

Airborne Tire Wear Particles: A Critical Reanalysis of the Literature Reveals Emission Factors Lower than Expected

Siriël Saladin,* Adam Boies, and Chiara Giorio*

Cite This: *Environ. Sci. Technol. Lett.* 2024, 11, 1296–1307

Read Online

ACCESS |

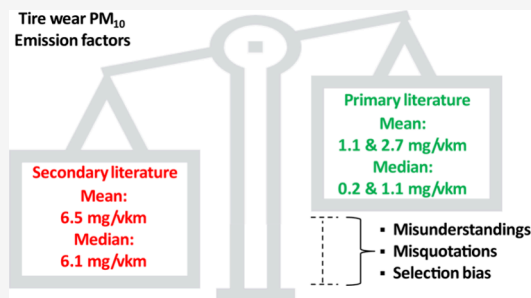
Metrics & More

Article Recommendations

Supporting Information

ABSTRACT: Tires are a ubiquitous part of on-road transport systems serving as the critical connecting component at the interface of the motive power and road surface. While tires are essential to automobile function, the wear of tires as a source of particulate air pollution is still poorly understood. The variety of reported emissions found in the secondary literature motivated us to summarize all known mass-based tire wear emission factors for light-duty vehicles in primary research. When excluding road wear and resuspension, mean emissions of 1.1 mg/km/vehicle (median 0.2 mg/km/vehicle) were found for tire wear PM₁₀ and mean emissions of 2.7 mg/km/vehicle (median 1.1 mg/km/vehicle) when including studies with resuspended tire wear. Notably, these factors are substantially lower than broadly cited and accepted factors in the secondary literature with mean emissions of 6.5 mg/km/vehicle (median 6.1 mg/km/vehicle). As revealed by our analysis, secondary literature reports emission factors systematically higher than those of the primary sources on which they are based. This divergence is due to misunderstandings and misquotations that have been prevalent since the year 1995. Currently accepted mass-based emission factors for directly emitted airborne tire wear particles need revision, including those from the United States Environmental Protection Agency and the European Environment Agency.

KEYWORDS: nonexhaust emissions, microplastics, tire abrasion, tire debris, particulate matter, PM₁₀, TWP, TRWP



1. INTRODUCTION

The World Health Organization estimated a global mortality of 4.2 million premature deaths due to outdoor air pollution for the year 2019.¹ This number related to particulate matter matches the estimated mortality of dementia² (1.62 million including Alzheimer's disease), road traffic injuries³ (1.19 million), suicides⁴ (700,000), and malaria⁵ (608,000) combined, prompting governments to regulate particulate matter with aerodynamic diameters smaller than 10 μm (PM₁₀) and 2.5 μm (PM_{2.5}). Road transport is reported to account for 11% of the total PM₁₀ primary emissions in the European Union, with tire wear as a relevant source.⁶ Tire wear emissions are expected to increase because of a persistent trend toward heavier vehicles in conjunction with transport electrification.^{7,8} As a result, the European Commission announced the intention to regulate tire wear emissions as part of the upcoming Euro 7 standards, which will be the first emission standard worldwide to move beyond regulating tailpipe emissions.⁹

The prevalence of tires and lack of alternative technologies motivates the study of tire wear as an aerosol emission source and eventually as a health risk, given that toxicological effects have been observed for tire-related airborne particles.^{10–12} Our own work has sought to measure tire elemental tracers for source apportionment and quantification of tire particles,¹³ which are reported to have sizes ranging from less than 10 nm

to more than 100 μm.^{14,15} The emission factors of airborne tire wear particles must be estimated such that meaningful health impacts can be studied based on representative exposures. Further, these factors play a critical role in the development of standards for industrial manufacturers and whether environmental policies should be developed targeting tire emissions, such as PM₁₀. The absolute magnitude of mass- and eventually number-based airborne emissions from tires needs to be assessed and critically reviewed by academia, industry, and policymakers.

The currently reported emission factors for tire wear PM₁₀ from light-duty vehicles range over a span of 5 orders of magnitude: from 0.00027 to 44 mg/vkm, expressing the mass of emitted tire wear per vehicle-kilometer.^{16,17} For context, the European Union¹⁸ and the United States¹⁹ currently regulate exhaust PM from cars to 4.5 mg/vkm and 1.9 mg/vkm, respectively. In other words, one end of the reported range indicates that the mass of tire wear PM₁₀ is relatively insignificant, whereas the other end exceeds the limits for

Received: September 23, 2024

Revised: November 16, 2024

Accepted: November 19, 2024

Published: November 24, 2024



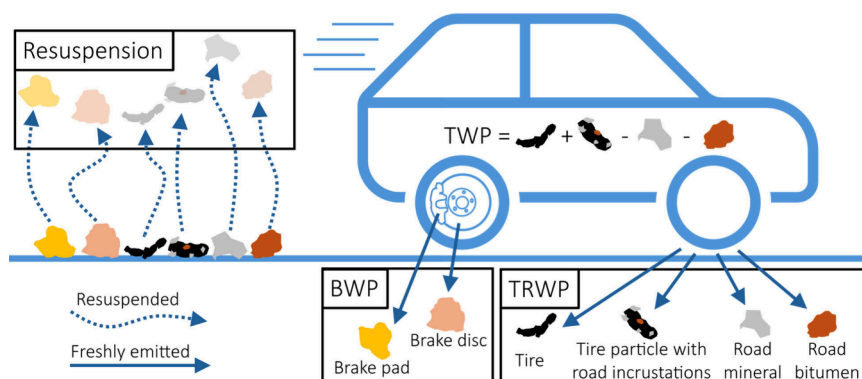


Figure 1. Illustration of our definitions for tire wear particles (TWP), tire and road wear particles (TRWP), brake wear particles (BWP), and “resuspension”. These definitions for TWP, TRWP, and BWP are limited to freshly emitted particles, while any resuspended particles are classified as “resuspension” to avoid double counting.

exhaust emissions 10-fold. If there is no consensus, what do the tire wear PM_{10} emission factors of 6.4 mg/vkm from the European Environmental Agency²⁰ (EEA) or 5.3 mg/vkm from the United States Environmental Protection Agency^{21,22} (EPA) signify? Motivated by this question, we summarized emission factors reported in the primary literature and compared them with emission factors from scientific reviews, reports, textbooks, and emission inventories. We sought to use the findings to assess the contribution of tire wear to air pollution and discuss a potential discrepancy between measured and propagated emission factors.

2. METHODS AND MATERIALS

Search engines (Google, Scopus, Web of Science, and ResearchGate) were used to identify primary studies estimating emission factors of airborne tire wear particles. Additionally, secondary studies summarizing such factors were identified, along with the references cited by these studies. Both spellings “tyre” and “tire” were considered. Research institutes, environmental agencies, local authorities, and authors of key publications were contacted by e-mail or telephone to obtain additional insights in the case of ambiguities or when a study was not accessible. Our team of authors consisted of native English and German speakers, allowing us to read key publications of both languages. Emission factors from studded tires were excluded due to interference from road wear. Similarly, results were excluded that referred to emergency braking or when primary literature authors expressed concern due to interferences from resuspension caused by insufficient cleaning prior to that run.

2.1. Definitions. In this study, we define tire wear PM_{10} or tire wear particles (TWP) as particles directly emitted from tires due to wear. Brake wear particles (BWP) and road wear particles are the equivalents for the brakes and roads, respectively. Our definition of TWP excludes the contribution from road wear particles. The total TWP and road wear particles is defined as tire and road wear particles (TRWP), which represent a mixture of TWP, road wear particles, and TWP incusted with road wear particles. TWP, BWP, or TRWP may settle and be resuspended by wind or the wake of passing vehicles. We define resuspended particles as “resuspension” and not as TWP, BWP, or TRWP. These definitions (illustrated by Figure 1) avoid double counting and agree with the practice of EEA²⁰ and EPA.^{21,22} However, different definitions can be found for tire wear in the literature.

For example, Piscitello et al.²³ defined tire wear particles as tire wear including road wear, in contrast to Baensch-Baltruschat et al.²⁴ who excluded road wear. Similarly, Hicks et al.²⁵ and Beddows et al.²⁶ excluded road wear in their usage of the term “tire wear”, while including both freshly emitted and locally resuspended tire wear particles.

Some studies have quantified the tire contribution within TRWP, in which case we have taken the tire mass fraction as TWP. Similarly, particulate emissions were classified as TWP when a tire on a wear resistant road surrogate like sandpaper was abraded. All emission factors are given as mass per distance (mg/vkm) expressing milligrams of emitted particles per kilometer driven by a vehicle with four tires. If a reference reported emission factors per tire, it was multiplied by 4 to obtain comparable emission factors, assuming identical emissions for all tires. Total suspended particles (TSP) correspond to airborne particles regardless of the size. PM_{10} aerosolization efficiency indicates the mass fraction of tire wear becoming airborne PM_{10} .

Relevant primary literature is defined as studies estimating mass-based emission factors for airborne TWP, TWP+BWP, or TRWP based on their own experiments, aimed at reflecting typical driving conditions. A publication was considered secondary literature (referred to as reviews) when elsewhere reported emission factors were quoted, and no independent measurements of airborne tire particles were performed. A publication was classified as a nonrelevant primary study when airborne particles were measured, but no mass-based emission factors for airborne tire wear were reported. A citation was considered to be inaccurate if the quoted information was not contained in the cited reference.

3. RESULTS AND DISCUSSION

3.1. Emission Factors in the Primary Literature. The accuracy and representativeness of emission factors for airborne tire wear depend greatly on the underlying methodology, as well as the conditions that prevailed during the experiment. Different approaches are subject to different limitations and uncertainties, as described in the Supporting Information (Text S1). This section does not provide a best estimate for a representative emission factor of airborne TWP. Instead, it gives an overview of the emission factors proposed within primary research.

