

Impacts of Tire Wear Emissions Compared to the Impacts of PM_{2.5} and PM₁₀ on Humans

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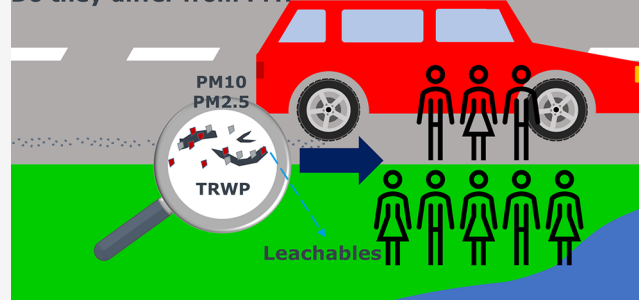


Supporting Information

ABSTRACT: The discussion of potential adverse effects of particulate tire wear emissions on ecosystems and human health highlights the need for systematic evaluation of their sources, exposure pathways, and health impacts. Global urbanization may increase exposure to tire and road wear particles (TRWPs) and tire-related chemicals, especially in high-traffic areas. This literature review examines current knowledge on human exposure to TRWPs and tire-related chemicals and explores whether TRWPs pose a distinctive risk compared with airborne particulate matter (PM). Analytical challenges persist in identifying airborne TRWPs, as most research focuses on tire wear particles (TWPs) alone, due to difficulties in defining mass ratios within the TRWP aggregate. TWPs constitute <5 wt % of ambient PM_{2.5} and PM₁₀; however, inconsistent analytical methodologies hinder a conclusive exposure assessment. Actual data on human exposure to TWPs or TRWPs are scarce. Tire-related chemicals have been found in human body fluids, but their exposure pathways are unclear. Toxicological data mainly derive from *in vitro* studies with few harmonized designs. Comparative research suggests that TRWPs are not more toxic than other PM fractions. This review emphasizes the need for harmonized methods, global and regional exposure characterization, and identification of TRWP exposure pathways for humans to address potential health implications more accurately.

KEYWORDS: TRWP, airborne, additives, exposure, hazard, risk assessment

Impact of tire wear emissions on human health Do they differ from PM?



1. INTRODUCTION

The potential for adverse effects of tire-related chemicals on different salmonid species,¹ the recent reports of possible human exposure to particulate tire wear,^{2,3} and the detection of tire-related chemicals in human body fluids,^{4,5} highlight an increased focus on tire and road wear particles (TRWPs) and their potential effects on the environment and human health. Today, most of the global population lives in urban areas with an increasing trend for urbanization.⁶ As the traffic in urban regions is higher compared to rural areas,⁷ the potential for exposure to TRWPs for much of the global population may exist. However, the multifaceted exposure of humans to naturally occurring and anthropogenic materials from diverse sources makes quantifying the sources, exposure routes and human health implications for TRWPs a complex undertaking.⁸ A conceptual exposure model for environmental and human exposure to tire wear emissions has been developed by Müller et al. (2025)⁸ based on available literature data. Müller et al. (2025)⁸ concluded that TRWP exposure via air may be a predominant pathway for human exposure because it is a direct pathway (inhalation of airborne TRWPs) while indirect pathways such as oral intake via food, water or soil may play a minor role. However, the relative importance of different exposure pathways remains unresolved as exposure via air is

more studied than water and food. Similarly, the exposure pathways are also a central research question in context of the broader micro- and nanoplastic discussion. While the presence of micro- and nanoplastics in the human body have been demonstrated, the exposure pathways and potential health impacts are also not yet fully understood.^{9,10} For TRWPs, their presence in the particulate phase of ambient air has been consistently demonstrated by mass-based^{11–13} and by single-particle analyses.^{14,15} These studies provide direct physical evidence of airborne TRWPs in urban and roadside environments, establishing a clear exposure pathway via inhalation. A recent study on uptake of tire-related chemicals via vegetable food may support this conclusion while it also points out that the air deposition may play a role in uptake of tire-related chemicals by plants.⁵ Hence, this structured critical literature review focuses on the direct human exposure via inhalation of

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airborne TRWPs and discusses also the relevance of tire-related chemicals for human health impact assessment.

