorporated into the tyre tread during driving, even before the tread is released into the environment [21].

The term “tyre wear particles” (TWP) has been ambiguously used in the literature. On one hand, it has been used for particles generated during the use of tyres without incorporating the road or any suspended dust constituents. On the other hand, some researchers also used this term to characterise tyre wear particles containing mineral incrustation from pavement. The term “tyre–road wear particles” (TRWP) has been introduced to characterise these particles even though it does not fully capture the diversity of the various constituents’ origins. Additionally, the term TRWP is not representative of tyre particles generated through thermochemical processes. For this reason, the terms TWP or TRWP will not be used in this paper. Instead, we use “tyre wear particles” to refer to the tread particles that are encrusted and mixed with foreign materials from the road, dust, brakes, and soil. We use the term “tyre abrasion particles” or “tyre particles” to refer only to the tread part emitted to the environment (even if other materials are encrusted). Tread particles (TPs) usually refer to the tread rubber particles produced by shaving and crushing the tyre tread or using a rotating abrader, rasp, or grinder. Recycled tyre crumb (for applications, such as rubber granules infilled on artificial turf, basketball courts, and recreation areas), and tyre repair-polished debris (generated from the inner liner by mechanical polishing for tyre repair when tyres are punctured) [22] are not covered in this paper, which deals only with the direct, unintentional release of tyre particles into the environment due to their use in road vehicles.

Particulate emissions from tyres are not a new topic of study. Discussions about particle emissions from tyres were already taking place in the 1970s [23]. However, interest in the pollution of all environmental compartments due to tyre particulate emissions has increased significantly in the past few years. While exhaust particulate emissions from new road vehicles have decreased to very low levels, non-exhaust particulate emissions, including tyre and brake emissions, have remained constantly at high levels [24]. Moreover, some studies have forecasted increased tyre and brake particulate emissions due to an increase in vehicle kilometres travelled [17]. Recent regulatory initiatives at both the United Nations Economic Commission for Europe (UNECE) World Forum for Harmonization of Vehicle Regulations (WP29) level and in Europe to tackle the issue have resulted in several studies and reviews on the topic [4,25–31]. A recent study criticised that many studies evaluating pollution from tyres are based on estimations of emission factors and not recently measured data [32].

The aim of this study is to provide a short and concise but at the same time critical overview of the current understanding on environmental pollution from tyres. For this review, keywords such as "tyre wear" and "microplastics" or "tyre emission factors" were used. However, due to lack of data in the scientific literature, especially on emission factors, documents and presentations from working groups on relevant topics were also consulted. Figure 1 is the basis of the analysis in this paper. Studies discussing the contribution of tyre particles to soil, water, and air are summarised in Section 2. Section 3 discusses the tyres' chemical composition and the tyre particles' properties. Section 4 presents new experimental studies that have measured the emissions of microplastics from tyres. Mitigation measures are proposed in Section 5. Finally, in Section 6, an update of the state of play of EU regulations on tyre emissions is also provided, highlighting the changes that have taken place since the previous reviews. Compared to other reviews, special emphasis is placed on recent measured data.

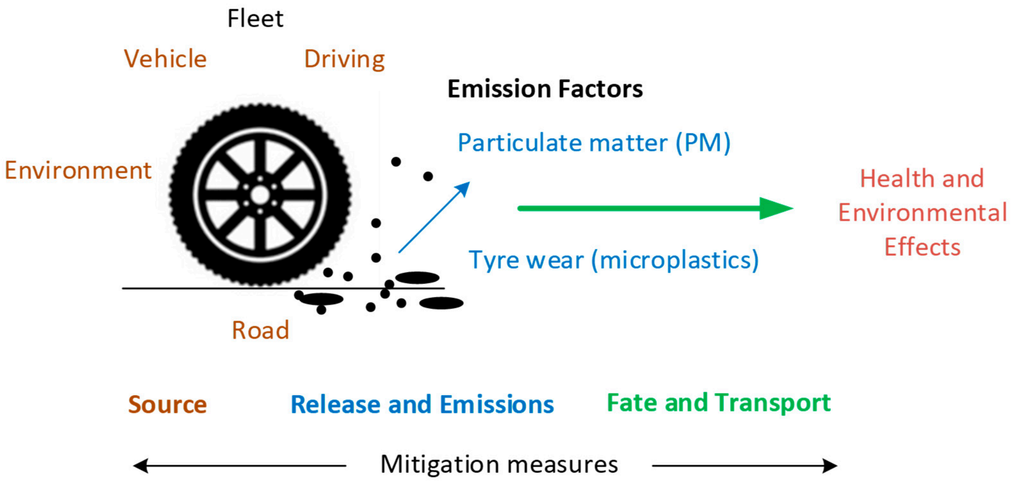

Figure 1. Schematic describing the factors and data needed to understand the role of tyre abrasion in microplastics and particulate matter (PM) pollution [33,34].

2. Tyre Particles in the Environment

A study estimated that in 2022, 2.2 billion tyres were produced globally; 0.42 billion of them were produced in Europe [35]. Other sources reported that approximately 1.8 billion tyres have been produced annually since 2017 to meet global demand [22,36], while in the EU, approximately 0.324 billion new tyres were sold in 2020 [37]. The 2020 sales corresponded to approximately 90% of the annual new tyre sales average between 2015 and 2019. The 2020 new tyre sales reduction may be attributed to COVID-19 restrictions that resulted in fewer km travelled. Among the newly sold tyres, 90% were for passenger cars (C1 tyres—tyres that are intended mainly for the M1 vehicle category plus O1 and O2) and light duty vehicles up to 3.5 t (C2 tyres—tyres that are intended mainly for the N1 vehicle category). Finally, 5% were for heavy-duty vehicles (either C2 tyres, tyres that are intended mainly for N2 vehicle category trucks plus O3 and O4, or C3 tyres, tyres that are intended mainly for M3 and N3 vehicle category trucks and buses plus O3 and O4) [37].

An average tyre for a passenger car typically lasts for 40,000 km. Some data indicate that for premium tyres, the average service life is around 45,000 km, for mid-range tyres, it is around 40,000 km, and for budget tyres, it is around 30,000 km [38]. Data recorded by Michelin in the United Kingdom between 2006 and 2011 on 5000 passenger car tyres (205/55 R16) from four tyre manufacturers fitted on one front-wheel-drive vehicle model showed that the average service life was around 37,000 $\pm$ 6000 km for tyres mounted on the front axle and around 64,000 $\pm$ 8500 km for tyres mounted on the rear axle [39]. The difference in service life between front- and rear-wheel tyres reflects the difference in load distribution, which is higher in front-wheel-drive vehicles, as will also be discussed in the main text. Different tyres from the same manufacturer can have a wide range of variation in their treadwear indices. The treadwear index gives an estimation of the expected service life of a tyre [40]. C2 tyres are expected to last 40,000–70,000 km [41] depending on the loads carried and the driving style. Finally, C3 tyres may last, on average, approximately 220,000 km before needing to be replaced or retreaded; in the second case, extending their service life to more than 600,000 km if the tire retreaded two times [42].

Throughout its service life, a tyre sheds approximately 10% of its mass [43] (0.6–1.5 kg for a 7–12 kg tyre), depending on parameters such as tyre characteristics, vehicle characteristics, road surface characteristics, and vehicle operation [44,45]. Measurements in Korea found an 11% mass loss for passenger car tyres and 18% for heavy-duty vehicle tyres [46]. Globally, tread abrasion from road tyres results in approximately 6000 kt of tyre rubber being emitted annually [4], equivalent to 0.80 kg per capita per year globally. A study reported that approximately 440 kt of tyre particles were emitted in China in 2008. The same study reported a significant increase, with more than 1500 kt of tyre particles emitted in 2018 [47]. The estimated mass of tyre abrasion generated in 2014 was 1120 kt for the United States and 1327 kt for the EU [26]. More conservative numbers have been reported for the EU (500 kt) [17,48]. In the EU, passenger cars contribute around two-thirds of the total release of microplastics from road transport [49]. However, the country specific contribution can vary significantly. For example, in the Netherlands, Denmark, and Norway, the contribution of passenger cars is estimated to be 62–71% [4]; in Japan, China, and Brazil, the contribution is reported to be 46–48%; in the United States, it is estimated to be 33%; and in India and South Korea, it is only 20% [4,46]. In India and South Korea, the heavy-duty sector (trucks and buses) contributed >50% to the road transport tyre wear.

2.1. Tyres' Contribution to Microplastics

Tyre wear particles consist of tyre tread fragments incorporating materials from the road surface with a commonly cited ratio of 1:1 [50], which is also used in standards. However, many experimental studies have found that tyre constituents are the major contributor. A study found only a 25% contribution from encrusted particles [51]. Another study found that only 6% of the particles had a ratio of road to tyre fractions of 1:1 or higher [52]. The road contribution (in terms of volume) was as low as 6%. On the other hand, a laboratory study found a 70–80% contribution of asphalt to the particles [53]. This ratio can vary depending on the road, tyre materials, and particle size.