A total of 26 primary studies were found that reported 63 mass-based emission factors for airborne TWP, TRWP, or

Table 1. Emission Factors in Primary Literature for Airborne TWP, TRWP, and TWP+BWP of Light-Duty Vehicles with Unstudded Tires if Not Otherwise Stated

reference	sampling	speciation	emission (mg/vkm)	reference	sampling	speciation	emission (mg/vkm)
TWP TSP				TWP PM ₁₀ (directly emitted)			
Williams and Cadle ³⁰	drum		2–5 ^a	Rauterberg-Wulff ⁴⁵	tunnel	CMB (carbon)	6.1
Pierson and Brachaczek ³¹	tunnel	rubber, zinc	2.5 ^b	Zhang et al. ⁴⁶	tunnel	CMB	1.1–4.5 ^{b,j}
TRWP PM ₁₀				Tonegawa and Sasaki ⁴⁷	on-road	styrene	4.1 ^k
Kupiainen et al. ³²	asphalt track		9 and 11	Woo et al. ¹⁵	safety walk drum		0.46–1.34 ^e
Gustafsson et al. ³³	asphalt track		0.2–7	Zhang et al. ⁴⁸	tungsten carbide drum		1.27
Beji et al. ³⁴	on-road		5.0 ^c	Park et al. ⁴⁹	safety walk drum		0.144–0.8908
Gehrig et al. ³⁵	asphalt track		0–3 ^{d,e}	Gehrig et al. ³⁵	asphalt track	zinc	≤0.80 ^{d,e}
Charbouillot et al. ³⁶	on-road	density separation	2.64 ^f	Allen et al. ^{50,51}	tunnel	unidentified tracers	0.120–0.354 ^{b,h}
Alves et al. ³⁷	asphalt track		2	Kupiainen et al. ³²	asphalt track	CMB	0.17
Khari ³⁸	on-road		1.45 ^{c,g}	Kim and Lee ⁵²	sandpaper drum		0.0011–0.0210 ^e
Aatmeeyata et al. ³⁹	concrete drum		0.0037 ^{c,d,e}	Aatmeeyata et al. ³⁹	concrete drum	carbon	0.00093 ^{c,d,e}
TWP+BWP PM ₁₀				TWP+BWP PM _{2.5}			
Farahani et al. ⁴⁰	roadside	CMB	10.63 ^g	Fang et al. ²⁹	tunnel	CMB	0.03–0.48 ^b
Luhana et al. ⁴¹	tunnel	CMB	6.9				
TWP PM ₁₀ (including resuspended TWP)							
Hicks et al. ²⁵	roadside	zinc	3.5–11.0 ^{b,g}				
Beddows et al. ²⁶	roadside	zinc, CMB	9.92 ^{b,g,h} 10.9 ^{b,g,h}				
Panko et al. ⁴²	roadside	vinylcyclohexene, dipentene	2.4 ^{b,g}				
Sjödin et al. ⁴³	roadside	CMB	2.2 ^{b,g}				
De Oliveira et al. ⁴⁴	on-road	vinylcyclohexene, phenylcyclohexene	0.15 ^g				
Abu-Allaban et al. ²⁷	roadside	CMB	<i>b, g, i</i>				
Bukowiecki et al. ²⁸	roadside	XRF	<i>b, g, i</i>				

TWP+BWP from light-duty vehicles or mixed fleets. The term “mixed fleet” refers to traffic characterized by a mixture of different vehicles, such as motorcycles and light- or heavy-duty vehicles. Some authors quantified directly emitted tire-related particles, while others further included the resuspension of these particles. In two studies, no emissions of airborne TWP could be quantified.^{27,28} A few studies additionally examined two-wheelers, three-wheelers, or heavy-good vehicles, whose emission factors were excluded for better comparability. Most authors reported emission factors for PM₁₀, whereas only one study²⁹ quantified PM_{2.5} and not PM₁₀. For better comparability, PM₁₀ emissions are targeted hereafter. The reported emission factors should be discussed with respect to the individual limitations and uncertainties of the used approaches. Such an evaluation requires the primary literature to be presented in a comparable yet differentiated manner, which we attempt to provide in Table 1. Some factors were converted by us according to the overview in the Supporting Information.

In summary, the identified primary studies reported 35 TWP PM₁₀ emission factors ranging from 0.00093 to 11.0 mg/vkm with a mean of 2.7 mg/vkm and median of 1.1 mg/vkm when including estimates for mixed fleets and resuspended TWP. When excluding the estimates for resuspended TWP, a lower mean of 1.1 mg/vkm and median of 0.2 mg/vkm is obtained. The resuspension of TWP may contribute more to PM₁₀ than the direct emissions, considering the differences between

studies that excluded or included resuspended TWP (Table 1). The mean and median factors for TRWP PM₁₀ from light-duty vehicles were 2.7 and 1.5 mg/vkm, respectively. The mass dominating airborne material resulting from the tire–road interaction may abrade from the roadway rather than from the tire. This hypothesis from Pierson and Brachaczek³¹ in 1974 is supported by the results of various studies that chemically characterized airborne TRWP.^{32,33,35,37,39,43,55–57} When considering elsewhere reported tire tread losses of ~100 mg/vkm for light-duty vehicles under typical conditions,^{17,20} the available data, including the most conservative estimates, imply tire wear PM₁₀ aerosolization efficiencies below 10% or even below 1%.

Although mean and median are suitable metrics to describe typical emission factors within the primary (or secondary) literature, they are less suitable to identify the most accurate emission factor. Note that the means and medians in this section do not reflect individual uncertainties, limitations, and varieties between different conditions, such as speed or load. However, uncertainties, including systematic deviations, are generally not quantified. The identification of the most accurate factor is, therefore, subject to scientific discussions. For our study, we retained all estimates from Table 1. Consequently, our mean and median emission factors are a general description of primary research and not a best estimate of a true emission factor.

The emission factors in Table 1 range over 4 orders of magnitude, which can partly be explained as not all estimates refer to the same emission type. Nevertheless, a substantial variety can still be observed, even within one emission type. For example, considering directly emitted tire wear PM_{10} of light-duty vehicles, estimates ranging from 0.00093 mg/vkm (Aatmeeyata et al.³⁹) to 6.1 g/vkm (Rauterberg-Wulff⁴⁵) can be found. The remaining paragraphs in this section provide important methodological details attempting to explain part of the variety.

The lowest TWP PM_{10} emission factors (<0.1 mg/vkm) were reported by Kim and Lee⁵² and Aatmeeyata et al.³⁹ It should be borne in mind that both studies used abnormally low lateral loads due to experimental limitations. Similarly, the worst case estimate of 0.80 mg/vkm from Gehrig et al.³⁵ was derived using a relatively low load, which corresponds to approximately one-third of a car. Aatmeeyata et al. and Gehrig et al. corrected for the low load assuming a linear relationship between load and tire wear PM_{10} emissions. However, the validity of this assumption is unclear. Generally, tire wear on nonasphalt surfaces like sandpaper (Kim and Lee) or concrete (Aatmeeyata et al.) could be drastically different to asphalt. Additionally, Schläfle et al.⁵⁷ reported the relevance of third-body particles, since a complete lack of dirt between the tire and the road was observed to prevent the release of fine TRWP. It is further unclear whether electric charges impair the collection efficiency of airborne TWP. These considerations could explain low emission factors compared to other studies.

On the other side, the six highest emission factors (ranging from 6.3 to 11.0 mg/vkm) for tire wear PM_{10} were reported by Hicks et al.²⁵ and Beddows et al.²⁶ This can partly be explained as both studies used a similar methodology based on roadside increments to quantify the total of directly emitted and locally resuspended TWP. Additionally, both studies used zinc as a tracer, assuming that 50% by mass of the detected zinc originated from tire wear. This assumption dates back to the year 1974 when Pierson and Brachaczek³¹ used the same zinc specificity for tire wear TSP. However, the specificity of zinc for PM_{10} could be lower than generally assumed according to the observations from Wang et al.⁵⁸ and the caution urged by Chen et al.⁵⁹ An overestimated zinc specificity could lead to overestimated emission factors. This may explain why Hicks et al. did not observe a decrease of TWP emissions during the reduced traffic volumes associated with the coronavirus pandemic (unlike BWP).

Panko et al.⁴² quantified roadside tire wear PM_{10} including resuspended TWP in Paris (France) using rubber pyrolysis products as tracers. The authors calculated an emission factor of 2.4 mg/vkm using a box model in combination with traffic data from the Ile-de-France region. It would be misleading to describe this region as urban, although its center is urban. The employed model assumes that the measured TWP concentration at the roadside in Paris is representative for Ile-de-France. However, it seems that the TWP concentrations near the emission source are higher than, for example, in forests or on agricultural land,⁶⁰ thus indicating that the emission factor of Panko et al. potentially represents a rather conservative estimate.

The highest estimate (6.1 mg/vkm) for tire wear PM_{10} without resuspension was found in the doctoral thesis from Rauterberg-Wulff⁴⁵ (1998). The author has provided us with a printed copy, since this dissertation, written in German, is unavailable online. Its emission factor is widely quoted and

forms the rationale of the current tire wear PM_{10} emission factors from both EPA and EEA (see Text S2). To make it more accessible, we have briefly summarized the underlying methodology in the Supporting Information (Text S3). The methodology is based on a chemical mass balance, assuming no contribution from road wear to carbon in PM_{10} . This assumption seems uncertain in view of the considerations in the Supporting Information (Text S3), implying that the estimate of 6.1 mg/vkm is potentially overestimated.

3.2. Comparison with Secondary Literature. A total of 14 reviews were identified that have summarized mass-based emission factors for airborne tire wear: seven reviews^{16,17,23,24,61–63} published in peer-reviewed scientific journals, three reports^{64–66} from research institutes, one chapter⁶⁷ of a textbook, one report⁶⁸ from the EPA, one report⁶⁹ affiliated with the European Union, and one Web site⁷⁰ affiliated with the United Nations. In all reviews combined, a total of 135 emission factors for airborne TWP, TRWP, or TWP+BWP were found, including duplicates, as multiple reviews have quoted emission factors from the same sources. The reviews did not differentiate between directly emitted and resuspended tire-related particles. Similarly, they did not differentiate between light-duty vehicles and mixed fleets. For better comparability with primary studies, we excluded emission factors for $PM_{2.5}$ or vehicles other than light-duty vehicles. A table of all considered emission factors is provided in the Supporting Information. Note that the EPA and EEA use emission factors for tire wear PM_{10} from light-duty vehicles to derive factors for other vehicles and $PM_{2.5}$ (Text S2).