Urban or roadside airborne particulate matter (PM) has a complex composition with inorganic and organic particles that come from multiple natural and anthropogenic sources, e.g., sea salt, soil/sand erosion, wildfire smoke, combustion engines, brake wear, pavement wear, tire wear and mineral particles from other sources, e.g., facades.¹⁶ To date, limited efforts have been made to differentiate the specific contributions of individual airborne PM constituents—such as TRWPs—to observed adverse health effects in humans.^{17–19} These investigations are complicated by the nature of TRWPs as heterogeneous aggregates consisting of particles of various origins, including tire wear, brake wear and road pavement wear. Hazard data for PM reveal that PM_{2.5} can elicit adverse health effects due to its fine size and chemically diverse constituents.²⁰ An important research question is to what extent TRWPs differ in toxicity compared to other non-TRWP PM constituents or more substantially contribute to the PM fractions relevant for human exposure—an inquiry complicated not only by the challenges of isolating and characterizing individual PM components but also by the logistical constraints of conducting controlled human or animal airborne exposure studies. Recently, researchers have published biomonitoring studies that indicate the presence of tire-related chemicals in human body fluids,^{21–26} but exposure pathways remain under discussion because some of these chemicals have uses in products other than tires.^{27–29} Therefore, an understanding of the contribution to human exposure from tire emissions is a critical first step toward advancing the understanding of potential health impacts.

This literature review addresses first exposure conditions to PM_{2.5} and PM₁₀ for urban and rural locations, which were compared with exposure to TRWPs and tire-related chemicals. Second, data on the occurrence of tire-related chemicals in human body fluids were analyzed. Third, data on the adverse effects of PM and airborne TRWPs are compared, whereby the available information in the literature was compared to the human health impacts associated with PM_{2.5} and PM₁₀. Finally, literature data on the potential effects of tire-related chemicals measured in human body fluids were assessed. The literature review concludes by identifying and summarizing knowledge and data gaps as well as important methodological requirements for reliable exposure and hazard data of TRWPs and tire-related chemicals with respect to human impact assessments.

2. LITERATURE SEARCH AND NUMBER OF RELEVANT PUBLICATIONS

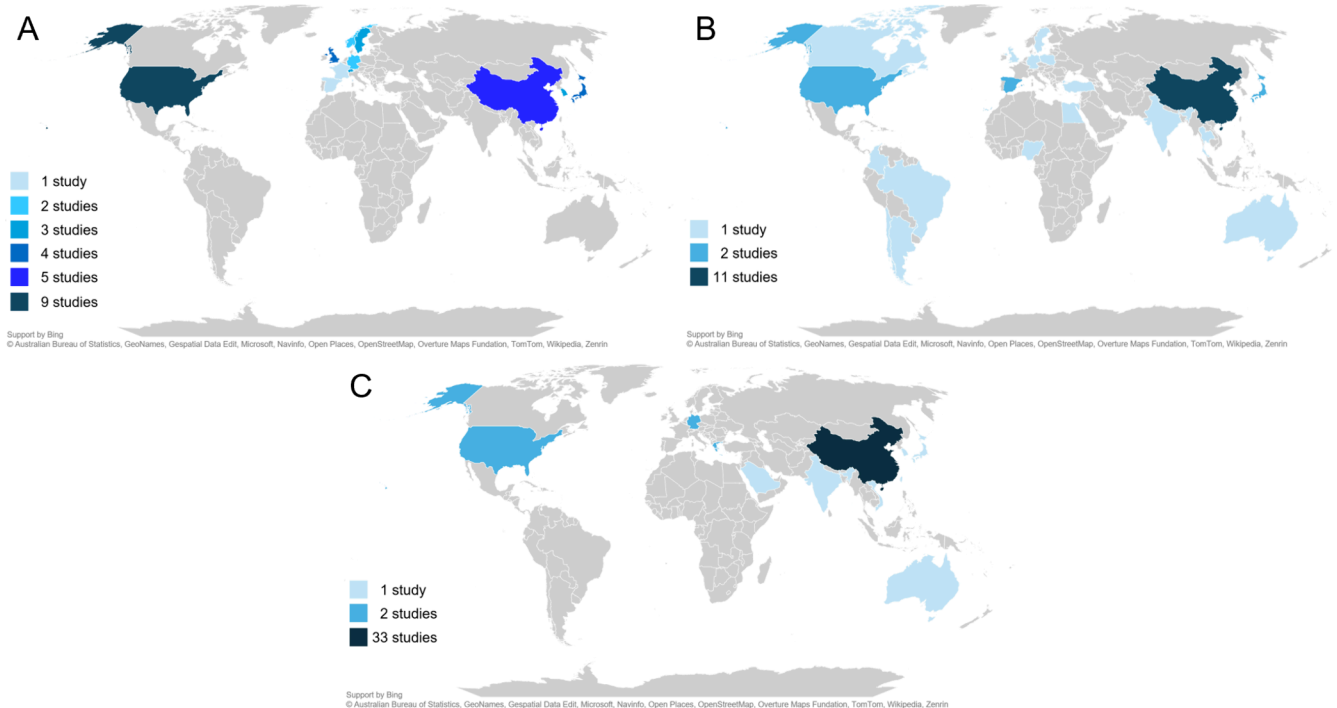
A structured literature search was conducted to review and evaluate the state of knowledge of tire wear emissions covering the following three topics: (1) tire wear emission during the use phase of tires, (2) environmental impact assessment of tire wear emissions, and (3) human impact assessment of tire wear emissions. While based on one comprehensive literature search, a separate literature review was carried out for each topic. This state-of-the-art review comprises all relevant literature on the topic “human impact assessment of tire wear emissions”. The two other reviews have been published previously.^{8,30}