The study of the fate of tyre microplastics emitted into the environment has received increased attention in recent years. Most published studies base their results on modelling and report that the major part of tyre wear particles end up in the soil. Concentrations of around 10 mg of tyre per gram of soil (mg_{tyres}/g_{soil}) near roads have been reported [54], but this value can reach up to 158 mg_{tyres}/g_{soil} [27]. The concentration in soil depends on traffic intensity, the type of road surface/asphalt, speed, and the presence of a runoff and drainage system. The concentration at the roadside and runoff also depend on the number of days without rain [55]. Another significant part is initially deposited on the road surface and can be flushed into surface waters directly via road runoff (approximately 50 mg_{tyres}/g_{runoff}; range: 10–150 mg_{tyres}/g_{runoff}) [27,54] after precipitation. Alternatively, tyre wear can reach surface waters indirectly when road runoff is first discharged to a wastewater treatment plant. Only a small amount of tyre becomes airborne (2–5%) [27,56], although other studies assume a much higher percentage (10%) [57]. Around 34% of the airborne fraction can reach oceans, suggesting that the direct deposition of airborne road microplastics is at least an equal source for the ocean compared to direct wash-out from the land [57]. Others found microplastics, including tyres, from the Alps to the Arctic [58]. Figure 2 plots the modelled fate of tyre particles based on the concept of [34,59–62], but with additional data from [4,26,63,64]. End-of life tyres (ELTs) [65] are discarded non-reusable tyres. ELTs in Europe in 2019 were 3500 kt; 55% of these tyres were treated through material recovery, while 40% went through energy recovery. Less than 5% (160 kt) were stocked or unknown (e.g., illegally landfilled) [66,67].

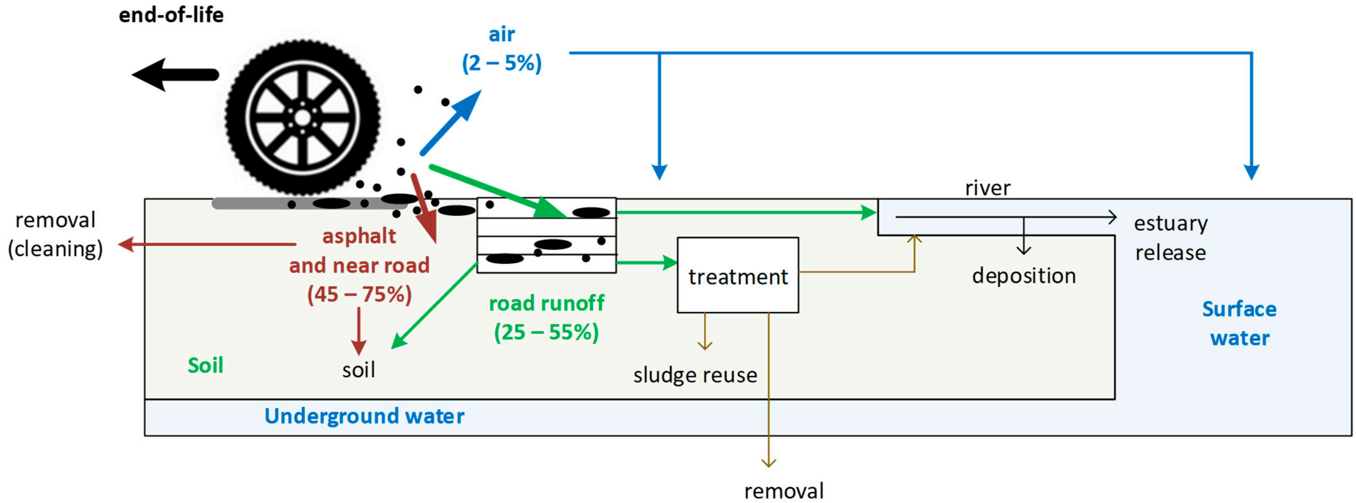

Figure 2. Modelled source, release, and transportation of tyre particles in the environment based on [34,59–61]. Arrows indicate pathways of tyre particles release to environment.

Several studies identify tyre particles as the main source of microplastics emissions into the environment, with a share ranging between 11 and 93% (35–85% excluding the min–max values) (Table 1). Some of the variation in the fraction of TWP comes from differences in the microplastics sources taken into account in each study. In many of these studies, the second contributing source accounted for 10 to 29% of the total microplastics emissions. For example, household dust and laundry, 12% [68]; rubber granules, 10% [69]; artificial turf, 18% [70]; synthetic fibres, 29% [71]; road markings, 12%; and pre-production plastics, 12% [48]. Nevertheless, sources such as paints, pellets, packaging, and agriculture are also considered important [17,72,73]. The European Commission completed a cost–benefit analysis of policies for combating microplastics pollution in the European Union. This study identified paints as similar contributor to microplastics emissions in the EU as tyres, with a percentage of approximately 36% [17].

Tyres have been found to also be a major contributor of microplastics at a local level. For example, 53% at a storm water detention reservoir in Sao Paulo, Brazil [74], 41% based on particles captured by spider webs in a medium-sized city in Germany [75], 51% at a road in a German city [76], and 38–39% at medium- and high-traffic sites in the United States [77]. These studies used chemical markers to apportion particles to the source. A study in India in an urban traffic site found a 31% contribution of tyres to road dust particles up to 75 µm [78]. Comparisons of road-deposited sediments at curves or traffic light spots show much higher concentrations of tyre wear particles compared to, e.g., parks [79]. More tyre wear particles were found within roadside drains where driving required increased braking and accelerating than within the drains of roads with high traffic densities [80]. Another study demonstrated that a high traffic volume and high manoeuvring density resulted in higher brake, tyre, and road particle emissions compared to other types of sampling sites [81].

Table 1. Tyres' contribution to microplastics (MP) pollution in various countries.

Year	Ref.	Country	MP Emissions (kt)	Tyres' Contribution to MP Emissions	Tyre Fraction Released to Aquatic Environment
2014	[68]	Norway	8.4	54%	50%
2015	[69]	Denmark	5.5–13.9	56%	12–26%
2016	[61,82]	The Netherlands [1]	5.4–32.9	11–96%	10–18%
2017	[70]	Sweden	10.5–13.5	60–77%	42% [2]
2018	[83]	Germany	330	43%	22%
2018	[64]	Switzerland	87.8	93% [3]	22%
2018	[48]	EU	787	64%	19%
2019	[71]	China	737	54%	10%
2019	[84]	Global	3000	47%	n/a
2022	[85]	Sweden	9.6	85%	n/a
2022	[73]	The Netherlands	7.6	35%	9%
2023	[17]	EU	450	36%	n/a
2023	[86]	Global	800	62%	14%

[1] ranges provide values from the two studies; the high contribution from tyres in one study is because land-based litter fragmentation was not included; [2] value of 42% reported in [83]; [3] also includes end-of-life tyre losses but not paints.

Table 1 also presents the estimated percentages from emitted tyres reaching the aquatic environment (9–50%). These percentages are in line with other studies. For example, a study found that 12–20% of tyre particles in Germany are reaching surface waters [63]. A study in Switzerland reported 22% of tyre particles reaching surface waters [64]. Another study estimated that worldwide, the tyre material ending up in the oceans is 28–46% [3]. A modelling study estimated that the proportion of tyre material transported by European rivers to seas was 42% of total tyre abrasion [87]. Reviews concluded that the relative contribution of tyre abrasion to the total global amount of plastics ending up in the oceans is 5–10% [4,26].

2.2. *Tyres Contribution to Ambient Particulate Matter (PM)*

Overall, road transport is estimated to be responsible for 10–15% of particulate matter below 10 µm in diameter (PM_{10}) [88]. This percentage can be much higher in cities and near roads [89,90] or in closed environments such as tunnels [91,92]. Tyres contribute 5–31% to road transport PM_{10} (based on the overview table in [89]), which, based on the figures reported above, would translate into an overall contribution of tyres to the total PM_{10} of 0.3% to 4.5%. A review found the contribution of tyres to the total PM_{10} to be below 10% in most studies [93]. In addition to the size distribution of tyre particles, the cut-off size of the cyclone or impactor is important. Similarly, the contribution of tyre particles to ambient concentrations of $PM_{2.5}$ (particulate matter below 2.5 µm in diameter) has been estimated to vary between 1 and 10% by mass; however, these values are mostly based on data from 20-year-old studies and indirect calculations from only a few observational studies [93]. Furthermore, the contribution of emitted volatile organic compounds to secondary aerosol formation has not been quantified [94]. Source apportionment studies indicate a contribution from tyres to ambient PM_{10} of 5–6% and a contribution of 0.1–0.4% to ambient $PM_{2.5}$ at traffic sites [24]. Recently, the German Environment Agency (UBA) reported that in Germany, road traffic contributed an overall 13.8% to ambient PM_{10} in 2017, of which tyres had a share of 3.1%. For $PM_{2.5}$, the respective numbers were 18.8% and 4.6% [95]. Similar estimations were also published by the Air Quality Expert Group for the UK [96]. The European Environmental Agency estimated a 4% contribution to PM_{10} and a 2% contribution to $PM_{2.5}$ from tyres [88].

In general, these estimates are in good agreement with field measurements for PM_{10}, whereas for $PM_{2.5}$, field measurements show contributions towards the lower end of the estimations. For example, measurements of airborne concentrations of tyre particles in urban and rural areas of France, Japan, and the United States found 0.6–22% contributions to PM_{10} [97]. Results from the same project (i.e., the Tire Industry Project, TIP) [98] indicated tyre particle contributions of 0.1–0.7% to ambient $PM_{2.5}$ concentrations in the same areas [99]. On-road and laboratory measurements in South Korea revealed that tyre particles accounted for 3–7% of $PM_{2.5}$ and PM_{10} [100]. Similar percentages for PM_{10} (4–6%) were measured in Stockholm (Sweden) [101]. The annual average mass fraction of tyres in PM_{10} was 1.8% at an urban background site in Switzerland and 10.5% at an urban kerbside site [102]. Road dust samples from a highway in Sweden contained more than 10% tyre particles [103]. A study with a single-particle aerosol mass spectrometer roadside of a port highway in China found a 6.6% contribution of tyres to the total PM [104].