Notably, clear definitions for “tire wear” were only found in 3 of 14 reviews, while the others provided no definitions or used inconsistent definitions. In the latter cases, we have classified the emission factors as TWP, since the factors were presented in a context characterized by the word “tire” in combination with the absence of the words “road”, “pavement”, “asphalt”, or “resuspension”. This explains why 129 of the 135 identified emission factors from the secondary literature are listed as TWP PM_{10} , whereas only 35 of the 58 PM_{10} emission factors from primary research referred to TWP (Table 2).

The emission factors for TWP PM_{10} reported by secondary literature ranged from 0 to 44 mg/vkm with a mean of 6.5 mg/vkm and median of 6.1 mg/vkm. These emission factors are in good agreement with the emission factor of 6.4 mg/vkm from EEA²⁰ and 5.3 mg/vkm from EPA^{21,22} for light-duty vehicles.

Table 2. Emission Factors (Light-Duty Vehicles and Mixed Fleets) for PM_{10} from TWP and TRWP According to Primary Literature (prim. lit.) and Secondary Literature (sec. lit)

	TWP PM_{10}			TRWP PM_{10}	
	prim. lit. ^a	prim. lit. ^b	sec. lit.	prim. lit. ^c	sec. lit.
N (studies)	16	21	14	8	14
N (factors)	23	35	129	21	2
min. (mg/vkm)	0.00093	0.00093	0	0.0037	2
max. (mg/vkm)	6.1	11.0	44	11	9
mean (mg/vkm)	1.1	2.7	6.5	2.7	5.5
median (mg/vkm)	0.2	1.1	6.1	1.5	5.5

^aDirect emissions. ^bIncludes five studies with resuspended TWP.

^cIncludes one study with resuspended TRWP.

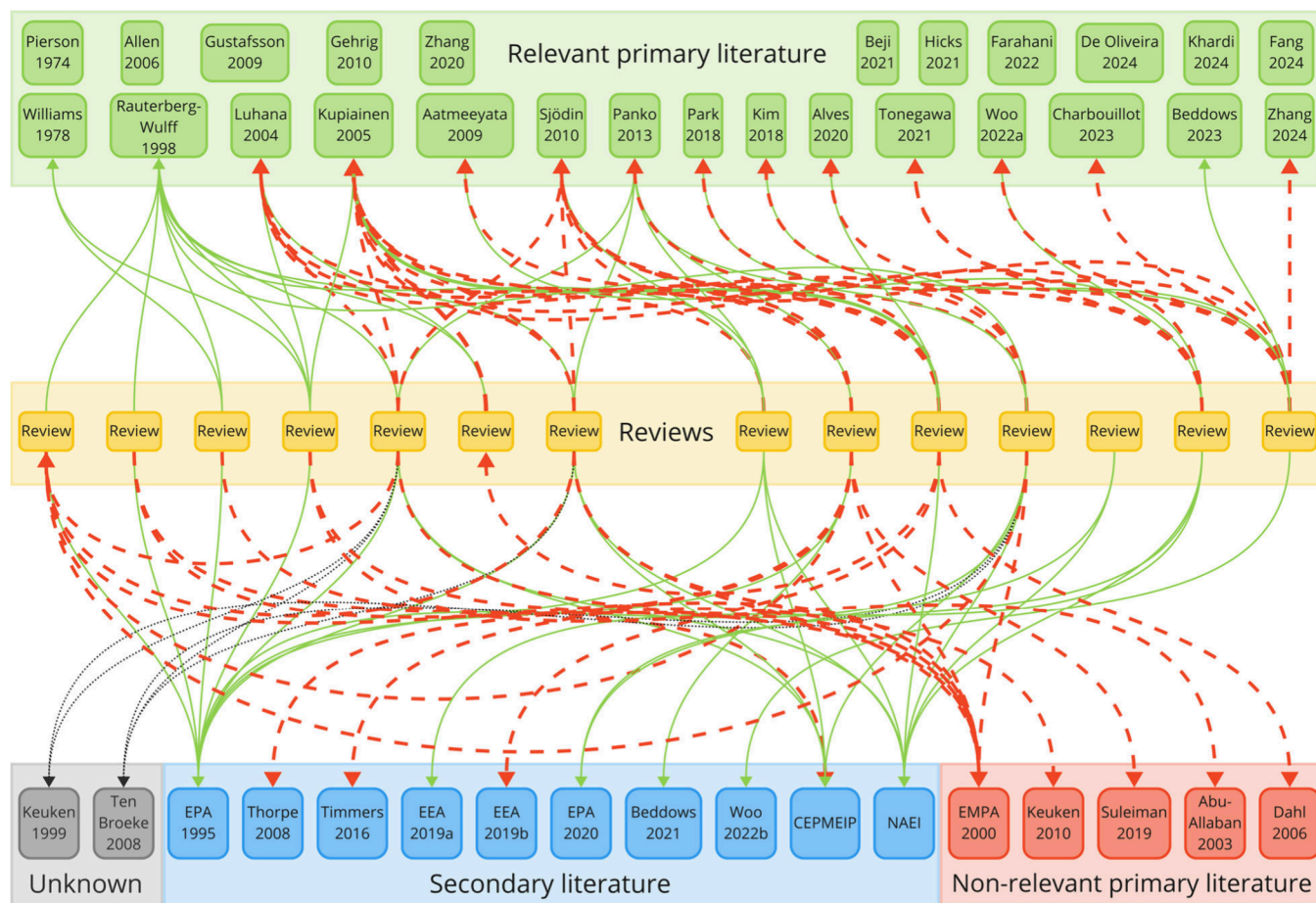


Figure 2. Overview of all 107 citations from 14 reviews to 34 references regarding emission factors for airborne tire wear particles. Accurate and inaccurate citations are highlighted by solid green and dashed red arrows, respectively.

However, the mean from secondary literature is 2 times and the median is 6 times higher than the equivalents from the primary literature including studies with resuspended TWP. When excluding studies with resuspended TWP, the secondary literature reports 6 times higher means and 30 times higher medians than primary research. Similarly, the upper end of the TWP range reported by the reviews is 4 times higher than the highest estimate found within primary research.

A detailed comparison between the primary and secondary literature was performed to assess the underlying reasons behind the discrepancy identified in Table 2. For example, the reviews may have quoted studies that we have missed, or we may have included studies that were excluded by the reviews due to high uncertainties. Similarly, the factors in secondary literature may result from “worst case” emission factors implemented for regulatory purposes. To elucidate these hypotheses, we have assessed the citations from the reviews according to the tire wear definitions in these reviews. The references cited by the reviews were classified as either relevant primary literature, nonrelevant primary literature, secondary literature, or unknown in case the cited reference was not accessible for us (see definitions for the criteria). Additionally, the accuracies of the citations were classified as either accurate, inaccurate, or unknown. Multiple emission factors from one source quoted by one review were counted as one citation. A detailed table of all citations is provided in the Supporting Information, clarifying the classification for all citations and references.

The reviews made a total of 107 citations to 34 different references, whereof we could read all except for 2. The availability of Keuken et al.⁷¹ is unclear according to correspondence with one of the authors and the issuing research organization. The report of ten Broeke et al.⁷² appears to be secondary literature, albeit written in a language we do not comprehend (Dutch). The reviews did not quote references that we have missed. Figure 2 provides an overview of the analyzed reviews, citations, references, and uncited relevant primary studies.

The reviews referred to relevant primary literature in 56 of 107 citations, while 34 referred to secondary literature, 12 to nonrelevant primary literature, and five citations were unknown. In 13 of 14 cases, the reviews presented an undifferentiated mix of emission factors from primary and secondary research, which may introduce a bias as frequently quoted factors could be given unproportional importance. Many of the cited references like CEPMEIP⁷³ or the United Kingdom National Atmospheric Emissions Inventory⁷⁴ (NAEI) are different versions of the same source and are somehow linked to the EMEP/EEA emission inventory guidebook²⁰ from the European Union. NAEI quotes the emission factors from the guidebook,⁷⁵ which in turn cites the initially mentioned CEPMEIP database (base year 1995), which in turn was written under the same program as the guidebook. CEPMEIP is not peer-reviewed and does not provide references for TWP. Its developers were unable to explain how the tire emission factors were derived when we

contacted them by email. Today's tire wear emission factors from the EEA and EPA rely on the same rationale from the year 2003 (outlined in Text S2), implying that 19 citations from the reviews to secondary literature are based on two references: EMEP/EEA and CEPMEIP. Both references are linked to each other and were developed 20 years ago. This observation was not mentioned by the 14 reviews.

We could in 24% of the citations confirm that they accurately referred to relevant primary literature. Of the 107 citations, 56 referred to relevant primary literature, whereof 30 were considered inaccurate and 26 were accurate. Inaccurate citations were found in 13 of 14 reviews (Figure 3). The

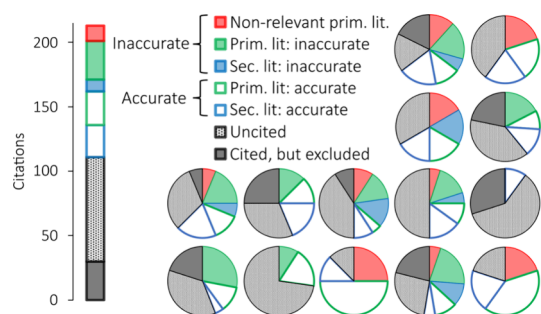


Figure 3. Illustration of the citations from the 14 reviews. Every pie chart represents one review. The bar chart refers to the total of all of the reviews. References that were not considered by the reviews are colored light and dark gray.

inaccuracy was attributable to confusion with different or unclear definitions for tire wear (TWP, TRWP, or TWP +BWP), units (per tire or vehicle; milligram or microgram), and particle size (PM_{10} or $PM_{2.5}$). Some reviews quoted factors that were not stated by the reference, quoted references that did not estimate tire emission factors, or made assumptions that contradicted the cited references. Ideally, all pie charts in Figure 3 are blank with green borders (not filled or semifilled).