The structured literature search was conducted using the online databases Web of Science and PubMed comprising the years 1985–January 2024 and continuously updated until June

2025. While no structured review was done, individual foundational papers from before 1985 were included as they were among the first detecting TRWPs in air.^{31–33} We focused on peer-reviewed literature as well as gray literature, including white papers and reports. Preprints which have not undergone peer review were not considered. The list of keyword combinations used in the search has been provided elsewhere.⁸ In addition to those keywords, the search terms “urine”, “blood”, and “milk” in combination with “PPD”, “benzothiazole”, and “amine” have been included to ensure the identification of all relevant literature of exposure and hazard measurements of TWPs, TRWPs, and tire-related chemicals in air and humans. After duplicate removal all literature items were prescreened based on their title and accordingly assigned to the three topics. A literature item was assigned to the topic “human impact assessment of tire wear emissions” if the title referred to environmental exposure of tire wear emissions, human exposure of tire wear emissions or ecotoxicological studies in context of human exposure or PM exposure. This prescreening resulted in 274 literature items. After the first assignment, each literature item was re-evaluated based on their abstract to identify false positives that did not cover a relevant topic of this literature review. Subsequently, the literature items were assigned to predefined topics covering the relevant themes of TWPs, TRWPs and tire-related chemicals: exposure in air, exposure in human and hazard assessment. Items were also assessed for quality to ensure they contained relevant and reliable information for the literature review. The quality criteria include the following: (I) journal type: peer-reviewed journal, gray literature (only reports with clear origin), information on author and publisher provided, English language; (II) methodology: complete description of the sampling and analytical methodology available; (III) data/results: literature contains extractable data/results and no complete modeled or predicted data, and data evaluation is comprehensible. The exclusion of completely modeled and predicted data within quality criterion III was to ensure the validity of the health risk assessment, as the utilization of measured data is preferred over modeling in this study. Direct monitoring data of PM₁₀ and PM_{2.5} as well as of TRWPs captures local spatial and temporal variability. It further reduces the uncertainties associated with exposure estimation inherent in modeling and directly relates to actual environmental conditions. According to Yu et al. (2024),³⁴ models are often inadequately tested for reliability and potential exposure errors in epidemiological studies. The use of station data reduces inherent uncertainties and establishes a direct link to actual environmental conditions. Furthermore, Saladin et al. (2024)³⁵ showed that current tire wear PM₁₀ emission factors need revision, as secondary literature, including emission inventories from environmental agencies, report 2 to 30 times higher emission factors than primary research. Our aim was to base the comparison of airborne TRWP to PM_{2.5} and PM₁₀ on measurement-derived concentrations. Recognizing the importance of TRWP environmental measurements for exposure assessment, recent research has focused on analytical method refinements.^{36–38} Hence, no receptor model study was included, as well as source apportionment studies solely based on emission factor calculations. Data from source apportionment studies based on actual air sample measurements were extracted but are displayed separately from complete measured data.

Table 1. Numbers of Studies for Human Impact Assessment Identified from the Structured Literature Search

topic	total (containing quantitative data)
overall	211 (153)
(i) exposure of TRWP in air	64 (34)
(ii) exposure of tire-related chemicals in air	26 (18)
(iii) exposure of TRWP in humans	1 (0)
(iv) exposure of tire-related chemicals in human body fluids	41 (40)
(v) hazard assessment of TRWP	37 (<i>in vitro</i> 19; <i>in vivo</i> 6)
(vi) hazard assessment of tire-related chemicals	66 (<i>in vitro</i> 34; <i>in vivo</i> 23)