In terms of particle number concentration, a study found that tyre particles contributed 4% (in number) to samples of London road dust collected in 2006, decreasing to zero for marine sites [105].

As a point of comparison, based on modelled microplastics emissions and reported traffic emissions, the contribution of microplastics to ambient PM_{10} in EU is estimated at 25% and for ambient $PM_{2.5}$ at 4% [106]. However, as also stated in the report, these values are probably overestimations.

3. Characterisation of Tyre Wear Particles

3.1. Chemical Composition

A typical tyre tread consists of approximately 40–60% rubber polymers, 20–45% reinforcing/filler agents, and 5–15% chemical additives. Two main types of rubber can be found in light-duty vehicle tyres: natural rubber (NR—polyisoprene $[C_5H_8]_n$) and synthetic rubbers, which include styrene butadiene rubber (SBR) and butadiene rubber (BR) [107,108]. NR is the preferred material for high-performance tyres used in aircraft, trucks, and buses [43]. However, this was disputed recently: a study showed that SBR and BR are also present in heavy-duty vehicle tyres, sometimes even at higher concentrations than in some light-duty vehicle tyres [109]. A recent study also highlighted the high variability in natural and synthetic rubber between brands and models [109]. Tables A1 and A2 in the Appendix A summarise reported chemical compositions of heavy-duty vehicle (C3) and passenger car (C1) tyres. For the typical composition of waste tyre feedstock rubber, see elsewhere [110].

Overview studies [4,25,29,106,108] show that a variety of different compounds are added to improve the properties of tyre rubber. Sulphur (and other chemicals such as thiazoles, sulphenamides, selenium, tellurium, organic peroxides, nitro compounds, and azo compounds) are added to vulcanise the rubber and obtain a highly elastic material. Zinc oxide (also calcium, lead, or magnesium oxides) is added as a catalyst (an activator for the vulcanisation process), whereas carbon black is added as a filler and to make the tyre resistant. Over time, these additives have also been modified, e.g., carbon black has been partially replaced by silica to improve the rolling resistance of tyres. Furthermore, oils are added to make the tyre more flexible and control hardness. It should be highlighted that this is a simplistic view of tyre composition: a common-sized all season passenger tyre may contain 30 kinds of synthetic rubber, 8 kinds of natural rubber, 8 kinds of carbon black, and 40 different chemical additives [111]. More detailed information about the ingredients, their role, and their concentrations can be found in [112,113].

Metals in high concentrations are Si, S, Zn, Ca, Al, and Fe [114–120]. Zn is commonly used as a marker for tyre-wear emissions in ambient PM source apportionment studies [25,94,121]. However, the high concentrations of these metals may originate from encrusted material from other sources. A commonly formulated criticism to this approach is that other sources of Zn from traffic sources such as corrosion of crash barriers and brake wear may influence the quality of the source apportionment studies by overestimating the contribution of tyre wear emissions [54].

In addition to inorganic compounds, tyre wear particles contain a large variety of organic chemicals. A recent study identified 214 different organic chemicals in tyres among which 145 were classified as leachable, thus indicating a large potential for transport in the environment [122]. Examples of tyre-derived chemical compounds are benzothiazoles, N-(1,3-dimethylbutyl)-N′-phenyl-1,4-phenylenediamine (6-PPD), 1,3-diphenylguanidine (DPG), and a wide variety of polycyclic aromatic hydrocarbons (PAHs) [123,124]. In ISO standards for the determination of tyre–road wear particles, dipentene is used as a marker for natural rubber, and 4-vinylcyclohexe is used for SBR and BR (e.g., ISO 20593:2017, ISO 21396:2017) [125,126]. Potential markers for tyre wear sources are discussed in relevant publications [26,94]. Older studies found PAHs, including phenanthrene, pyrene, benzo(a)pyrene, benzo(g,h,i)perylene, and indeno-1,2,3(c,d)pyrene, in tyre wear emissions [127,128]. In the EU, the concentrations of PAHs in tyre wear emissions declined after January 2010 due to the implementation of EU Directive 2005/69/EC and European Regulation 1907/2006/EC (REACH), which limit the sum of eight PAHs to 10 mg/kg [129]. Nevertheless, values higher than the limit have also been measured [120,130].

Of the aforementioned substances present in tyres, Zn can be toxic to living organisms [131,132], butadiene is considered carcinogenic to humans [133], benzothiazoles and derivatives are carcinogens and genotoxicants [134], and PAHs are toxic [135] and carcinogenic [136]. Recently, a transformation product of 6-PPD was linked to the acute mortality of coho salmon [137], and the same chemical was shown to shorten the lifespan and health span of Caenorhabditis elegans an in vitro study [138,139].

3.2. Physical Characterisation

The size distribution of tyre wear particles spans a wide range of sizes [25,31] with typical bimodal distribution [115]. Figure 3 presents typical images of tyre particles collected at various sites. More images can be found in the literature [52,102,115,116,140–142]. Typically, based on road samples, the mass distribution peaks at 10–200 µm (mostly 50–100 µm) [56,76,115,143–146]. In the airborne sub-20 µm range, a peak in the 2–10 µm was also found in laboratory studies (see reviews [25,28,31]). In a few cases, a nucleation mode in the 10–50 nm range is measured due to localised high-temperature hot spots on the tyre tread [29,141,142,147,148]. In general, due to the large particles generated, the total suspended matter and the PM_{10} and $PM_{2.5}$ fractions are considered low, as will be discussed in Section 4.3.2.

Regarding morphology, the shape of the large particles is elongated, cylindrical, and "sausage-like". Spherical or round particles are commonly seen, especially in the lower size ranges. Some researchers report that the elongated/round particles appear with variable amounts of mineral encrustation from road material [144]. Irregularly sized particles have also been reported. A recent laboratory study could detect two separate types of tyre wear particles, denoted as firm elastic and sub-elastic, where the sub-elastic type was characterised by the commonly seen cigar shape and embedded mineral grains, while the firm-elastic type was more irregular and knobbly and with superficial mineral encrustations. In the laboratory, the sub-elastic type was vastly more common than the firm-elastic type [149]. The average aspect ratio of particles collected from roadside or tunnel samples is around 1.65 [76,102].

The densities of the different materials typically found in tyres are 5.1 g/cm^3 for metallic particles, 2.7 g/cm^3 for minerals, and 1.2 g/cm^3 for rubber. Road constituents such as bitumen have a density of 1.0 g/cm^3, and road coarse particles have a density of around 2.5 g/cm^3 [53]. Depending on the ratio of tread and road dust particles (see Section 2.1), different densities can be calculated for tyre wear particles. For a highway with little road-encrusted material (<10%), a tyre wear particle density of 1.26 g/cm^3 was estimated [52]. Tyre wear particles (sizes 63–500 µm) collected from road dust near a bus stop had densities in the range of 1.3–1.7 g/cm^3 [107]. Highway or parking lot particles (i.e., tyre wear and others) had densities between 1.55 and 1.94 g/cm^3 [150]. Recent studies found densities of 1.8–1.9 g/cm^3 for tyre wear particles [102,151], but higher values have been reported as well [53,107].

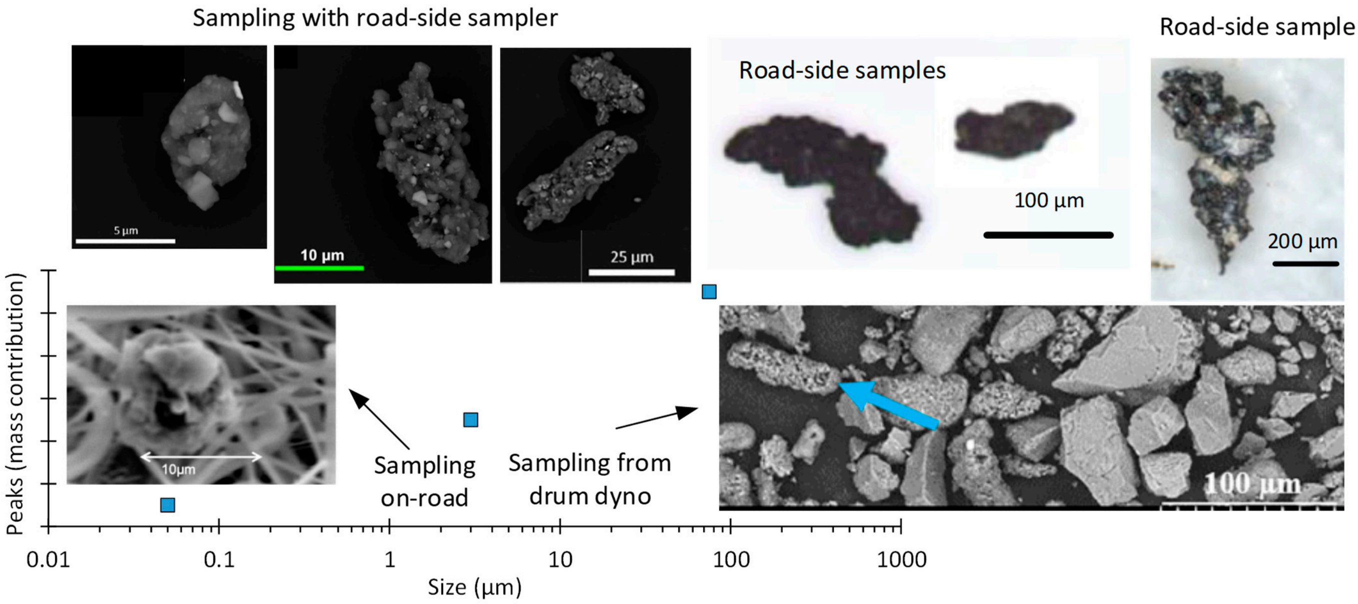

Figure 3. Typical images of tyre wear particles collected on the road, from the roadside with sampler, from a drum dyno, or from roadside dust. Blue squares indicate typical mass size distribution peaks and their relative contributions to the total mass. Sources from smaller to larger particles (all open access articles) are [77,102,107,144,152,153]. The blue arrow indicates a tyre wear particle to distinguish it from the stone particles in the same figure.