Uncited references were examined in addition to the existing citations. In total, only 34% of the relevant primary studies that could have been quoted were quoted by the reviews. The 14 reviews combined did not make a total of 81 possible citations to relevant primary studies, although the primary literature was published before the reviews (referred to as “uncited”). Additionally, eight of the reviews made 30 citations to relevant primary studies without quoting the emission factors for unexplained reasons (referred to as “cited, but excluded”). The emission factors from 11 relevant primary studies were not quoted in any of the 14 reviews: Pierson and Brachaczek³¹ (1974), Allen et al.^{50,51} (2006, 2007), Gustafsson et al.³³ (2009), Gehrig et al.³⁵ (2010), Zhang et al.⁴⁶ (2020), Beji et al.³⁴ (2021), Hicks et al.²⁵ (2021), Farahani et al.⁴⁰ (2022), De Oliveira et al.⁴⁴ (2024), Khardi³⁸ (2024), and Fang et al.²⁹ (2024). The mean emission factors for tire wear PM_{10} from “uncited” and “cited, but excluded” references were 1.6 and 1.1 mg/vkm, respectively. The corresponding medians were both relatively low at 0.2 mg/vkm. Note that all known types of methodologies are represented in the unquoted studies: indoor road simulators as well as real-world experiments such as on-road, roadside, and tunnel measurements.

The numerous inaccurate citations prompted us to investigate whether they were random or systematic. Figure 4 illustrates a quantitative comparison of 130 emission factors from 14 reviews with 61 emission factors from 25 relevant

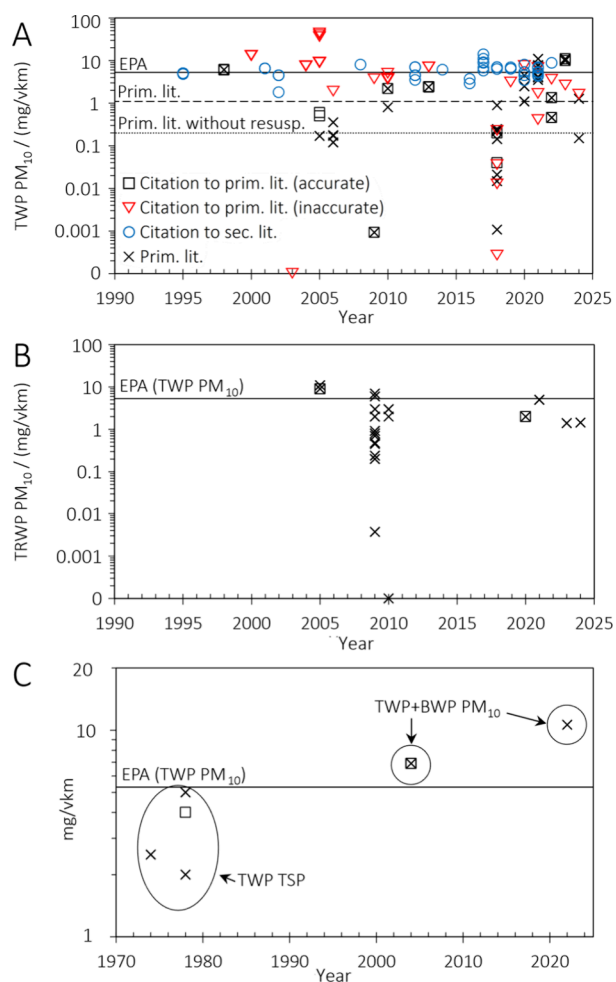


Figure 4. Emission factors for light-duty vehicles and mixed fleets with unstudded tires: (A) TWP PM_{10} , (B) TRWP PM_{10} , and (C) TWP TSP and TWP+BWP PM_{10} . Accurate and inaccurate citations to primary literature, citations to secondary literature, and estimates from primary literature are shown as squares, triangles, circles, and crosses, respectively. The year refers to the year of publication from the primary study or the cited reference.

primary studies. For comparison, TWP PM_{10} emission factors for light-duty vehicles from the EPA and medians from the primary literature including and excluding studies with resuspended TWP are shown as solid, dashed, and dotted horizontal lines, respectively.

Surprisingly, more than half of the emission factors within relevant primary literature, as defined by us, have been exclusively misquoted or not quoted in the reviews. In total, 47 triangles, 30 squares, 38 crosses with, and 23 crosses without corresponding squares were found (Figure 4). Ideally, every cross would be framed by a square, while no triangles would appear. Notably, the TWP PM_{10} mean of 8.5 mg/vkm for the triangles (inaccurately quoted primary studies) was higher than 32 of 35 emission factors reported by primary studies. The mean emission factor of 6.5 mg/vkm for tire wear PM_{10} according to the reviews decreases to 4.1 mg/vkm when excluding primary references that did not estimate mass-based tire wear PM_{10} emission factors and when replacing the mistaken figures with the corresponding measured figures. The mean further decreases to 2.5 mg/vkm when excluding secondary references. When including “cited, but excluded” references, an emission factor of 1.7 mg/vkm is obtained,

which falls between our mean tire wear PM_{10} emission factors of primary literature excluding (1.1 mg/vkm) and including (2.7 mg/vkm) studies with resuspended TWP. This analysis demonstrates three aspects: 1) misquotations and 2) frequent citations to other secondary literature have introduced systematically higher emission factors compared to the underlying primary sources, which 3) represented the upper end of primary literature. Note that the demonstration of aspects 1) and 2) is independent from our selection of primary studies, as it relies on the studies selected by the reviews. For aspect 3), the reviews did not clarify why sources with lower emission factors were systematically excluded, implying a selection bias.

The significance of the bias introduced by misquotations, frequent citations to other secondary sources, and exclusion of low emission factors is further illustrated in Figure 5, which

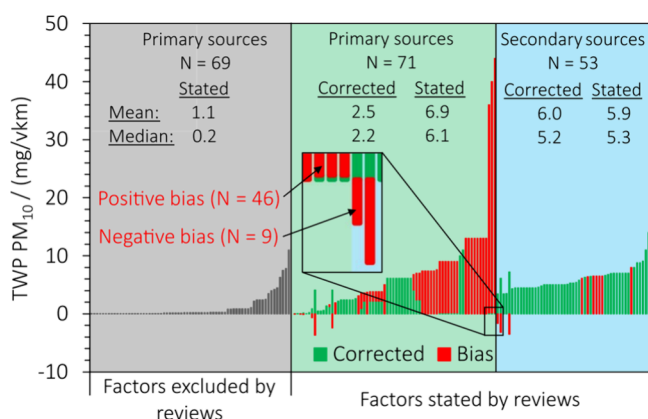


Figure 5. Histogram of emission factors for tire wear PM_{10} in the reviews referring to primary sources (green background) or other secondary sources (blue background). Some primary sources were found by the reviews but not quoted for unexplained reasons (gray background). Differences between reviews and the cited sources (“corrected”) are shown in red to visualize the bias introduced by misquotations.

visually demonstrates four aspects for tire wear PM_{10} : 1) high emission factors in the reviews are more likely misquoted than low ones. Most extreme cases are the highest emission factors for tire wear PM_{10} around 40 mg/vkm from two reviews quoting Kupiainen et al.,³² although this reference measured 200 times lower emission factors of ~ 0.17 mg/vkm. 2) The differences between the factors stated by the reviews and the cited sources are more likely to be positive than negative. In other words, misquotations systematically introduced a bias toward higher and not lower emission factors. 3) Although they are relatively accurate, the citations from the reviews to other secondary sources are 2–3 times higher than the corrected primary sources selected by the same reviews. 4) The majority of the ‘cited, but excluded’ emission factors are below 1 mg/vkm and therefore not in agreement with the other factors stated by the reviews, which may explain why these factors were not considered.

Tire wear PM_{10} emission factors exclusively below EPA’s factor for light-duty vehicles (5.3 mg/vkm) were reported by 13 of 16 primary studies, in 7 studies by 1 order of magnitude or more. Of 35 TWP PM_{10} emission factors based on on-road, roadside, tunnel, and road simulator experiments with different road surfaces (concrete, asphalt, sandpaper) and different driving styles, only 7 emission factors were found high enough

to support tire wear PM_{10} emission factors of ≥ 5.0 mg/vkm, whereof 6 were estimated for mixed fleets including resuspended TWP. Additionally, only 6 of 26 factors for TRWP PM_{10} , TWP+BWP PM_{10} , and TWP TSP were higher than 5.0 mg/vkm despite the mass contributions from bigger or nontire particles (Figure 4B,C). This comparison between measured and propagated emission factors questions the validity of currently established emission factors as a best estimate for TWP PM_{10} from light-duty vehicles, including the factors of EPA^{21,22} with 5.3 mg/vkm and EEA²⁰ with 6.4 mg/vkm.

3.3. Critical Analysis of Selected Examples. We elaborate on selected examples to demonstrate the discrepancy between primary and secondary research. For example, some citations referred to references that did not report tire emission factors (EMPA⁷⁶) or no emission factors at all (Suleiman et al.,⁷⁷ Keuken et al.⁷⁸). Keuken et al. (2010) were potentially cited as an attempt to find Keuken et al.⁷¹ (1999), which may have been confused with a more recent study from the same lead author. It is unclear why numerous studies quoted EMPA at 13 mg/vkm for tire wear PM_{10} , as we were unable to locate this figure in the report, whose final version is exclusively available in German language. Our perception has been confirmed by the lead author of that study, who emphasized by email that no estimates for tire emission factors have been made, as further stated by other authors⁷⁹ of the same research institute. Nevertheless, 8 of 14 reviews quoted EMPA⁷⁶ with an emission factor of 13 mg/vkm. Boulter⁶⁶ (2005) indicated to have cited EMPA indirectly through Lükewille et al.⁶⁴ (2001), which was the first publication quoting EMPA (2000) with 13 mg/vkm to our knowledge. The origin of this figure is unclear according to e-mail correspondence with the lead author of the EMPA report and one author of Lükewille et al.

Potentially, the 13 mg/vkm are based on the emission inventory from EPA in 1985, which stated a tire wear PM_{10} emission factor of 0.002 g/mile/vehicle (= 1.2 mg/vkm). In 1995, the EPA inaccurately quoted this factor as 0.002 mg/mile/tire (= 5 mg/vkm) for the new PARTS emissions model, presumably due to a mix-up of units (Text S4). Incorrect conversion from miles to kilometers (multiplying instead of dividing by 1.61) may have eventually led to 13 mg/vkm, as for example seen in the calculations from Alexandrova et al. in 2007.⁵¹ The citations to EPA with 5 mg/vkm and EMPA with 13 mg/vkm are of great relevance, as they form the rationale behind today’s tire wear PM_{10} emission factors from both EPA and EEA (Text S2). Note that both agencies use these PM_{10} emission factors to derive estimates for $PM_{2.5}$ as well as for vehicles other than light-duty vehicles.