**Figure 1.** World map highlighting the countries based on the number of studies that analyzed samples originating from each respective country. (A) Tire wear particle air concentration. (B) Air concentration of tire-related chemicals. (C) Concentration of tire-related chemicals in human body fluids.**Table 2. Terminology Used in This Review That Is Relevant for Tire Wear Emission Research**

terminology	definition
tire wear particles (TWP)	Material from tire tread which is released in particulate form during the wear process covering a size range from nanometer to micrometer. It is a constituent of TRWP and usually does not occur in the environment as an individual particle. Only in case of artificially produced tire tread particles, e.g., by milling, individual TWP exist.
tire and road wear particles (TRWP)	Heteroaggregates consisting of TWP and particles from mineral aggregate and bitumen that are formed during the wear process, as well as other wear particles e.g. brake wear
airborne TWP	Fine TWP of the size fraction PM10 and PM2.5
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tire tread particles produced, e.g., cryo-milled (CMTT)	Artificially produced particles from tire tread, e.g., by cryogenic milling process; usually used for testing purposes in laboratories; There are other grinding methods available.
total suspended particles (TSP)	All airborne particulate matter materials
particulate matter $\leq 20 \mu\text{m}$ (PM20)	All particles with a diameter of $20 \mu\text{m}$ or less of any particle type.
particulate matter $\leq 10 \mu\text{m}$ (PM10)	All particles with a diameter of $10 \mu\text{m}$ or less of any particle type.
particulate matter $\leq 2.5 \mu\text{m}$ (PM2.5)	All particles with a diameter of $2.5 \mu\text{m}$ or less of any particle type.
tire-related chemicals	Chemicals which are tire constituents but may also have other sources
leachables	Chemicals which are released/leached from tires and from TRWP to aqueous phases

Eventually, 211 publications were identified that are related to human impact assessment of tire wear emissions (Tables 1 and S1). Most of these studies (64) investigate the contribution of TWP or TRWP to airborne PM, of which 34 studies report extractable airborne TWP or TRWP concen-

trations. Concentrations of tire-related chemicals in human body fluids were reported in 40 studies. However, most studies on tire-related chemicals in air and in human body fluids originate from China, while for other countries, only one or two studies exist. Hence, a globally diverse interpretation of the

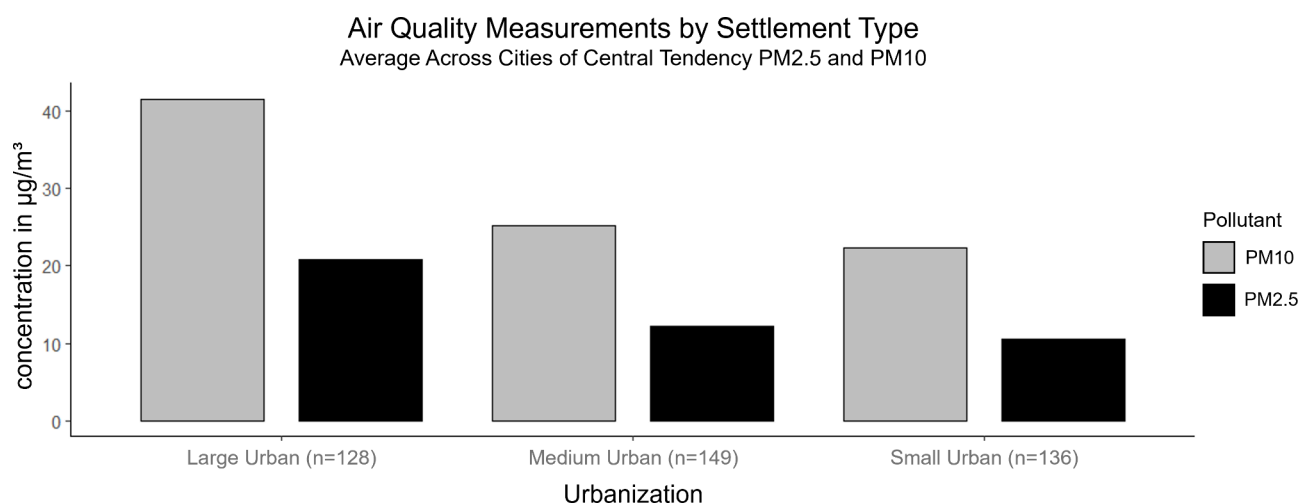


Figure 2. Average PM10 and PM2.5 in cities with populations >1 million (large), 300,000 to 1 million (medium) and 100,000 to 300,000 (small). Data were taken from the Air Quality Open Data Platform, 2024.⁴⁷

reported concentrations has not yet been possible. Only the airborne TRWP concentration has been investigated globally (Figure 1). Hazard assessment studies are dominated by *in vitro* studies of TRWP, while only six *in vivo* studies were available.