4. Emission Factors

4.1. Measurement of Tyre Properties and Emissions

Measurements of PM and microplastics release from tyres can be carried out using various methods [29,115,154]:

- In the laboratory, using (i) road simulators, where one or several wheels are run on real pavement materials (e.g., asphalt), either in a carousel setting [142,155,156] or an inner drum setting [53,148,157]; (ii) an outer drum dynamometer, where one wheel rolls on the outer surface of the drum with a wearing counter-surface, e.g., sand paper [141]; or (iii) a chassis dynamometer on which the whole vehicle is driving [117,158]. Sampling is usually performed in a room for road simulators and drums or behind one tyre in chassis laboratories. Alternatively, the mass loss or tread depth reduction of tyres before and after the test can be determined.
- On-road, near the tyres, using portable devices [100,147,159–163] or by measuring the mass loss (or tread depth) of the tyres before and after the test.
- Roadside, through ambient air sampling using real-time instruments or filters via sampling and analysis [56].
- Directly from road runoff, soil, or water samples [56,76].

The advantage of the laboratory is that the conditions are well controlled and easily repeatable. The disadvantage can be the less realistic movement of the wheels, the low representativeness of real-world driving patterns, and the use of a non-realistic counter surface for the tyres to wear against. On-road sampling has a significant contribution from resuspension or other sources (e.g., brakes) that needs to be considered. In most cases, only a portion of the tyre-derived particles are captured; therefore, researchers must make assumptions regarding proportionality or dilution. For roadside ambient measurements, source apportionment methods need to be applied or specific tyre wear tracers must be used to distinguish tyre particles from other sources (e.g., dust) [24,164,165]. The same applies to samples taken from water or soil. While the first two methods may be used to measure tyre-specific emission factors, they do not consider possible transportation and transformation which may introduce significant errors in the final estimation of the emission factors. On the other hand, the last two methods provide average fleet emissions in the specific collection area; thus, no information about the tyres is available.

The measurement of tyre particles can be performed with real-time instruments or the analysis of particles collected on filters (see also [29]):

- Condensation particle counters (CPCs) for measuring the total particle number concentration from a few nm up to a few µm.
- Electrical particle sizers for measuring the size distribution of particles, starting from a few nm up to <1 µm (e.g., EEPS) or 10 µm (e.g., ELPI).
- Optical particle counters based on light scattering to determine the size distribution of µm particles, typically between 0.3 and 10–20 µm (e.g., OPC, OPS, APS, DustTrak).
- Filter weighing for total mass, and transmission/scanning electron microscope (TEM/SEM) with an energy-dispersive X-ray analysis of filters for morphology and chemical composition are also typically carried out, or pyrolysis–gas chromatography/mass spectrometry (Pyr-GC/MS) techniques are used for tyre wear quantification. Cyclones or impactors are used to classify particles < 10 µm and/or <2.5 µm.
- Tyre weighing before and after a test in order to determine the total tyre material release (i.e., tyre abrasion).

Description and details of the principle of the instruments is out of the scope of this study and can be found elsewhere [166,167]. CPCs have the highest accuracy for counting particles, but do not provide information about the size of particles. Electrical and optical sizers give size distribution and mass concentration in real time, assuming aerosol properties such as density (for electrical sizers), particle shape, or refractive index (for optical sizers). Instruments for roadside, run-off, soil, or water samples are discussed elsewhere [121]. Nevertheless, standardised methods for sampling, preparation, and analysis are still missing. Many assumptions also need to be re-assessed. For example, the International Organization for Standardization (ISO) (ISO/TS 21396:2017(E) and ISO/TS 20593:2017(E)) quantifies tyre wear particles in soil/sediment assuming that the total mass of synthetic and natural rubber in all tyre tread is constant. More specifically, the ISO assumes that the total rubber content is 50% of the mass of the tread and that passenger tyres contain 44% SBR+BR and truck tyres contain 45% NR. However, as was discussed in Section 3.1, there is significant variability in the composition [109]. Similarly, different markers are used to identify and quantify the mass of the tyre tread, but the applied percentages have a high degree of uncertainty as well [121].

4.2. Influencing Parameters

Table 2 summarises the factors influencing on tyre wear and their relative importance, as discussed in various studies [24,29,60,154,168,169]. The classification of the table is based on a summary study [33] carried out under the auspices of the "European tyre and road wear particles platform" [170] but is supplemented with studies that investigated the influence of specific factors on PM or abrasion (such as mass loss or tread depth decrease). PM studies in most cases include road wear particles. Those studies that had contributions from the resuspension of road dust were not considered (e.g., [160]). Theoretical studies were included (e.g., [171,172]). In general, the abrasion rate and the PM emissions depend on the following parameters: (i) tyre characteristics, (ii) vehicle characteristics, (iii) road characteristics, (iv) driving style, and (v) environmental conditions. The factors with the highest impact other than the tyre, which will be discussed in the next section, are lateral and longitudinal accelerations, the road surface, the load of the vehicle, wheel alignment, and the ambient temperature.

One factor that has been studied is the mass of the vehicle (the tyre load). A dedicated study with tyres of the same construction but different sizes and loads demonstrated a linear relationship [173]. This has also been confirmed by other experimental (e.g., [174,175]) and theoretical (e.g., [176]) studies of abrasion. A linear relationship has also been demonstrated for PM [174]. Longitudinal and lateral forces play also a very important role [44]. With at least second-order functions, per force unit, the lateral acceleration is more important [53].

The road surface has also an impact by a factor of at least two [177,178]. The difficulty lies in comparing this factor across different studies. A proposal is to use the standard deviation of the accelerations over a trip. This is included in the proposed method for future tyre regulation to measure the abrasion rate of tyres [179]. Regarding the ambient temperature effect, recent experimental studies showed a decrease in emissions with increasing temperature [180]. However, this is not always the trend [181]; sometimes it depends on the tyre type (summer or winter) [157]. The complex effect of temperature was already discussed in the 1970s and was found to depend on how far the ambient/tyre temperature was from the glass transition temperature [182].

Table 2. A qualitative analysis of the parameters influencing tyre abrasion and PM emission levels, modified from [33] and supplemented with studies that assessed each factor.

Influencing Factor	Impact from	Impact Level on Abrasion	Abrasion	PM
Tyre	Construction and structure	Very high	[183,184]	-
	Tyre size (surface area)	Medium	[185,186]	-
	Summer, winter, studded	High	[168,187]	[155,157,188]
	Treadwear resistance [1]	High	[156,178,189]	[156,189,190]
	Driving distance and aging	Medium	[191]	-
	Tyre pressure	Low/Med.	[171,176,185,192]	[158,193]
	Tyre storage	Low	-	-
Vehicle	Weight (tyre load)	High	[175,176,185,192,194,195]	[116,148,157,159,180,193]
	Suspension (toe angle)	High	[186,195–198]	-
	Suspension (camber angle)	Low	[175,194,195,197,198]	-
	Vehicle control (hybrids)	Med./High	[168,199]	-
Road [2]	Surface (micro and macro)	Very high	[177,178]	[161]
	Material/binder	High	-	[200]
	Road dust loading	Low	-	-
Driving style	Speed	Medium	[116,168,171,185,195]	[116,140,148,152,155,161,180]
	Acceleration, long.	High	[53,168]	[53,116,148]
	Acceleration lat., cornering [3]	Very high	[171,172,176,186,192,194,201]	[141,148,161]
	Braking	High	[116,192]	[116,140,159]
Environment	Ambient temperature	High	[171]	[157,180]
	Humidity/wetness	Low/Med.	[178,186]	-

[1] includes chemical composition; [2] road curvature included in lateral acceleration; [3] includes slip angle variations.

4.3. Emissions Factors of Tyre Abrasion and PM

The amounts of tyre particles emitted during driving of vehicles over a certain period of time or distance are typically estimated using one of the two following approaches: (1) using tyre wear or PM emission factors (EFs) and multiplying by the total distance driven; or (2) determining the mass loss per tyre during its lifetime and multiplying by the number of tyres consumed.