Kupiainen et al.³² estimated PM_{10} emission factors of ~ 10 mg/vkm resulting from abrasion at the tire and road interface. The authors did not classify these particles as tire or road wear particles. However, 8 of 10 reviews presented these results as emission factors for TWP alone. It would be likely more accurate to interpret the reported emission factors as mainly road rather than tire particles, given that Kupiainen et al. quantified the mineral content in the PM_{10} fraction to $\geq 90\%$ (by number). Their chemical mass balance implied average PM_{10} tire contributions of 1.5% with a maximum of 5%, which was accounted for in one⁶⁶ of ten reviews.

Luhana et al.⁴¹ estimated an emission factor of 6.9 mg/vkm for TWP+BWP PM_{10} , which was accurately quoted by 2 of 7 reviews. Surprisingly, the other 5 reviews quoted this study with 7.4 mg/vkm tire wear PM_{10} . This can be explained as

Luhana et al. additionally measured a total tire tread loss of 74 mg/vkm, which was used by Grigoratos and Martini⁶⁹ to calculate emission factors for tire wear PM₁₀ assuming an elsewhere found aerosolization efficiency of 10%. Notably, the asserted approach using aerosolization efficiency did not appear within Luhana et al., who quantified BWP and TWP combined to a lower emission factor. The other 4 reviews directly cited Luhana et al. with 7.4 mg/vkm for tire wear PM₁₀, although this factor was calculated by Grigoratos and Martini.

Sjödin et al.⁴³ estimated an emission factor of 2.2 mg/vkm using roadside measurements and a chemical mass balance (CMB). The authors used a source profile for TWP based on TRWP partly generated with studded tires, which introduced considerable uncertainty due to increased road wear, as highlighted by the authors. Surprisingly, 6 of 7 reviews quoted this reference with an emission factor of 3.6 or 3.8 mg/vkm. The origin of these figures is not discernible to us and two authors of Sjödin et al. according to email correspondence. Only one review quoted this study with 2.2 mg/vkm.²⁴

3.4. Emergence and Perception of the Discrepancy.

Although such efforts must be decoupled from the best measures of airborne TWP emissions, environmental agencies may have intentionally set high emission factors to use a conservative approach for human health protection or induce industry to demonstrate better performance. However, given the prevalence and nature of frequently misquoted emission factors, it seems more plausible that the discrepancy between the primary and secondary literature has arisen unintentionally. Note that most of the mistaken figures are associated with half-truths or terminological inconsistencies, emphasizing the unintentional character of the misquotations.

The three examples of EMPA,⁷⁶ Luhana et al.,⁴¹ and Sjödin et al.⁴³ demonstrate how 7 of 14 reviews reproduced emission factors from other secondary studies while citing primary research. This pseudodirect citation practice (referencing the primary study but taking the values from the secondary source) introduced a lack of traceability and prevented others from comprehending where the stated numbers originated. This practice likely emerges from an ambivalence between the challenge of encapsulating a wide research subject, the aversion toward indirect citations, and the temptation to trust reputable secondary sources. Language barriers and difficulties in accessing key publications further exacerbated the persistence of the discrepancy. The potential role of the illusory truth effect⁸⁰ shall not be ignored. This phenomenon describes the increased probability to perceive frequently reiterated statements as being more truthful because of the repeated exposure.

No authors were found who considered a discrepancy between primary and secondary literature as a contributing reason for the variety of emission factors found in the literature, demonstrating the novelty of our work. Nevertheless, we have found a few authors who questioned the general opinion in the literature. De Oliveira et al.⁴⁴ and Charbouillot et al.³⁶ proposed that currently established emission factors for airborne tire wear are potentially overestimated. Mennekes and Nowack⁷⁹ highlighted that country-based total TWP emission studies lack scientific support. Charbouillot et al., DEFRA,⁷⁵ and Harrison et al.⁸¹ implied that emission factors in emission inventories are based on old studies. We are unaware of historical studies stating emission factors of ≥ 6.4 mg/vkm for tire wear PM₁₀.

3.5. Implications of the Discrepancy. It may matter decisively whether emission factors for tire wear PM₁₀ are, for example, 1 mg/vkm rather than 5 mg/vkm. The latter exceeds the legal limit for exhaust emissions in the European Union¹⁸ and United States,¹⁹ whereas the former remains below these limits (note differences in size and chemical composition between exhaust emissions and TWP). Research focus in academia and industry is determined by current emission factors. The higher the factors, the more motivation is created to conduct research and the more pressure is built up on governments to take measures. Resource management and political agendas should be based on emission factors, reflecting scientific evidence.

Currently established emission factors for airborne TWP are part of national emission inventories and have been widely used for governmental reports^{75,82,83} and academic research,^{84–92} for example to study the impact from electric vehicles on air pollution.^{7,8,93–98} The conclusions of these studies can be misleading if the underlying emission factors are inaccurate. For example, the increased vehicle mass associated with electric vehicles is potentially accompanied by less direct PM₁₀ emissions than those currently anticipated due to the TWP bias.

Primary study authors may compare their results with the literature and conclude that more research is needed due to an alleged lack of consensus. They may not recognize the mistaken emission factors in the secondary literature. For example, Panko et al.⁴² contextualized their result (2.4 mg/vkm) by comparing it with a literature benchmark for light-duty vehicles ranging from 2 to 13 mg/vkm for tire wear PM₁₀. Notably, the lower end of this benchmark was 2 times higher than the median emission factor we have found in the primary literature (including studies with resuspended TWP). Similarly, although the factors stated by Hicks et al.²⁵ (~6 mg/vkm) and Beddows et al.²⁶ (~10 mg/vkm) were the highest emission factors we have found in primary literature, the authors did not express astonishment after comparing their results with emission factors from EEA. On the other side, we found several authors in primary research questioning their results due to “relatively low” emissions in comparison to misquoted emission factors from secondary literature. Woo et al.¹⁵ commented on the discrepancy, stating: ‘this significant difference is presumed to be the reason why laboratory measurements cannot accurately reflect the wear characteristics that occur under real-world driving conditions’. Similar statements were made by other authors,^{34,39,41,48,49,52} where “relatively low” emission factors of airborne TWP were contextualized with a secondary literature benchmark. However, this benchmark contained bias, as revealed by our analysis. Authors stating to have measured “relatively high” emissions were not found.

Secondary literature appears to propagate high emission factors while excluding low factors, also due to concerns from primary study authors. These concerns, however, may result from unexpectedly low emissions relative to secondary literature: an example of circular reasoning driven by the illusory truth effect. We observed cases where primary literature authors quoted their own work with misperceived emission factors without being able to explain by email where they originated, demonstrating the dominance of frequently misquoted figures in comparison to the measured figures.

3.6. Limitations. Low emission factors for tire wear PM₁₀ do not imply that TWP is unimportant for air quality as these

factors only provide insights into mass metrics for directly emitted particles with aerodynamic diameters below 10 μm . Although TWP are believed to contribute significantly to bigger airborne particles,^{99,100} the environmental and health impacts of these bigger particles remain unclear. Additionally, the chemical composition or shape of tire wear PM_{10} may pose health risks despite potentially low exposures.

Mass-based PM_{10} emission factors do not accurately reflect tire wear nanoparticles and number-based emissions in general. The mass contribution from ultrafine tire particles to tire wear PM_{10} could be higher than is currently anticipated. De Oliveira et al.⁴⁴ observed that the rubber mass within tire wear PM_{10} was most dominated by particles smaller than 0.39 μm . Tonegawa and Sasaki⁴⁷ stated tire wear $\text{PM}_{2.5}/\text{PM}_{10}$ ratios close to unity. During harsh braking, Kim and Lee⁵² reported surprisingly high mass concentrations of nanoparticles along with nanoparticle growth due to coagulation and condensation of volatile tire material. Considering the hypothesized role of evaporation and condensation of an unidentified tire component,^{15,49,52,53,101–104} it seems plausible that tire wear nanoparticles are semivolatile oil droplets subject to coalescence. Note that Williams and Cadle³⁰ in 1978 reported roughly equal mass emissions of gaseous tire wear and tire wear TSP.

Finally, the large mass of nonairborne emissions from tires along with unclear effects for the environment and health are concerning and subject of ongoing research. It is critical that studies carefully differentiate between direct and indirect emissions into the atmosphere. Tire particles may degrade, decrease in size, resuspend, and thus become PM_{10} indirectly.¹⁰⁵ It is reported that the wear-related stress is accompanied by chemical alterations accelerating chemical and biological degradation of TWP, hypothetically due to cleavage of covalent bonds within the rubber framework.^{30,106,107} Williams and Cadle showed in 1978 that approximately 30% of styrene–butadiene–rubber in sedimentary TWP is unvulcanized—a fraction 15 to 30 times higher than in tire tread.³⁰ The breakdown and subsequent evaporation of rubber potentially explains the elevated levels of zinc on the surface of TWP reported by Li et al.¹⁰⁷ This evidence may shift the focus from directly to indirectly emitted airborne TWP, underlining the roles of microplastic emissions and physical removal of curbside dust. Consequently, the assumption of chemical similarities between tire wear particles and tire tread seems to be questionable, which may have relevant implications when quantifying tire wear using chemical tracers. The term TWP is potentially misleading when referring to airborne matter originating from tires, for example, if rubber and filler separate during degradation.

4. FUTURE PERSPECTIVES

Currently accepted mass-based emission factors of airborne TWP do not adequately reflect the scientific evidence from primary research. Secondary literature reports tire wear PM_{10} emission factors 2 to 30 times higher than primary research, depending on the definition of primary research, the statistical metrics, and whether studies quantifying resuspended TWP are included or not. The discrepancy, dating back to 1995, is due to misunderstandings and misquotations that arose during the knowledge transfer from the primary to secondary literature. Inaccurate quotations have led to an unfounded but prevalent opinion of relatively high emission factors, which permeated emission inventories from environmental agencies and

hindered the formation of a scientific consensus. Thus, revision of current tire wear PM_{10} emission factors and the associated conclusions is warranted. The accuracy of prospective knowledge transfers between primary and secondary research can be improved by using clear terminologies and avoiding pseudodirect citations.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.estlett.4c00792>.