3. PROPOSAL OF A HARMONIZED NOMENCLATURE FOR IMPACT ASSESSMENT OF TIRE WEAR EMISSIONS

The available literature does not provide a consistent and uniform nomenclature in the field of tire wear research.³⁹ Therefore, it is necessary to define the terminology used in this manuscript to avoid misunderstanding and misinterpretation of results, conclusions, and suggestions presented here (Table 2). Ambient PM2.5 and PM10 represent two size fractions of airborne PM, both of which may contain TRWPs. TRWPs are heteroaggregates composed of various materials, including tire tread fragments from the wear process, which we term tire-wear particles (TWP). As a result, the complexity decreases from PM to TRWPs to TWP, with respect to both their composition and their sources. Moreover, while TRWPs are particle components found within PM10 and PM2.5, TWPs are generally not present as individual particles; rather, they exist as material constituents within TRWPs. In terms of exposure assessment, the physical entity relevant to exposure is the TRWP itself. Conversely, from a source identification perspective, the TWP is the entity, as it represents the original material arising from the tire tread.

This distinction is important when quantifying particulate airborne tire wear emissions. Direct measurement of TRWP mass concentration is generally not feasible; instead, quantification is usually performed by measuring TWPs as the constituent material within TRWPs. The TWP concentration is again quantified by its constituent, such as the rubber content, e.g., by pyrolysis GC-MS,^{11–13} or zinc, e.g., by GF-AAS.⁴⁰ Eventually, the TRWP concentration is calculated using a conversion factor based on the assumption of a mineral fraction in the TRWP. However, this conversion introduces additional uncertainty because the factor is usually a fixed value not accounting for the range of mineral contents in TRWPs.⁴¹ Hence, most available studies measure and report the airborne TWP concentration and not the TRWP concentration to

estimate the contribution of tire wear to the airborne PM fraction. In case airborne TRWP concentrations are reported, several studies define “TRWP” differently or even define TWP = TRWP, meaning that TRWP concentrations between studies are not comparable. To have uniform data we always extracted the reported airborne TRWP concentrations of the cited studies for this review. In cases where only the TRWP concentration is reported, the TWP concentration was calculated manually based on the conversion factor the corresponding study used. If no manual conversion was possible, the TRWP concentration was reported and highlighted accordingly.

4. HOW DOES TRWP CONTRIBUTE TO AIRBORNE FINE PARTICULATE MATTER?

Total Airborne Particulate Matter Concentration

Historically, airborne PM in population dense areas has been investigated as a single entity, and those investigations revealed adverse health impacts on human population,⁴² leading to the establishment of regulations and air quality standards for PM in air.^{43,44} Across various countries, PM2.5 standards include those for a 1 year averaging period ranging from <5 µg/m³ to >35 to 80 µg/m³ and those for a 24 h averaging period ranging from <15 µg/m³ to >50 to 75 µg/m³. For PM10, the standards for a 1 year averaging period range from <15 µg/m³ to >70 to 120 µg/m³, and the 24 h standards range from <45 µg/m³ to >150 to 340 µg/m³.⁴⁵ These air quality standards are nonspecific total mass (sum) parameters and do not differentiate between possible PM constituents like TRWPs, brake dust, pavement wear and possibly wildfire smoke. Given the diversity of ambient PM contributors, exposure assessments for TRWPs and TWPs should account for their contribution to PM2.5 and PM10 while also considering the potential for distinct toxicological profiles and exposure dynamics compared to other PM constituents.⁴⁶

In this study, the global PM2.5 and PM10 concentrations were evaluated based on open-source data from the World Air Quality Index (WAQI) Project.⁴⁷ WAQI data used here consist of measurements from certified air quality monitoring stations in urban, rural, and near-road environments from the year 2024. For the year 2024, these stations provided direct observations of PM2.5 and PM10 concentrations, offering a robust empirical foundation for evaluating the ambient air

Table 3. Mean, Minimum, and Maximum Air Concentrations of Tire Wear Particles (TWPs) and the Corresponding Total Suspended Particles (TSP), PM₂₀, PM₁₀, or PM_{2.5} and Mean, Minimum, and Maximum Contributions of TWPs to TSP, PM₂₀, PM₁₀, or PM_{2.5}, Separated Based on the Speciation Technique