Many studies have summarised emissions factors of tyre abrasion and/or PM_{10} [29,30,202]. However, as a critical review study highlighted, only a few emission factors were based on actual experimental measurements [32]. Furthermore, almost all experimental studies were conducted before the year 2000. For this reason, we searched for recent tyre abrasion measurements to provide more recent and representative emission factors.

4.3.1. Tyre Abrasion

The abrasion rate of tyres is determined experimentally by measuring the difference in the tyre mass before and after driving a specific distance (usually 5000–15,000 km). As abrasion is different at the front- and rear-axle tyres, the sum of all four tyres is typically used. When data are available for one tyre only, assumptions for front- and rear-axle tyres are made: For front-wheel-drive (FWD) vehicles, the average abrasion rate of the front tyres is greater than that of the rear tyres, with front tyre abrasion accounting for between 69% and 85% of the total tyre material lost per vehicle km [108], 63% [168], between 57% and 67% [203], or 61 and 74% [204]. For rear-wheel-drive (RWD) vehicles, the abrasion is higher at the rear wheels, accounting for 71% of the total material lost in one study [205]. The higher degree of wear of front tyres for front-wheel-drive vehicles can be attributed to the higher load and the higher friction forces associated with both steering the vehicle and providing traction [108]. More details about the studies are given in Table 3. It should also be added that the abrasion rate is much higher during the first 1000 km driven, decreasing slowly or even stabilising after 5000 km [203,206]. For example, in one study, the tyres had an abrasion rate of 230–250 mg/km over the first 1000 km; however, the abrasion rate significantly reduced to 44–63 at 7000 km [203].

Table 3 summarises studies published after the year 2000 with on-road testing reporting abrasion rates for passenger cars (expressed per vehicle). Emission factors of studies conducted before the year 2000 are summarised elsewhere [108]. To put the results into perspective, tyres 165/65 R14 and 155/65 R14 are typical for small-size (A and K) car segments, 205/55 R16 is typical for a medium-size car segment, and 235/55 R19 is typical for Sport Utility Vehicles (SUVs). The range of abrasion rates is very broad. For example, for the tyre 205/55 R16, abrasion rates from 25 up to 227 mg/km have been reported, with most values falling in the 50–125 mg/km range. According to the General German Automobile Club (ADAC) [207], the test results can also be transferred to "neighbouring" dimensions within a vehicle class (±10 mm tyre width). For example, the results of a 205/55 R16 91V could apply to a 195/55 R16 91V and 215/55 R16 91V. These are not transferable to run-flat versions of the same tyre (i.e., tyres designed to resist the effects of deflation when punctured).

Many factors can affect emissions, as discussed in Section 4.2; for example, the tyre tread material itself, the load, the ambient temperature, the driving style, and the road characteristics. Table 3 includes additional information that was available for the vehicles, the type of road, and the driving style.

We found no studies on the impact of a vehicle's electrification level on tyre emissions, an important topic based on the rapid increase in electric vehicles [208]. To account for this, most studies assume an increase due to the higher mass of electric vehicles compared to similar conventional ones. There is a positive relationship between vehicle mass and non-exhaust emissions, especially for PM derived from dust resuspension [209,210]. A study showed experimentally that an electric vehicle with a 20% higher mass than two internal combustion engine vehicles had 25–30% higher tyre abrasion [174]. A monitoring study of 76 taxis found, on average, 72 mg/km per vehicle for hybrids and 53 mg/km per vehicle for taxis with only an internal combustion engine [168]. All vehicles in the study were fitted with 205/55R16 94V tyres and had similar curb masses [168]. A sub-group of the data with taxis with only an internal combustion engine yielded 53 mg/km per vehicle for summer tyres, 112 mg/km per vehicle for all-season tyres, and 160 mg/km per vehicle for winter tyres. Such large differences between winter and summer tyres were also reported in other studies (factor 3 to 5 difference) [157], but considering many tyres, the differences seem to be smaller [206]. For example, the differences were <5% for 205/55 R16 tyres [206,211] and 23% for 185/65 R14 tyres [206].

Even though the above-mentioned factors play an important role in the wide range of abrasion rates in Table 3, the characteristics of a tyre itself remain key factors defining the tyre's abrasion rate. This can be concluded from the wide range of abrasion values, even when tests were conducted in the same facilities. For example, the ADAC found a range of 82–151 mg/km for 15 summer tyres, 205/55 R16, tested in 2021 [206] and a range of 56–202 mg/km for 50 similar tyres tested in 2023 [212]. This clearly shows that there can be a factor of at least two between low- and high-emitting tyres with similar characteristics.

It is difficult to derive an average value for the fleet as this depends not only on the measured value but also on the share of the tyres in the market (and the distance travelled). Nevertheless, the fact that the specific tyres (of Table 3) have been measured indicates that they are commonly used in their respective markets; 205/55 R16 tyres cover around 13% of the market [213]. Based on a survey to relevant stakeholders, the most popular sizes per tyre class are as follows [38,214]:

- C1: 205/55 R16, 225/45 R17, 195/65 R15, 175/65 R14, 225/40 R18, and 225/60 R16;
- C2: 215/65 R16, 235/65 R16, 205/65 R16, 205/75 R16, and 225/65 R16;
- C3: 315/80 R22.5, 315/70 R22.5, 385/65 R22.5, 295/80 R22.5, and 385/55 R22.5.

Table 3. Abrasion rates of various tyres determined from on-road tests.

Year	Ref.	No. of Tyres × Types of Tyres	Vehicle	Abrasion (mg/km)	Comment
2013	[41]	1 × 175/70 R13	n/a	127	Data (per tyre) from the Russian Federation, based on mass loss and average travelled distance. Multiplied by four, assuming that they were based on both front and rear wheels. Exact number of vehicles is not provided.
		2 × 185/60&70 R14		132	
		1 × 195/65 R15		149	
		4 × 205/60-70 R14&15		141 (125–154)	
		1 × 215/65 R16		119	
2004	[108]	195/65 R15	FWD	56	36,000 km (motorway), 90–94 km/h
		185/65 R14	FWD	67	40,370 km (motorway), 65–75 km/h
		145/80 R13	RWD	86	11,300 km (urban), 43–51 km/h
		185/65 R14	FWD	193	3665 km (urban), 60–64 km/h, misaligned wheels
		175/70R	FWD	85	15,000 km (rural), 61–66 km/h
2022	[174]	205/55 R16	Gasoline 1370 kg	158	Based on tread depth loss; 550 km test track with asphalt concrete (KS F 2349, b19 mm). 50 km/h (3 h), 80 km/h (2 h), and 110 km/h (2 h).
			Diesel 1395 kg	168	
			Electric 1665 kg	202	
2022	[168]	205/55 R16 94	ICEs	72 (36–105)	Based on tread depth loss; 76 taxis in Rome (Italy) and Athens (Greece). Hybrids (Toyota-Auris) and ICEs (Škoda Octavia) had a similar curb mass.
			Hybrids summer	53 (26–91)	
			Hybrids M + S	112(56–175)	
			Hybrids winter	160 (109–180)	
2022	[215]	18 × (models)	Mercedes C-class [1]	67 (38–161)	5000 km (motorway) in U.K.
2021	[204]	6 × 205/55 R16 91	Peugeot 308	37–63	15,000 km (65% rural, 30% motorway) in France 71 km/h, LoAS 0.68 m/s^2, LaAS 0.87 m/s^2
2022	[203]	2 × 205/55 R16 91	VW T-Roc	217–227	7000 km (39% motorway, 31% rural) in Spain
2021	[211]	4 × 205/55 R16 [S]	VW Golf 8	91 (70–115) [2]	France and Germany up to 24,000 km, at temperatures from 7 °C to 25 °C (summer tyres) and 4 °C to 16 °C (winter tyres).
		6 × 205/55 R16 [W]	VW Golf 7	94 (58–163) [2]	
		2 × 235/35 R19 [S]	VW Golf 8	92 (59–123) [2]	
2022	[206]	14 × 185/65 R15 [S]	VW Polo	89 (58–126)	15,000 km (55% rural, 40% motorway) in Germany, 85 km/h average speed
2019		16 × 185/65 R15 [S]	VW Polo	93 (59–124)	
2019		16 × 185/65 R15 [W]	VW Polo	109 (85–109)	
2021		15 × 205/65 R16 [S]	VW Golf 7	118 (82–151)	
2020		15 × 205/65 R16 [W]	VW Golf 7	121 86–149)	
2016		7 × 205/65 R16 [M + S]	VW Golf 7	117 (82–152)	
2020		16 × 225/40 R18 [S]	VW Golf 7	130 (115–157)	
2021		16 × 195/65 R15 [W]	VW Golf 7	139 (100–171)	
2023	[212]	50 × 205/65 R16 91 [S]	(VW Golf 7)	125 (56–202) [2]	35× on a drum, 19× on-road
2023	[216]	5 × 245/45 R19 102 [S]	BMW X1, iX1	171 (134–202) [3]	15,000 km (50% rural, 35% motorway) in France

[1] RWD; [2] assuming 1.6 t vehicle mass; [3] assuming 2.28 t vehicle mass. FWD = front-wheel-drive; ICE = internal combustion engine; LaAS = lateral acceleration standard deviation; LoAS = longitudinal acceleration standard deviation; M + S = mud and snow; RWD = rear-wheel-drive; S = summer; W = winter. Example: 50 × 205/65 R16 91 [S] means 50 summer [S] tyres were tested with 205 mm width, a 65% aspect ratio (distance between the wheel and the edge of the tyre to the to the tyre width), radial R construction, a 16-inch rim size (internal diameter of tyre), and a 91 load index (=615 kg).