Elaborations on methodologies, EPA's and EEA's emission factors, Rauterberg-Wulff's dissertation, and the studies in the 1970s (PDF)

Overview, a detailed table of all analyzed emission factors, and summaries of the data used in Figure 3, 4, and 5 (XLSX)

■ AUTHOR INFORMATION

Corresponding Authors

Siriël Saladin – Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge CB2 1EW, United Kingdom; orcid.org/0000-0001-6923-521X; Email: sls87@cam.ac.uk

Chiara Giorio – Yusuf Hamied Department of Chemistry, University of Cambridge, Cambridge CB2 1EW, United Kingdom; orcid.org/0000-0001-7821-7398; Email: chiara.giorio@atm.ch.cam.ac.uk

Author

Adam Boies – Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom; orcid.org/0000-0003-2915-3273

Complete contact information is available at:

<https://pubs.acs.org/doi/10.1021/acs.estlett.4c00792>

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Annette Rauterberg-Wulff (SenMVKU) for providing a physical copy of the dissertation and Jonathan Allen (Allen Analytics), Mats Gustafsson (VTI), Christoph Hüglin (EMPA), Bogdan Muresan (Gustave Eiffel University), Tiago De Oliveira (Gustave Eiffel University), Åke Sjödin (IVL), and Harry ten Brink (TNO) for valuable elaborations on their publications. This work was supported by EPSRC with funding through the Centre for Doctoral Training in Aerosol Science under grant code EP/S023593/1.

■ REFERENCES

- (1) World Health Organization (WHO). *Ambient (outdoor) air pollution*. <https://www.who.int/news-room/fact-sheets> (accessed Jun 13, 2024).
- (2) GBD 2019 Collaborators. Global Mortality from Dementia: Application of a New Method and Results from the Global Burden of Disease Study 2019. *Alzheimer's Dement. Transl. Res. Clin. Interv.* **2021**, *7* (1), No. e12200.
- (3) World Health Organization (WHO). *Road traffic injuries*. <https://www.who.int/news-room/fact-sheets> (accessed Jun 13, 2024).
- (4) World Health Organization (WHO). *Suicide*. <https://www.who.int/news-room/fact-sheets> (accessed Jun 13, 2024).

- (5) United Nations Children's Fund (UNICEF). *Malaria*. <https://data.unicef.org/topic/child-health/malaria> (accessed Jun 13, 2024).
- (6) EEA. *Air Quality in Europe — 2019 Report*; EEA, 2019.
- (7) Timmers, V. R. J. H.; Achten, P. A. J. Non-Exhaust PM Emissions from Electric Vehicles. *Atmos. Environ.* **2016**, *134*, 10–17.
- (8) Beddows, D. C. S.; Harrison, R. M. PM10 and PM2.5 Emission Factors for Non-Exhaust Particles from Road Vehicles: Dependence upon Vehicle Mass and Implications for Battery Electric Vehicles. *Atmos. Environ.* **2021**, *244*, 117886.
- (9) European Commission. *Commission proposes new Euro 7 standards to reduce pollutant emissions from vehicles and improve air quality*. <https://ec.europa.eu/commission/presscorner> (accessed Jun 13, 2024).
- (10) Poma, A.; Aloisi, M.; Bonfigli, A.; Colafarina, S.; Zarivi, O.; Aimola, P.; Vecchiotti, G.; Arrizza, L.; Di Cola, A.; Cesare, P. Particle Debris Generated from Passenger Tires Induces Morphological and Gene Expression Alterations in the Macrophages Cell Line RAW 264.7. *Nanomaterials* **2023**, *13* (4), 756.
- (11) Mantecca, P.; Sancini, G.; Moschini, E.; Farina, F.; Gualtieri, M.; Rohr, A.; Misericocchi, G.; Palestini, P.; Camatini, M. Lung Toxicity Induced by Intratracheal Instillation of Size-Fractionated Tire Particles. *Toxicol. Lett.* **2009**, *189* (3), 206–214.
- (12) Karlsson, H. L.; Ljungman, A. G.; Lindbom, J.; Möller, L. Comparison of Genotoxic and Inflammatory Effects of Particles Generated by Wood Combustion, a Road Simulator and Collected from Street and Subway. *Toxicol. Lett.* **2006**, *165* (3), 203–211.
- (13) O'Loughlin, D. P.; Haugen, M. J.; Day, J.; Brown, A. S.; Braysher, E. C.; Molden, N.; Willis, A. E.; MacFarlane, M.; Boies, A. M. Multi-Element Analysis of Tyre Rubber for Metal Tracers. *Environ. Int.* **2023**, *178*, 108047.
- (14) Kreider, M. L.; Panko, J. M.; McAtee, B. L.; Sweet, L. I.; Finley, B. L. Physical and Chemical Characterization of Tire-Related Particles: Comparison of Particles Generated Using Different Methodologies. *Sci. Total Environ.* **2010**, *408* (3), 652–659.
- (15) Woo, S.; Jang, H.; Mun, S.; Lim, Y.; Lee, S. Effect of Treadwear Grade on the Generation of Tire PM Emissions in Laboratory and Real-World Driving Conditions. *Sci. Total Environ.* **2022**, *838* (P4), 156548.
- (16) Zhang, M.; Yin, H.; Tan, J.; Wang, X.; Yang, Z.; Hao, L.; Du, T.; Niu, Z.; Ge, Y. A Comprehensive Review of Tyre Wear Particles: Formation, Measurements, Properties, and Influencing Factors. *Atmos. Environ.* **2023**, *297*, 119597.
- (17) Giachaskiel, B.; Grigoratos, T.; Mathissen, M.; Quik, J.; Tromp, P.; Gustafsson, M.; Franco, V.; Dilara, P. Contribution of Road Vehicle Tyre Wear to Microplastics and Ambient Air Pollution. *Sustainability* **2024**, *16* (2), 522.
- (18) European Union. *Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on Type Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6)*; European Union, 2020.
- (19) EPA. *Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards*; EPA, 2014; Vol. 79.
- (20) EEA. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023*; EEA, 2023.
- (21) EPA. *Brake and Tire Wear Emissions from Onroad Vehicles in MOVES3*; EPA, 2020.
- (22) EPA. *Overview of EPA's Motor Vehicle Emission Simulator (MOVES4)*; EPA, 2023.
- (23) Piscitello, A.; Bianco, C.; Casasso, A.; Sethi, R. Non-Exhaust Traffic Emissions: Sources, Characterization, and Mitigation Measures. *Sci. Total Environ.* **2021**, *766*, 144440.
- (24) Baensch-Baltruschat, B.; Kocher, B.; Stock, F.; Reifferscheid, G. Tyre and Road Wear Particles (TRWP) - A Review of Generation, Properties, Emissions, Human Health Risk, Ecotoxicity, and Fate in the Environment. *Sci. Total Environ.* **2020**, *733*, 137823.
- (25) Hicks, W.; Beever, S.; Tremper, A. H.; Stewart, G.; Priestman, M.; Kelly, F. J.; Lanoisellé, M.; Lowry, D.; Green, D. C. Quantification of Non-Exhaust Particulate Matter Traffic Emissions and the Impact of COVID-19 Lockdown at London Marylebone Road. *Atmosphere (Basel)*. **2021**, *12* (2), 190.
- (26) Beddows, D. C. S.; Harrison, R. M.; Gonet, T.; Maher, B. A.; Odling, N. Measurement of Road Traffic Brake and Tyre Dust Emissions Using Both Particle Composition and Size Distribution Data. *Environ. Pollut.* **2023**, *331* (P1), 121830.
- (27) Abu-Allaban, M.; Gillies, J. A.; Gertler, A. W.; Clayton, R.; Proffitt, D. Tailpipe, Resuspended Road Dust, and Brake-Wear Emission Factors from on-Road Vehicles. *Atmos. Environ.* **2003**, *37* (37), 5283–5293.
- (28) Bukowiecki, N.; Lienemann, P.; Hill, M.; Furger, M.; Richard, A.; Amato, F.; Prévôt, A. S. H.; Baltensperger, U.; Buchmann, B.; Gehrig, R. PM10 Emission Factors for Non-Exhaust Particles Generated by Road Traffic in an Urban Street Canyon and along a Freeway in Switzerland. *Atmos. Environ.* **2010**, *44* (19), 2330–2340.
- (29) Fang, T.; Fu, J.; Gao, Y.; Song, A.; Zhang, Y.; Zhang, Q.; Wu, L.; Peng, J.; Wang, T.; Mao, H. Real-World Vehicular Source Indicators for Exhaust and Non-Exhaust Contribution to PM2.5 During Peak and Off-Peak Hours Using Tunnel Measurement. *J. Geophys. Res. Atmos.* **2024**, *129* (13), DOI: 10.1029/2024JD040853.
- (30) Williams, R. L.; Cadle, S. H. Characterization of Tire Emissions Using an Indoor Test Facility. *Rubber Chem. Technol.* **1978**, *51* (1), 7–25.
- (31) Pierson, W. R.; Brachaczek, W. W. Airborne Particulate Debris from Rubber Tires. *Rubber Chem. Technol.* **1974**, *47* (5), 1275–1299.
- (32) Kupiainen, K. J.; Tervahattu, H.; Räisänen, M.; Mäkelä, T.; Aurela, M.; Hillamo, R. Size and Composition of Airborne Particles from Pavement Wear, Tires, and Traction Sanding. *Environ. Sci. Technol.* **2005**, *39* (3), 699–706.
- (33) Gustafsson, M.; Blomqvist, G.; Brorström-Lundén, E.; Dahl, A.; Gudmundsson, A.; Hjort, M.; Johansson, C.; Jonsson, P.; Swietlicki, E. *Nanoparticles from the Abrasion of Tyres and Pavement (Translation of VTI Report 660)*; VTI, 2009.
- (34) Beji, A.; Deboudt, K.; Khardi, S.; Muresan, B.; Lumière, L. Determinants of Rear-of-Wheel and Tire-Road Wear Particle Emissions by Light-Duty Vehicles Using on-Road and Test Track Experiments. *Atmos. Pollut. Res.* **2021**, *12* (3), 278–291.
- (35) Gehrig, R.; Zeyer, K.; Bukowiecki, N.; Lienemann, P.; Poulidakos, L. D.; Furger, M.; Buchmann, B. Mobile Load Simulators - A Tool to Distinguish between the Emissions Due to Abrasion and Resuspension of PM10 from Road Surfaces. *Atmos. Environ.* **2010**, *44* (38), 4937–4943.
- (36) Charbouillot, T.; Janet, D. C.; Schaal, P.; Beynier, I.; Boulat, J. M.; Grandchamp, A.; Biesse, F. Methodology for the Direct Measurement of Tire Emission Factors. *Sci. Total Environ.* **2023**, *863*, 160853.
- (37) Alves, C. A.; Vicente, A. M. P.; Calvo, A. I.; Baumgardner, D.; Amato, F.; Querol, X.; Pio, C.; Gustafsson, M. Physical and Chemical Properties of Non-Exhaust Particles Generated from Wear between Pavements and Tyres. *Atmos. Environ.* **2020**, *224*, 117252.
- (38) Khardi, S. Emission Factors of Tyre Wear Particles Emitted by Light Road Vehicles in Real Driving Conditions: A New Challenge for Clean Road Transport to Improve Urban Air Quality. *Atmosphere (Basel)*. **2024**, *15* (6), 665.
- (39) Aatmeeyata; Kaul, D. S.; Sharma, M. Traffic Generated Non-Exhaust Particulate Emissions from Concrete Pavement: A Mass and Particle Size Study for Two-Wheelers and Small Cars. *Atmos. Environ.* **2009**, *43* (35), 5691–5697.
- (40) Jalali Farahani, V.; Altuwajjiri, A.; Taghvaei, S.; Sioutas, C. Tailpipe and Nontailpipe Emission Factors and Source Contributions of PM10 on Major Freeways in the Los Angeles Basin. *Environ. Sci. Technol.* **2022**, *56* (11), 7029–7039.
- (41) Luhana, L.; Sokhi, R.; Warner, L.; Mao, H.; Boulter, P.; McCrae, I.; Wright, J.; Osborn, D. *Measurement of Non-Exhaust Particulate Matter*; European Commission, 2004.
- (42) Panko, J. M.; Chu, J.; Kreider, M. L.; Unice, K. M. Measurement of Airborne Concentrations of Tire and Road Wear Particles in Urban and Rural Areas of France, Japan, and the United States. *Atmos. Environ.* **2013**, *72*, 192–199.