size fraction	sampling location	TWP concentration ($\mu\text{g}/\text{m}^3$)			TSP or PM _x concentration ($\mu\text{g}/\text{m}^3$)			contribution of TWPs to TSP or PM _x (%)		
		mean	min	max	mean	min	max	mean	min	max
Speciation: Rubber Marker/SEM-EDX/SR-XRF/TXRF										
TSP	roadside ^{31,33,40,51}	0.51	0.12	6.00	72.1	35.0	271	1.35	0.15	6.60
	tunnel ³¹	1.54	0.96	2.44	134	90.0	210	1.16	1.01	1.42
	urban ⁵²	2.03	0.39	6.96	96.5	26.0	198.0	2.03	0.51	3.52
	marine ^{53,54}	0.02	<LOD	0.04						
PM ₂₀	roadside ^{31,40}	2.36	0.92	2.90	55.2	33.0	109	4.40	2.00	5.79
	tunnel ³¹	4.20	0.80	9.68	232	103	321	1.63	0.39	3.03
PM ₁₀	roadside ^{11–14,32,40,50,52,55–60}	2.17	0.02	16.1	43.6	10.0	163	2.55	0.07	9.63
	urban ^{14,52,56,58,60}	1.25	0.13	4.53	4.7			2.80	0.83	5.9
PM _{2.5}	roadside ^{11–14,61}	0.64	0.002	2.84	12.5	1.5	28.4	1.65	0.05	7.60
	tunnel ⁶²	2.17	1.84	2.48	162			1.34		
	urban ¹⁴	<LOD			0.7			0.00		
Speciation: Model										
PM ₁₀	roadside ^{63–68}	1.07	<LOD	3.40	64.2			4.85	0.00	10.7
	tunnel ⁶⁹							5.75	4.0	9.0
PM _{2.5}	roadside ^{3,65,66,70,71}		<LOD	6.60	53.9	28.4	81.2	8.85	0.00	25.0
	tunnel ⁶⁹							5.00	3.00	6.00

pollution levels. However, despite their utility, several limitations inherent to the WAQI data set must be acknowledged when estimating human exposure. Not all regions are uniformly covered, and the spatial distribution of stations results in an emphasis on urban areas with comparatively fewer monitoring locations in rural and roadside environments. This imbalance complicates attempts to derive comprehensive exposure estimates across the full spectrum of the human microenvironments.

To contextualize TRWP concentrations relative to total PM_{2.5} and PM₁₀, WAQI data archived in units of air quality index (AQI) were converted to units of $\mu\text{g}/\text{m}^3$ and summarized using R version 4.2.1. Considering cities with at least 300 days of both PM_{2.5} and PM₁₀ data in 2024, central tendency (daily median) of total airborne PM_{2.5} and PM₁₀ exhibits appreciable global variability (Table S2) with more heavily populated cities characterized by higher PM_{2.5} and PM₁₀ concentrations (Figure 2). Less populated regions like Oceania show lower PM concentration in air compared to densely populated and industrialized regions, e.g., south and east Asia (Table S2). However, this PM data does not provide a conclusion on human exposure to TRWP. Therefore, this present study examines also available data reflecting the contribution of airborne TRWP to the PM_{2.5} and PM₁₀ fractions.

Airborne Tire Wear Particle Concentrations in Ambient Air

The size of TRWPs ranges from the nanometer up to the micrometer scale,^{48,49} and TRWPs are just one among other constituents of the PM_{2.5} and PM₁₀.⁵⁰ Quantifying TRWP mass concentrations is usually performed by determination of the TWP mass concentration, followed by a calculation using a conversion factor. This conversion introduces additional uncertainty because the factor is usually a fixed value that does not account for the range of mineral contents in TRWP.⁴¹ Therefore, most available studies provide the concentration of TWPs instead of TRWPs to estimate the contribution of tire wear to the airborne PM fraction. To ensure a uniform data

set, only TWP data were extracted from each study during this review (Tables 3 and S3).

The airborne portion of TWPs accounts for a mass fraction of less than 5–10% of the total airborne PM.^{11,14,31} The contribution of airborne TWPs to airborne PM for urban, roadside, and tunnel sampling sites was between 0 and 8.8% for all size fractions in the studies analyzed here (Tables 3 and S3). The maximum contribution of TWPs to the total suspended matter (TSP) was between 6.6% for roadsides and 3.5% for urban sites (Table 3). The collated concentration data set of TWPs for urban sites, roadside, and tunnel sampling sites varies considerably, and the resulting high uncertainty of the data complicates the identification of trends (Table S3). Still TWPs at roadsides in the smallest size fraction PM_{2.5} showed approximately 1 order of magnitude lower concentrations compared to PM₁₀ and between two to 3 orders of magnitude lower concentrations compared to PM₂₀ (Table 3).