The mean value of all values in Table 3 is 110 mg/km per vehicle (n = 303). Based on assumptions of the mass of the vehicles, (in most cases, 1.6 t), this corresponds to 68 mg/km/t. The same numbers are calculated even when considering only the studies from 2019 (n = 289). As mentioned above, this value is not necessarily the true average of all tyres in the market. This would need a proper market assessment with measurements. Nevertheless, it should be representative for the majority of the market. Figure 4 presents the data in Table 3 in graphical form separately for each country in which the measurements were obtained (not necessarily the origin of the tyres). All sizes and types of tyres were mixed. The mean of the countries mean is 118 mg/km (73 mg/km/t) when considering all countries and 100 mg/km (58 mg/km) when considering only European countries. Emission inventories provide a value of 57.3 mg/km/t [209]. These values are in agreement with the rough approximation that a 10 kg tyre loses 10% of its mass after 40,000 km of use, which results in an abrasion rate of 100 mg/km per vehicle.

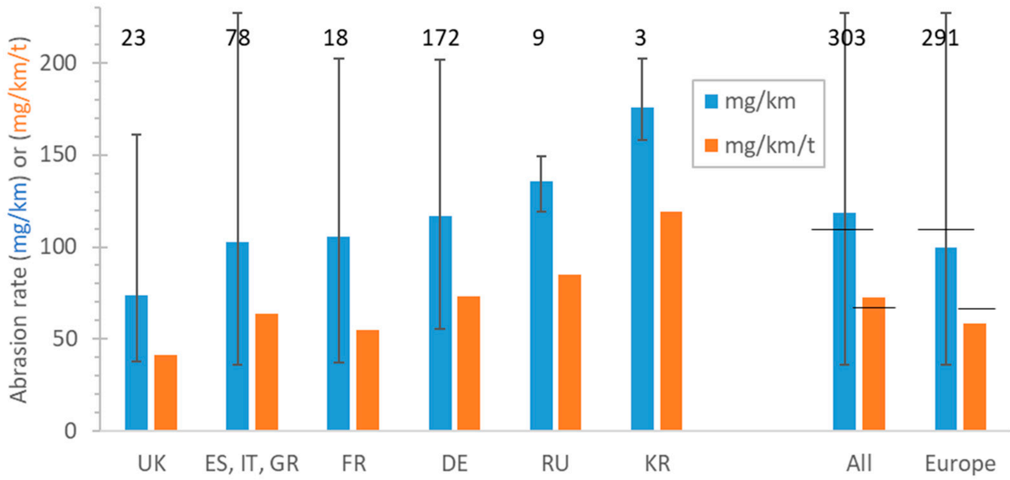

Figure 4. Summary of abrasion rates in various countries. Error bars show min–max. Numbers indicate the number of tyres. The small horizontal lines indicate the weighted mean of all studies.

There are no measurements for light commercial vehicles and heavy-duty vehicles (trucks and buses) after the year 2000 except for data that were submitted by the Russian Federation at the Working Party on Pollution and Energy (GRPE) of UNECE in 2013 [41], where values of 257–370 mg/km per vehicle for light commercial vehicles (six tyres) and 950–1200 mg/km per vehicle (six tyres) or 1270–1770 (eight tyres) for heavy-duty vehicles were reported. Another study from Russia cited abrasion rates of 130 mg/km for passenger cars and 320–1500 mg/km for (light) trucks and buses; however, the details of the previous study are not described [217]. A study in South Korea, assuming around 94,000 km before the replacement of tyres losing 14% of their mass (25 kg), estimated 224 mg/km for light commercial vehicles (6 tyres) [46]. For buses and trucks, the estimations were 799 mg/km per vehicle (six tyres) and 949 mg/km per vehicle (eight tyres), respectively. These values correspond to 2.5 times higher emissions (in mg/km) for light commercial vehicles and 8–11 times for heavy-duty vehicles than passenger cars. However, the differences in mg/km/t and tyre are expected to be much smaller.

4.3.2. PM

The on-road determination of PM is difficult due to the influence of other sources (background, brakes, road, and resuspension). Thus, PM emissions are based on laboratory measurements or an estimation of the PM fraction from the total tyre abrasion.

A review in 2014 concluded that the ratio of PM_{10} to total abrasion is less than 10% [25]. Another recent study [162] argued that this ratio (PM_{10} to total tyre abrasion) is even smaller: 1.5% on average; this value is in agreement with recent studies (1.5% [141] to 3% [152]). In general, PM_{10} is assumed to be 2–10% of the total tyre abrasion [25,26,57,59]. Table 4 provides the percentages that have been measured in the literature. The mean value is 2.5% or 1.9% weighted with the number of tyres tested in each study. For $PM_{2.5}$, the values were 1.6% and 1.0%, respectively.

Table 4. Particulate matter (PM) values (per tyre) and ratios.

Year	Ref.	No. of Tyres	PM_{10} mg/km	PM_{10}/ Abrasion	$PM_{2.5}$ mg/km	$Pm_{2.5}$/ Abrasion	$PM_{2.5}$/ PM_{10}	Comments
2005	[188]	2	(9–11)	-	1–2	-	0.11	Road simulator
2010	[181]	3 types	{0.9}	-	-	-	-	Up to 350 mg/km [1]
2013	[100]	1	-	-	-	-	0.73	On-road

Table 4. *Cont.*

Year	Ref.	No. of Tyres	PM_{10} mg/km	PM_{10}/ Abrasion	$PM_{2.5}$ mg/km	$Pm_{2.5}$/ Abrasion	$PM_{2.5}$/ PM_{10}	Comments
2018	[156]	5	-	-	-	-	0.45	Road simulator
2018	[141]	4	(0.05)	1.5%	0.04	1.2%	0.82	Drum, abrasion 3.4 mg/km
2018	[116]	1	(0.01)	0.3%	0.00	0.1%	0.55	Drum, abrasion 3–9000 mg/km
2019	[218]	5	-	-	-	-	0.70	Drum
2020	[130]	4	1.9	-	-	-	-	Road simulator
2021	[180]	1	-	-	-	-	0.25	Abrasion device
2021	[152]	1	1.7	3.7%	1.3	3.3%	0.76	Drum-like
2022	[174]	3	2.2	-	0.4	-	0.16	Drum [2]
2022	[189]	4	0.9	-	0.2	-	0.23	Drum
2023	[162]	3	-	2.4% [3]	-	0.2%	0.08	On-road
2024	[219]	9	0.4	-	0.1	-	0.15	Drum
Average			2.2 (1.4) [4]	2.5%	0.5	1.6%	0.42	
Weighted average			1.9 (1.1) [4]	1.9%	0.3	1.0%	0.37	

[1] the value in {...} not considered in the analysis. The value of the summer tyre was calculated using a factor of 100 less than the studded tyre, based on the graphs of the study and dividing by four; [2] the values reported for vehicles were divided by four; [3] the original study assumed an abrasion rate of 120 mg/km, so the percentages were recalculated using 110 mg/km; [4] the value in parenthesis (...) was calculated without the studies with values in parenthesis (too high or too low PM).

The ratio of $PM_{2.5}/PM_{10}$ for tyre particles used in the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook is 0.70 (70%). A laboratory study reported a ratio of 80% [141], while others reported values around 35–55% [156,193] or even lower (<15%) [174,188,219]. An atmospheric study reported values ranging widely between 1% and 100%, with most of the calculated ratios being smaller than 20%. The same study found that in a ring road in Tokyo, the PM_{10} concentration included only particles in the $PM_{2.5}$ size fraction [99]. However, the $PM_{2.5}/PM_{10}$ ratio from ambient air studies can be affected by factors such as road wear, resuspended soil-dust, long-distance dust transport, coal mining and processing industries in the vicinity, and other mechanical activities. Based on all experimental studies (Table 4), the $PM_{2.5}/PM_{10}$ ratio is around 40%.

The emission factor for the tyre PM_{10} used in inventories is 5.8–8.7 mg/km per vehicle for motorway and urban driving [220]. One of the latest reviews from 2021 [28] cited similar studies with older reviews in 2014 [25], and the most recent studies cited were published in 2013 for tyre wear, indicating a lack of new research. The last review in 2023 [29] additionally included a study of 2020 [130]. That study [130] measured a tyre PM_{10} emission factor of 2 mg/km, and other recent ones [141,219] almost ten times lower. Another laboratory study found low levels that were increasing significantly with increases in longitudinal or lateral forces [53]. Roadside measurements (from passing vehicles 5% were heavy-duty vehicles) estimated fleet average tyre PM_{10} emissions of 10–11 mg/km [221]. Table 4 summarises research after the year 2000 and provides an average PM_{10} emission value per tyre of 1.9–2.2 mg/km or 1.1–1.4 mg/km, excluding studies with max and min values. Applying the 2.5% PM_{10} to the total abrasion and 110 mg/km abrasion rate results in PM_{10} emissions around 2.7 mg/km per vehicle, which is similar with the average value for one or two tyres. This discrepancy could be due to instrumentation (the mass was calculated with real-time instruments and not filters) and the methodology (cycles, loads, laboratory, surface, etc.). This difference highlights the need for more dedicated studies on the topic.