- (43) Sjödin, Å.; Ferm, M.; Björk, A.; Rahmberg, M.; Gudmundsson, A.; Swietlicki, E.; Johansson, C.; Gustafsson, M.; Blomqvist, G. *Wear Particles from Road Traffic - a Field, Laboratory and Modelling Study. Final Report*; IVL, 2010. DOI: 10.13140/RG.2.2.18594.35524.
- (44) De Oliveira, T.; Muresan, B.; Ricordel, S.; Lumière, L.; Truong, X. T.; Poirier, L.; Gasperi, J. Realistic Assessment of Tire and Road Wear Particle Emissions and Their Influencing Factors on Different Types of Roads. *J. Hazard. Mater.* **2024**, *465*, 133301.
- (45) Rauterberg-Wulff, A. *Beitrag Des Reifen- Und Bremsenabriebs Zur Rußimmission an Straßen*, Ph.D. Thesis, Technische Universität: Berlin, 1998.
- (46) Zhang, J.; Peng, J.; Song, C.; Ma, C.; Men, Z.; Wu, J.; Wu, L.; Wang, T.; Zhang, X.; Tao, S.; Gao, S.; Hopke, P. K.; Mao, H. Vehicular Non-Exhaust Particulate Emissions in Chinese Megacities: Source Profiles, Real-World Emission Factors, and Inventories. *Environ. Pollut.* **2020**, *266* (P2), 115268.
- (47) Tonegawa, Y.; Sasaki, S. Development of Tire-Wear Particle Emission Measurements for Passenger Vehicles. *Emiss. Control Sci. Technol.* **2021**, *7*, 56–62.
- (48) Zhang, Q.; Fang, T.; Men, Z.; Wei, N.; Peng, J.; Du, T.; Zhang, X.; Ma, Y.; Wu, L.; Mao, H. Direct Measurement of Brake and Tire Wear Particles Based on Real-World Driving Conditions. *Sci. Total Environ.* **2024**, *906*, 167764.
- (49) Park, I.; Kim, H.; Lee, S. Characteristics of Tire Wear Particles Generated in a Laboratory Simulation of Tire/Road Contact Conditions. *J. Aerosol Sci.* **2018**, *124*, 30–40.
- (50) Allen, J. O.; Alexandrova, O.; Kaloush, K. E. *Tire Wear Emissions for Asphalt Rubber and Portland Cement Concrete Pavement Surfaces*; Arizona State University, 2006.
- (51) Alexandrova, O.; Kaloush, K. E.; Allen, J. O. Impact of Asphalt Rubber Friction Course Overlays on Tire Wear Emissions and Air Quality Models for Phoenix, Arizona. *Airshed. Transp. Res. Rec.* **2007**, *2011* (1), 98–106.
- (52) Kim, G.; Lee, S. Characteristics of Tire Wear Particles Generated by a Tire Simulator under Various Driving Conditions. *Environ. Sci. Technol.* **2018**, *52* (21), 12153–12161.
- (53) Cadle, S. H.; Williams, R. L. Gas and Particle Emissions from Automobile Tires in Laboratory and Field Studies. *J. Air Pollut. Control Assoc.* **1978**, *28* (5), 502–507.
- (54) Røddland, E. S.; Samanipour, S.; Rauer, C.; Okoffo, E. D.; Reid, M. J.; Heier, L. S.; Lind, O. C.; Thomas, K. V.; Meland, S. A Novel Method for the Quantification of Tire and Polymer-Modified Bitumen Particles in Environmental Samples by Pyrolysis Gas Chromatography Mass Spectroscopy. *J. Hazard. Mater.* **2022**, *423*, 127092.
- (55) McAtee, B.; Gustafsson, M.; Blomqvist, G.; Gudmundsson, A.; Sweet, L.; Panko, J.; Finley, B. Physio-Chemical Analysis of Airborne Tire Wear Particles. *Toxicol. Lett.* **2009**, *189*, S205.
- (56) Gustafsson, M.; Blomqvist, G.; Gudmundsson, A.; Dahl, A.; Swietlicki, E.; Bohgard, M.; Lindbom, J.; Ljungman, A. Properties and Toxicological Effects of Particles from the Interaction between Tyres, Road Pavement and Winter Traction Material. *Sci. Total Environ.* **2008**, *393* (2–3), 226–240.
- (57) Schläfle, S.; Unrau, H. J.; Gauterin, F. Influence of Longitudinal and Lateral Forces on the Emission of Tire–Road Particulate Matter and Its Size Distribution. *Atmosphere (Basel)*. **2023**, *14* (12), 1780.
- (58) Wang, X.; Gronstal, S.; Lopez, B.; Jung, H.; Chen, L. W. A.; Wu, G.; Ho, S. S. H.; Chow, J. C.; Watson, J. G.; Yao, Q.; Yoon, S. Evidence of Non-Tailpipe Emission Contributions to PM_{2.5} and PM₁₀ near Southern California Highways. *Environ. Pollut.* **2023**, *317*, 120691.
- (59) Chen, L. W. A.; Wang, X.; Lopez, B.; Wu, G.; Ho, S. S. H.; Chow, J. C.; Watson, J. G.; Yao, Q.; Yoon, S.; Jung, H. Contributions of Non-Tailpipe Emissions to near-Road PM_{2.5} and PM₁₀: A Chemical Mass Balance Study. *Environ. Pollut.* **2023**, *335*, 122283.
- (60) Kumata, H.; Takada, H.; Ogura, N. 2-(4-Morpholinyl)-Benzothiazole as an Indicator of Tire-Wear Particles and Road Dust in the Urban Environment. *ACS Symp. Ser.* **1997**, *671*, 291–305.
- (61) Liu, Y.; Chen, H.; Gao, J.; Dave, K.; Chen, J. Gap Analysis and Future Needs of Tyre Wear Particles. *SAE Technol. Pap.* **2021**, 2021-01-0621.
- (62) Guo, D.; Wei, H.; Guo, Y.; Wang, C.; Yin, Z. Non-Exhaust Particulate Matter Emission from Vehicles: A Review. *E3S Web Conf.* **2021**, *268*, 01015.
- (63) Fussell, J. C.; Franklin, M.; Green, D. C.; Gustafsson, M.; Harrison, R. M.; Hicks, W.; Kelly, F. J.; Kishta, F.; Miller, M. R.; Mudway, I. S.; Oroumijeh, F.; Selley, L.; Wang, M.; Zhu, Y. A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures. *Environ. Sci. Technol.* **2022**, *56* (11), 6813–6835.
- (64) Lükewille, A.; Bertok, I.; Amann, M.; Cofala, J.; Gyarfas, F.; Heyes, C.; Karvosenoja, N.; Klimont, Z.; Schoepp, W. *A Framework to Estimate the Potential and Costs for the Control of Fine Particulate Emissions in Europe*; IIASA, 2001.
- (65) Klimont, Z.; Cofala, J.; Bertok, I.; Amann, M.; Heyes, C.; Gyarfas, F. *Modelling Particulate Emissions in Europe: A Framework to Estimate Reduction Potential and Control Costs*; IIASA, 2002.
- (66) Boulter, P. G. *A Review of Emission Factors and Models for Road Vehicle Non-Exhaust Particulate Matter*; TRL Limited, 2005.
- (67) Panko, J.; Kreider, M.; Unice, K. *Chapter 7 - Review of Tire Wear Emissions: A Review of Tire Emission Measurement Studies: Identification of Gaps and Future Needs*; Elsevier Inc., 2018. DOI: 10.1016/B978-0-12-811770-5.00007-8.
- (68) EPA. *Brake and Tire Wear Emissions in MOVES2014*; EPA, 2014.
- (69) Grigoratos, T.; Martini, G. *Non-Exhaust Traffic Related Emissions. Brake and Tyre Wear PM*; Joint Research Centre, 2014. DOI: 10.2790/21481.
- (70) Task Force on Emission Inventories and Projections (TFEIP). *Automobile tyre and brake wear*. <https://www.eng.auth.gr/mech0/lat/PM10/> (accessed Jun 13, 2024).
- (71) Keuken, M.; Teeuwisse, S.; ten Brink, H. M. *Research on the Contribution of Road Dust Emissions to PM₁₀ Concentrations in the Netherlands*. TNO Report Nr. R99/S05; TNO, 1999.
- (72) ten Broeke, H.; Hulskotte, J.; van der Denier Gon, H. *Emissies Door Bandenslijtage Afkomstig van Het Wegverkeer*; Rijkswaterstaat - Waterdienst, 2008.
- (73) Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO). *CEPMEIP Database*. <http://tno.air.sk/cepmeip/> (accessed Jun 13, 2024).
- (74) NAEI. *Fleet Weighted Road Transport Emission Factor 2018*; Ricardo, 2020.
- (75) Department for Environment Food & Rural Affairs (DEFRA). *Non-Exhaust Emissions from Road Traffic*; DEFRA, 2019.
- (76) Eidgenössische Materialprüfungs- und Forschungsanstalt (EMPA). *Beitrag Des Strassenverkehrs Zu Den PM₁₀- Und PM_{2.5}-Immissionen*; Schlussbericht; NFP41 Verkehr und Umwelt, 2000.
- (77) Suleiman, A.; Tight, M. R.; Quinn, A. D. Applying Machine Learning Methods in Managing Urban Concentrations of Traffic-Related Particulate Matter (PM₁₀ and PM_{2.5}). *Atmos. Pollut. Res.* **2019**, *10* (1), 134–144.
- (78) Keuken, M.; Denier van der Gon, H.; van der Valk, K. Non-Exhaust Emissions of PM and the Efficiency of Emission Reduction by Road Sweeping and Washing in the Netherlands. *Sci. Total Environ.* **2010**, *408* (20), 4591–4599.
- (79) Mennekes, D.; Nowack, B. Tire Wear Particle Emissions: Measurement Data Where Are You? *Sci. Total Environ.* **2022**, *830*, 154655.
- (80) Hasher, L.; Goldstein, D.; Toppino, T. Frequency and the Conference of Referential Validity. *J. Verbal Learning Verbal Behav.* **1977**, *16* (1), 107–112.
- (81) Harrison, R. M.; Allan, J.; Carruthers, D.; Heal, M. R.; Lewis, A. C.; Marner, B.; Murrells, T.; Williams, A. Non-Exhaust Vehicle Emissions of Particulate Matter and VOC from Road Traffic: A Review. *Atmos. Environ.* **2021**, *262*, 118592.
- (82) Organisation for Economic Co-operation and Development (OECD). *Non-Exhaust Particulate Emissions from Road Transport: An*