The large variations in TWP concentrations observed in Table S3, sometimes reaching 2 orders of magnitude, are likely due to differences in sampling locations, sampling methods, analysis methods and the time of the study. Nearly 23% of the studies (eight out of 34 studies) are more than 20 years old and two of them even date back to over 50 years. While this study aims to compile all relevant publications and present the state of knowledge of airborne TWP concentrations, considerable advancements have occurred over the past decades. These include changes in tire design and materials, evolution of vehicle fleets, increased traffic density, modifications in road construction practices, increased urbanization, changing weather conditions due to climate change and improvements in analytical methodologies. Consequently, the applicability of findings from these studies to present-day conditions is limited. Yet, no significant difference in the TWP concentration between studies from before 20 years ago and from the last 20 years is observed, e.g., mean (min–max) TWP concentrations in the PM₁₀ fraction of 2.03 (0.02–16.1) $\mu\text{g}/\text{m}^3$ vs 2.05 (0.0–6.44) $\mu\text{g}/\text{m}^3$. Hence, the inclusion of the data does not lead to a bias in the data set. Rather, a variation of the

data due to the sampling location is expected (Table S3 and Figure 1A). For example, a PM sample from the roadside of a busy highway junction will have higher TWP concentrations compared to a sample from the roadside of a less busy side road. However, there is also uncertainty in the data due to the analytical methodology applied. This uncertainty is often related to variations in sampling methods concerning the technique used (Figure S1), as well as the employed air flow rate over filter and charge effect of the filter.^{72,73} Besides sampling methods, differences in quantification methods also contribute to the variations (Figure S2). In total 14 different sampling techniques and 12 different quantification methods were used by the 34 studies. Furthermore, the data suggests that the selected target analyte may also contribute to the variation in TWP concentration. Different markers may have additional sources other than tires, resulting in an overestimation of the concentrations. A bias toward the quantification method cannot be assessed due to the insufficient size of the data set. For greater consistency and reliability regarding the abundance of airborne TWPs, it is recommended that comparable data sets are generated by means of harmonized sampling and analytical efforts. To enhance the robustness of the data, it may be advisable to apply multiple chemical markers for the purpose of quantification.

Despite the uncertainties, the current data set indicates that the total contribution of TWP to the PM fraction in the air varies depending on the sampling location and time and averages less than 5 wt % across various size fractions. From the obtained data set on airborne TWP concentrations (Table S3), it can be inferred that there is a lack of comparable and robust data on TWP exposure levels in different environments (urban, rural, near highways) which is needed for human exposure assessment.

It should be noted that the ambient TWP concentrations reported in this section represent only the airborne fraction of the total tire wear generated at the road surface. On the basis of recent measurement-derived emission factor data, only about 2.5% of total tire wear mass becomes airborne as PM₁₀, with PM_{2.5} representing approximately 40% of that fraction.⁷⁴ The remaining mass is deposited on road surfaces or is incorporated into road dust. This context is important for interpreting the <5 wt % TWP contributions to ambient PM reported here: the small airborne fraction reflects both the physics of particle generation and the limitations of current emission inventories, which have historically overestimated airborne TWP by factors of 2 to 30 relative to primary measurement data.³⁵ Harmonized, measurement-based emission factors disaggregated by particle size fraction and vehicle type remain a critical need for improving both ambient exposure estimates and the reliability of human health risk characterization for TWPs or TRWPs.

Exposure to Tire-Related Chemicals in PM Fractions

As TRWPs and TWPs contain a complex mixture of substances, it is also relevant for human impact assessment to determine which tire-related chemicals can be detected in airborne PM fractions and at what concentrations. Few studies have investigated concentrations of tire-related chemicals in PM_{2.5} and PM₁₀ in urban, roadside, and tunnel air samples (Table S5). Among these studies, 6PPD and 6PPD-Q as well as BTs were most often investigated for PM_{2.5} and PM₁₀ (for substance name abbreviations, see Table S4). Besides these three chemicals, compounds such as PPDs (IPPD, 7PPD,

77PD, CPPD, DPPD, DTPD, and DNPD), PPD-Qs (IPPD-Q, 7PPD-Q, CPPD-Q, DPPD-Q, and DTPD-Q), and other tire-related substances (DPG, DPG derivatives, amines, phthalates) have been analyzed.^{2,21,75,76} Generally, these substances were frequently detected in PM samples. For instance, Xia et al. (2025)⁷⁵ reported a 100% detection frequency in urban PM samples for PPDs and PPD-Qs. Kuntz et al. (2024)² detected 37 out of 39 compounds in PM₁₀ samples from roadside sampling sites. Despite the high detection frequency, no general trend in concentration of tire-related substances in PM_{2.5} and PM₁₀ was derived from the available data set, as only few studies analyzed PM₁₀ and PM_{2.5} together. The number of data sets and the comparability of the data are very limited due to differences in analytical methodologies and sampling sites (Figure 1B and Table S5). Thus, no correlations between occurrence of tire-related chemicals and TWP concentrations are possible. But, where data are available, the chemical concentration trend seems to be tunnel > roadside and urban. However, chemical concentrations at the roadside are not always greater than those in urban areas (Table S5).