4.3.3. Particle Number

Tyre particle number emission factors are even more scarce. One of the first studies using the road simulator method reported values of 3.7×10^{11} to 1.1×10^{12} #/km per vehicle at 50 and 70 km/h for non-studded tyres [142]. However, there was a distinct semi-volatile nucleation mode (<50 nm). Another laboratory study measured particle concentrations of 1.1×10^5 #/cm^3 at 80 km/h straight driving (peak at 50 nm), which results in an emission factor of 2.5×10^{10} #/km/tyre at the given flow rate [141]. A laboratory study found various levels of emissions depending on the longitudinal and lateral acceleration applied, but the levels were below 10^{10} #/km [53].

An on-road study could hardly distinguish tyre particle emissions from background levels, and only at 120 km/h could an upper limit of up to 1×10^{11} #/km per vehicle be estimated [147]. Under extreme conditions, i.e., full-stop braking, extreme cornering, or a racing start, ultrafine particles peaking between 30 nm and 60 nm could be measured. A recent on-road study found average emission levels of 0.9–1×10^{10} #/km per tyre between 50 and 80 km/h after subtracting road dust particles' contribution [161]. The distribution was bimodal, with one of the peaks < 30 nm. Other researchers reported values between 1.1×10^{11} #/km (for particles > 23 nm) and 1.45×10^{12} #/km (for >6 nm) per vehicle; however, the experimental details were not given [215].

Not all studies found a separate nucleation mode (e.g., [130,181]), but the previously mentioned studies and others [130,141,156] showed that it is not rare as well. Furthermore, the reported numbers include both solid and volatile particles. For example, particle number emissions from one tyre, measured on the chassis dynamometer, were 3.3×10^9 #/km/tyre and ~0.6×10^9 #/km/tyre with hot sampling, illustrating a strong contribution of volatile particles [158]. The size distribution had a peak at 10–20 nm, and interestingly, even when heated at 180 °C, a peak at 30 nm remained. Higher emissions were observed on the road due to the influence of background particles. All previous reported values from on-road tests included road wear particles and resuspension, which can be a significant portion of total emissions. For example, in emission inventories, road wear particles are at the same level as tyre abrasion in terms of mass [222]. A review also found similar levels of tyre and road wear PM emissions [28]. An on-road study sampling behind the wheel of a vehicle found that tyre abrasion particles were <27% of total measured particles (including brakes and resuspension) in terms of number and 65% in terms of mass [161]. An analysis of a roadside sample from a bus stop found that asphalt particles were more than tyre abrasion particles [107].

In conclusion, based on all the above values, an emission factor of around 2–10×10^{10} #/km per tyre is calculated. Keeping only the studies after 2010 (except the one without experimental details), the mean value becomes 1×10^{10} #/km per tyre.

5. Mitigation Measures

In order to reduce the health and environmental risks of a pollutant, it is important to address its sources, release and emission pathways, and further fate and transport which, in the end, will determine the exposure effect [34]. The available options to mitigate tyre abrasion pollution can be broadly categorised as follows [106,223–225]:

- Preventing or reducing the formation of particles (source: road–tyre interaction);
- Collecting particles upon emissions (release: vehicle and road);
- Reducing exposure and treating particles (transport: atmosphere, run-off).

Another important aspect is the management of waste tyres, which is outside the scope of this paper [226–228]. On one hand, recycling waste vehicle tyres into crumb rubber has many applications (e.g., turf fields, playgrounds, or road asphalt pavement) [228]. On the other hand, there are concerns about the environmental and human health effects from some of the substances in waste tyres [229,230]. A short overview follows. Detailed discussion of mitigation measures is out of the scope of this paper. The interested reader can consult relevant reviews [28,225].

5.1. Reducing the Formation of Tyre Abrasion Particles

A reduction in the formation of tyre abrasion particles can be achieved either with technological or management measures. In all cases, directly or indirectly, these measures aim to reduce one or more of the factors discussed in Section 4.2.

- Technological measures: improved tyres (material resulting in reduced abrasion, the elimination of vent spews), road surface improvement, reduced vehicle mass, and speed/acceleration limiters.
- Management measures: traffic flow and volume (smooth driving, cornering, braking, and traffic flow, e.g., with support of Driver Assistance Systems), reduced total km driven, improved road maintenance, fleet maintenance (tyre pressure, tyre selection, wheel alignment), educational measures (the use of public transport, communication about environment friendly choices, and driving behaviour adaption), economic measures (e.g., taxation), and regulatory measures.

5.2. Collecting Particles upon Emissions

This category includes solutions such as tyre particle collectors [231] and constructing road surfaces as a trap for particles [232–236]. These measures reduce resuspension and particles reaching sewers and road runoff [237].

5.3. Reducing Exposure and Treating Particles

This category includes measures such as planting vegetation [234], street cleaning (e.g., sweeping or washing with water or chemical dust suppressants) [238], and treating road runoff (e.g., adding retention basins or improving wastewater treatment plants) [239]. For example, increasing the distance between cycle lanes and traffic can reduce cyclists' exposure [240], or vegetation barriers can reduce roadside concentrations [241]. Sweeping the material collected in, e.g., gutters or streets, will reduce the concentration arriving in the soil and aquatic environment. Street cleaning also has the potential to reduce resuspension and consequently ambient PM levels [242].

5.4. Discussion of Possible Measures

An obvious measure is the development of materials with greater abrasion resistance and which are sustainable, more environmentally friendly, and less toxic [243–245] without compromising comfort and safety [246]. Although the proposals in the previous sections are a good starting point, the exact impact on final emissions or exposure is not clear. For example, a road surface can be optimised for tyre abrasion, but it could have a negative impact on road wear or even safety issues (i.e., less grip). For some other measures, the impact is well known (e.g., vehicle mass), but the implementation is not straightforward since market trends currently favour heavier vehicles such as SUVs and electric vehicles. Although a reduction in vehicle-km travelled will reduce emissions, road transport activity is expected to increase [247]. Other non-tyre technologies (e.g., tyre particle collectors) are still in early development. Street cleaning addresses road dust in general [28,31,238], but its efficiency depends on many parameters (e.g., road configuration, the machine used, and amounts of deposited dust). Thus, it could be applied in streets with a high dust load (e.g., near construction sites). It should be also noted that particle collection or trapping does not necessarily solve the primary problem of material release into the environment: bad practices (e.g., saturated filters that are not cleaned, methods of disposal which are not environmentally friendly) will decrease the benefits.

A recent study proposed that management and treatment strategies can reduce tyre wear emissions by 70% [248]. Other studies [224,225] concluded that among the measures with the highest potential to reduce pollution caused by tyre and road wear are the following:

- Improved driving practices: avoiding strong accelerations, heavy braking, and fast cornering; choice of tyres adapted to environmental conditions; correct tyre pressure; and correct wheel alignment.
- Wear-resistant materials (without compromising safety or noise) and/or technologies capturing emitted particles.
- Reduced road traffic (relevant not only for tyre abrasion but also for road dust resuspension reduction): taxation, fees, and subsidies or incentives can help reduce the use of vehicles and/or increase the use of public transport.
- Street cleaning and road runoff treatment systems at hot spots (not only for tyre abrasion but also for road dust resuspension reduction).

In most reviews, the standardisation of measurement (analytical) procedures was recommended, as was better communication (knowledge sharing and collaboration) between countries and stakeholders.

6. EU Regulation

Various regulations cover the lifespan of tyres, i.e., from raw materials and production to use, end-of-life, and repurposing [227]. Different materials are used to produce a tyre (see Section 3.1). During the use of tyres, various compounds (PM, metals, volatile organic compounds, etc.) are emitted to the environment (Section 2.1). Worn tyres are recirculated back as end-of-life tyres through different recycling management systems in the EU. Recycling is the preferred option, either as material recovery (for artificial turfs, rubber modified asphalt, etc.) or de-vulcanisation (to obtain rubber for new tyres) [226]. Retreading (removing the old tread and applying a new one) truck tyres is also common [226]. UNECE Regulations Nos. 108 and 109, which are compulsory in the EU, deal with retreaded tyres.

Table 5 summarises the European Union's regulations regarding tyres. As can be seen, none directly target the contribution of tyre particles and their chemical constituents to the environment. The interested reader can find more information elsewhere [227].

Recent initiatives aim to introduce limits for tyre emissions. The proposed Euro 7 regulation includes limits on the tyre abrasion rate for light-duty and heavy-duty vehicle tyres; however, the limit values are yet to be defined. The corresponding testing methodology is under development by the UNECE task force on tyre abrasion (TFTA) under the working parties on noise and tyres (GRBP) and pollution and energy (GRPE). The proposed measurement methodology for tyre abrasion for passenger car tyres was submitted in November 2024 to amend United Nations regulation No. 117 [179]. The suggested methodology is based on the mass loss of the tyres (thus determining only tyre abrasion) after on-road driving under typical urban, rural, and highway driving conditions. The option using the drum method with a pre-determined vertical load and lateral and longitudinal force profiles is also included. The work will proceed with market assessment and determination of an appropriate level for a tyre abrasion rate limit in order to reduce the emission of microplastics into the environment.

Regulation EU 2020/740 on tyre labelling includes a provision to include information for tyre abrasion and service life (durability) on the tyre label as soon as appropriate methods to test and measure tyre abrasion and mileage will be available for use by European or international standardisation organisations. The proposal is to use tread depth measurements during tyre abrasion rate tests, and projections will provide indications of the tyre's service life. A similar method exists for the treadwear index in the United States [40].