- Ignored Environmental Policy Challenge; OECD, 2020. DOI: 10.1787/4a4dc6ca-en.
- (83) Vanherle, K.; Lopez-Aparicio, S.; Grythe, H.; Lükewille, A.; Unterstaller, A.; Mayeres, I. *Transport Non-Exhaust PM-Emissions. An Overview of Emission Estimates, Relevance, Trends and Policies*. ETC/ATNI Report 5/2020; EEA, 2021.
- (84) Singh, V.; Biswal, A.; Kesarkar, A. P.; Mor, S.; Ravindra, K. High Resolution Vehicular PM10 Emissions over Megacity Delhi: Relative Contributions of Exhaust and Non-Exhaust Sources. *Sci. Total Environ.* **2020**, *699*, 134273.
- (85) Piras, G.; Pini, F.; Di Girolamo, P. PM10 Emissions from Tires: A Disruptive Estimate Questioning Present Pollution Mitigation Strategies. *Atmos. Pollut. Res.* **2024**, *15* (1), 101939.
- (86) Svensson, N.; Engardt, M.; Gustafsson, M.; Andersson-Sköld, Y. Modelled Atmospheric Concentration of Tyre Wear in an Urban Environment. *Atmos. Environ. X* **2023**, *20*, 100225.
- (87) Kim, J.; Park, E.; Moon, H.; Son, H.; Hong, J.; Wi, E.; Kwon, J. T.; Seo, D. Y.; Lee, H.; Kim, Y. Estimation of the Concentration of Nano-Carbon Black in Tire-Wear Particles Using Emission Factors of PM10, PM2.5, and Black Carbon. *Chemosphere* **2022**, *303* (P1), 134976.
- (88) Thorpe, A. J.; Harrison, R. M.; Boulter, P. G.; McCrae, I. S. Estimation of Particle Resuspension Source Strength on a Major London Road. *Atmos. Environ.* **2007**, *41* (37), 8007–8020.
- (89) Braysher, E. C.; Brown, A. S.; Brown, R. J. C.; Molden, N. Traceable Determination of Metal Composition of Tyres Using Tandem ICP-MS and Benchmarking of Emissions Inventories. *Environ. Sci. Process. Impacts* **2024**, *26* (2), 298–304.
- (90) Sarica, T.; Chaillou, C.; Roustan, Y.; Larrieu, C.; Wali, S. E.; Sartelet, K. Differentiated Impact of Low-Exhaust-Emission Vehicles on NO2 and Particle Concentrations in the Paris Region. *Eur. Transp. Res. Rev.* **2024**, *16* (34), DOI: 10.1186/s12544-024-00660-2.
- (91) Tomar, G.; Nagpure, A. S.; Kumar, V.; Jain, Y. High Resolution Vehicular Exhaust and Non-Exhaust Emission Analysis of Urban-Rural District of India. *Sci. Total Environ.* **2022**, *805*, 150255.
- (92) Simons, A. Road Transport: New Life Cycle Inventories for Fossil-Fuelled Passenger Cars and Non-Exhaust Emissions in Ecoinvent V3. *Int. J. Life Cycle Assess.* **2016**, *21*, 1299–1313.
- (93) Liu, Y.; Chen, H.; Gao, J.; Li, Y.; Dave, K.; Chen, J.; Federici, M.; Perricone, G. Comparative Analysis of Non-Exhaust Airborne Particles from Electric and Internal Combustion Engine Vehicles. *J. Hazard. Mater.* **2021**, *420*, 126626.
- (94) Mehlig, D.; Staffell, I.; Stettler, M.; ApSimon, H. Accelerating Electric Vehicle Uptake Favours Greenhouse Gas over Air Pollutant Emissions. *Transp. Res. Part D Transp. Environ.* **2023**, *124*, 103954.
- (95) Castiglione, T.; Perrone, D.; Polistina, M. Evaluation of PM Emissions from Internal Combustion Engines, Electric and Plug-In Hybrid Vehicles by Using Emission Factors. *SAE Technol. Pap.* **2023**, 2023-24-0116.
- (96) Woo, S. H.; Jang, H.; Lee, S. B.; Lee, S. Comparison of Total PM Emissions Emitted from Electric and Internal Combustion Engine Vehicles: An Experimental Analysis. *Sci. Total Environ.* **2022**, *842*, 156961.
- (97) Liu, Y.; Chen, H.; Jiang, L.; Li, T.; Guo, J.; Wei, T.; Crowther, R. Environmental and Health Impacts of Banning Passenger Cars with Internal Combustion Engines: A Case Study of Leeds, UK. *Transp. Res. Part D Transp. Environ.* **2024**, *134*, 104343.
- (98) Schmitt, J.; Hatzopoulou, M.; Abdul-Manan, A. F.N.; MacLean, H. L.; Posen, I. D. Health Benefits of US Light-Duty Vehicle Electrification: Roles of Fleet Dynamics, Clean Electricity, and Policy Timing. *Proc. Natl. Acad. Sci. U. S. A.* **2024**, *121* (43), No. e2320858121.
- (99) Rausch, J.; Jaramillo-Vogel, D.; Perseguers, S.; Schnidrig, N.; Grobety, B.; Yajan, P. Automated Identification and Quantification of Tire Wear Particles (TWP) in Airborne Dust: SEM/EDX Single Particle Analysis Coupled to a Machine Learning Classifier. *Sci. Total Environ.* **2022**, *803*, 149832.
- (100) Sommer, F.; Dietze, V.; Baum, A.; Sauer, J.; Gilge, S.; Maschowski, C.; Gieré, R. Tire Abrasion as a Major Source of Microplastics in the Environment. *Aerosol Air Qual. Res.* **2018**, *18* (8), 2014–2028.
- (101) Dahl, A.; Gharibi, A.; Swietlicki, E.; Gudmundsson, A.; Bohgard, M.; Ljungman, A.; Blomqvist, G.; Gustafsson, M. Traffic-Generated Emissions of Ultrafine Particles from Pavement-Tire Interface. *Atmos. Environ.* **2006**, *40* (7), 1314–1323.
- (102) Mathissen, M.; Scheer, V.; Vogt, R.; Benter, T. Investigation on the Potential Generation of Ultrafine Particles from the Tire-Road Interface. *Atmos. Environ.* **2011**, *45* (34), 6172–6179.
- (103) Park, I.; Lee, J.; Lee, S. Laboratory Study of the Generation of Nanoparticles from Tire Tread. *Aerosol Sci. Technol.* **2017**, *51* (2), 188–197.
- (104) Haugen, M.; Buhler, P.; Schläfle, S.; O'Loughlin, D.; Saladin, S.; Giorio, C.; Boies, A. Method Development and Analysis of Nanoparticle Size Fractions from Tire-Wear Emissions. *Environ. Sci. Atmos.* **2024**, *4* (9), 1079–1090.
- (105) Wi, E.; Park, E.; Shin, H.; Hong, J.; Jeong, S.; Kwon, J. T.; Lee, H.; Lee, J.; Kim, Y. Overall Distribution of Tire-Wear Particles, Nanocarbon Black, and Heavy Metals in Size-Fractionated Road Dust Collected from Steel Industrial Complexes. *Sci. Total Environ.* **2023**, *884*, 163878.
- (106) Cadle, S. H.; Williams, R. L. Environmental Degradation of Tire-Wear Particles. *Rubber Chem. Technol.* **1980**, *53* (4), 903–914.
- (107) Li, K.; Yu, J.; Kong, D.; Chen, X.; Peng, Y.; Wang, L. Differential Cytotoxicity to Human Cells in Vitro of Tire Wear Particles Emitted from Typical Road Friction Patterns: The Dominant Role of Environmental Persistent Free Radicals. *Chemosphere* **2023**, *343*, 140256.