Table 5. Existing European Union (EU) regulation relative to the various life cycle stages of tyres (given as titles in bold) [226,227,249].

Regulation	Comments
	Raw materials
EU Critical Raw Materials Act [250]	Refers to critical raw material supply disruption and vulnerabilities. Natural rubber is recognised as a critical raw material.
	Production of synthetic rubber and tyres
Directive 2010/75/EU	Industrial Emissions Directive: polymers are considered PLCs
Regulation 1907/2006 (European chemical legislation REACH)	Manufacturers and importers must register substances of REACH list (PLCs are exempted) SVHCs with concentr. > 0.1%, quantity > 1 t/year are registered to ECHA [1]
Directive 2005/69/EC	Max 1 mg/kg BaP or 10 mg/kg of the sum of the 8 listed PAHs
	Use
Regulation EU 2019/214	General safety of motor vehicles
Directive 2004/107/EC	BaP in air < 1 ng/m^3 in PM_{10} averaged over a year
Directive 2008/50/EC	Ambient Air Quality (AQ) standards for PM_{10} and $PM_{2.5}$ and metals
Directive 2016/2284/EU	National Emissions reduction Commitments (NEC) emission reduction commitments for Member States and the EU for $PM_{2.5}$ [2]
Regulation EU 2019/214	Tyre pressure monitoring systems (TPMSs) have been mandatory since 2012
Directive 2014/45/EU	Wheel alignment control is part of regular vehicle inspections
Regulation EU 2020/740	Tyre labelling on fuel efficiency (rolling resistance), safety (wet grip), and noise reduction
Directive 2000/60/EC	Water Frame Directive priority list (tyre substances such as 6-PPD, aniline, and benzothiazole are not included)
	End of life and repurposing
Directive 1999/31/EC	Prohibits landfilling waste tyres
Directive 2000/53/EC	Prevents waste from vehicles and their components (incl. tyres) [3]
Decision 2000/532/EC	Rubber waste is non-hazardous
Regulation EC 1907/2006	<20 mg/kg PAHs in granules used as infill

[1] a ban of microplastics used as infill material on artificial turf pitches was recommended. [2] information also for PM_{10}; heavy metals; PAHs should be provided. [3] under the Green Deal and the new Circular Economy Action Plan (CEAP), the legislation on end-of-life vehicles was reviewed [251]. BaP = Benzo(a)pyrene; ECHA = European Chemicals Agency; PAHs = polycyclic aromatic hydrocabons; PLC = polymer of low concern; PM = particulate matter; REACH = registration, evaluation, authorisation and restriction of chemicals; SVHC = substance of very high concern.

Regulation EU 858/2018 introduced the mandatory compliance verification of motor vehicles, components and separate systems for both Member States and the European Commission. Regulations relevant to tyres under the framework set out by Regulation EU 858/2018 are mentioned below. The safety and environmental performance of tyres are regulated by Regulation (EU) 2019/2144 to guarantee minimum performances of tyres of cars, vans, trucks, buses, and trailers. The regulation refers to the following:

- UNECE Regulations Nos. 30 and 54 regarding pneumatic tyres on passenger cars, light commercial vehicles, and their trailers, respectively.
- UNECE Regulation No. 117 regarding rolling sound emissions, adhesion on wet surfaces, and rolling resistance.
- Regulation EU 2020/740 on tyre labelling.
- UNECE Regulation No. 142 on the installation of tyres on cars, vans, trucks, buses, and trailers.
- Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability, and recoverability implements the end-of-life vehicle directive (Directive 2000/53/EC).

7. Conclusions

Tyre abrasion is considered the main contributor to microplastics emissions into the environment (>35% at all studies). More than 0.5 million tonnes of tyre particles per year are emitted in Europe, and 6 million tonnes are emitted globally. Tyre particles are generated by shear forces between the tread and road or volatilisation. The mass distribution of emitted tyre particles is usually bimodal, with peaks at around 20–200 μm and at 2–10 μm. Tyre particles contribute to around 5% of ambient PM concentrations on average, with studies reporting values between 0.2% and 22% depending on various parameters. Even though many studies find a separate nucleation mode, which is high in particle number concentration, the contribution to the overall mass is negligible.

The previously mentioned estimates have high variability for various reasons. On one hand, emission rates depend on many parameters such as the tyre, road, the vehicle, driving style, and environment. On the other hand, different protocols and methodologies have been used. Abrasion rates can be determined by weighing the tyres before and after driving long distances and several thousand km. PM can be determined by sampling close to the wheel. For on-road tests, background particles, resuspension, road wear, or brake particles can interfere with measurements. In the laboratory, driving patterns and/or the pavement surface are not necessarily realistic. The instrumentation principles (optical, electrical counters, etc.) and the assumed particle properties can also influence the results. Roadside sampling can determine only fleet emissions for the specific region and specific period. Finally, source appointment also has uncertainties due to the lack of robust tyre markers and reference concentrations in the tyres.

Although there is a lack of high-quality data on emission factors and virtually no data for motorcycles, light commercial vehicles, and heavy-duty vehicles (buses and trucks), we derived a mean value of 110 mg/km or 68 mg/km/t for passenger cars based on our review of recent 300 on-road measurements of tyre abrasion. Based on a limited number of studies with differences in protocols and methodologies, the PM_{10} to total abrasion (wear) ratio was found to be around 2.5%, whereas the $PM_{2.5}$ to PM_{10} ratio was calculated to be around 40%. Emission factors per tyre were found to be around 1.4–2.2 mg/km for PM_{10} and on the order of 10^{10} #/km for the particle number.

To mitigate the impact of tyre particle pollution, the main approaches are (i) to reduce the formation of particles, (ii) to collect them after their formation, and/or (iii) to reduce exposure. Technological (e.g., improved tyres) and management measures (e.g., better fleet maintenance, traffic control, and smooth driving) can reduce the release of tyre particles into the environment. The determination of the potential of each measure needs better quantification. Measures of all three types are relevant; it remains to be seen which ones are most effective. A further cost–benefit analysis of these measures is needed.

Currently, the only regulations affecting tyre emissions directly are (i) the restriction of polycyclic aromatic hydrocarbons (PAHs) in oils during the production of tyres and (ii) the proposal for tyre abrasion rates in the upcoming Euro 7 regulation. However, the latter is still in the preparation phase, and it will take a few years before specific limits are defined for the different tyre categories.

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Appendix A

Tables A1 and A2 summarise chemical compositions of heavy-duty vehicle (C3) and passenger car (C1) tyres as reported in the literature. There are not many recent data, and the exact composition is not known.

Table A1. Composition of heavy-duty vehicle tyres (C3), as reported in the literature (percentages by mass). "Year" refers to the year the studies assessed the chemical composition. "Market" refers to the country in which the tyre was assessed for its composition (not the origin of the tyre).

Compound	**Year** **Market** **Ingredients**	**n/a** **U.S.** [252]	**2006** **EU** [111,253]	**2012** **Japan** [1] [254]
Rubber/ Elastomer	Natural rubber Synthetic rubber	34% 11%	45%	37–39% 10–11%
Fillers	Carbon black Silica others	24%	22% n/a n/a	23–25% 0–1% n/a
Process oils	Mineral oils	n/a	n/a	1%
Vulcanisation agents	ZnO Sulphur Others	n/a	2% 1% n/a	2% 1% n/a
Additives	Preservatives, antioxidants, etc.	10%	5%	n/a
Reinforcement agents	Textile fibres Steel wire	0% 21%	0% 25%	0% 21–22%

[1] 275/80R22.5 (55.5 kg). n/a = not available.

Table A2. Composition of passenger car tyres (C1) as reported in the literature (percentages by mass). "Year" refers to the year the studies assessed the chemical composition. "Market" refers to the country in which the tyre was assessed for its composition (not the origin of the tyre).

Year **Market** **Ingredients**	**n/a** **n/a** [26,52,108]	**n/a** **U.S.** [252]	**1994** **Sweden** [255]	**1998** **Germany** [256]	**2006** **EU** [111,253]	**2012** **Japan** [1] [254]	**2013** **Germany** [2] [257]	**2016** **EU** [61]	**2018** **Algeria** [3] [258]
Natural rubber Synthetic rubber	40–60%	19% 24%	40–60%	48–57%	45%	20–23% 26–31%	41%	17% 24%	44%
Carbon black Silica Others	20–35%	26%	20–35% [4]	23–33%	21.5% n/a n/a	20–25% 1–8% n/a	30%	18% 11% n/a	24%
Mineral oils	12–15%	n/a	15–20%	5%	n/a	4–5%	6%	7%	n/a
ZnO Sulphur Others	1–5%	n/a	1.5% 1% 1.5%	1% 1% n/a	1% 1% n/a	2% 1–2% n/a	6%	1% 1% n/a	1% 1% n/a
Preservatives, antioxidants, etc.	5–10%	14%	2%	3–8%	7.5%	n/a	2%	2%	11%
Textile fibres Steel wire	- [5]	4% 12%	- [5]	3% 18%	5.5% 16.5%	4–5% 11–12%	15%	n/a 12%	2% 18%

[1] 195/65R15; [2] 205/R16 (8.5 kg); [3] scrap tyres; [4] including reinforcement agents; [5] values refer to the tyre tread. n/a = not available.

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