5. WHICH CONCENTRATIONS OF TRWP AND TIRE-RELATED CHEMICALS CAN BE FOUND IN HUMAN BODY FLUIDS?

Earlier studies have demonstrated that human exposure to tire wear emissions may occur also through airborne TRWPs.^{77,78} An exposure with airborne TRWPs may result in an uptake of its TWPs constituent by humans, e.g., via inhalation. Yet, no study was identified demonstrating the presence of TWPs in human tissue. Recently, Nihart et al. (2025)⁷⁹ quantified SBR, a main constituent of TWP, pyrolysis products using pyr-GC/MS in human brain, kidney, and liver tissue. Yet, no potential source of origin was identified, and the SBR particle may originate from a variety of rubber products. Furthermore, the detection and quantification of SBR using this analytical technique are known to be affected by matrix interferences. Therefore, comprehensive analytical validation efforts are required to obtain robust and reliable data. In this specific case of brain tissue, false-positive findings during pyr-GC/MS analysis could be expected.⁸⁰ It is therefore essential that sufficient validation efforts are made to avoid false-positive analytical results.^{41,81} Taking this into account from the available literature, nothing can be concluded about the occurrence of TWPs in human bodies.

In contrast, there are many reports (41 studies) of tire-related chemicals (PPDs,^{22,23,25,82–95} PPD-Qs,^{22,23,25,26,82–89,91–101} BT and derivatives,^{24,25,92,95,102–113} BTR and derivatives,^{24,25,92,95,102–110} DPG and derivatives,^{4,21,22,25,86,87,94,114} HMMM⁸⁶) in human body fluids (Table S6). However, it should be noted that the class of tire-related chemicals a human could potentially be exposed to is much larger, as a tire can be composed of up to 200 different additives.¹¹⁵ The tread of a tire can contain around 20 different chemicals.¹¹⁶ Overall, most data sets are for PPDs and PPD-Qs and comprise concentrations in six different human body fluids (urine, blood serum, human milk, amniotic fluid, cerebrospinal fluid, and follicular fluid) among different population groups (children, adults, pregnant/postpartum women). For 6PPD-Q, 35 data sets for the six different media were found and concentration ranged from <0.0012 to 62.8 ng/mL (compare Table S6). However, all PPD and PPD-Q data sets originate solely from Chinese population groups. Hence, a globally diverse interpretation of the occurrence of 6PPD-Q in human

body fluids is not yet possible. For other substances, there are data from other countries (Australia, Germany, Greece, India, Japan, Korea, Saudi Arabia, Taiwan, USA, Vietnam), but often only one or two data sets, which hinders robust conclusion due to insufficient data (Figure 1C and Table S6). Based on the available data some differences among the groups (children, adults, pregnant/postpartum women) were observed but no general trend was found. These differences may be attributed to different pharmacokinetics and different living habits of these groups.^{4,21,23,82,85,98,111} To date, none of the examined studies reveal exposure pathways for these tire-related chemicals. Instead, hypotheses on exposure are suggested being predominately inhalation, ingestion via food or dust, drinking water consumption and dermal uptake.^{4,21,22,28,82,86,103,108,114,117,118} There is currently, however, no confirmation of human exposure pathways based on real world exposure studies available in literature. This confirmation is complicated by the fact that these chemicals are also used for other applications that are unrelated to tires. For instance, BT is even used as a flavoring substance in food and thus, ingested.¹¹⁹ DPG is a vulcanization accelerator used for rubber production and is present in many rubber products like surgery gloves and plumbing materials.^{28,120} Using these products may lead to other exposure like oral exposure or dermal exposure and subsequent dermal uptake of the chemical. For 6PPD, one market research firm indicates that other nontire applications, including rubber products and polymer modifications, might account for 70 to 75% of the global 6PPD market demand, although estimates vary.²⁷ One example of a nontire use is reflected in the hoses, weather strips, sealing strips, vibration insulators and other rubber parts reaching 3% of the weight of an automobile vehicle.²⁹ Recently, extractable and leachable analyses focused on 6PPD and DPG showed a “potential major contribution of other polymer materials used in household devices such as tap water aerators, particularly O-rings and seals of plumbing materials”.²⁸ The extent of 6PPD use in agricultural polymers is unknown, however, the potential for 6PPD to leach into whole milk or food simulants from the rubber hoses of milk lines with sufficient contact time has recently been confirmed.¹²¹ At present time, it is not possible to determine whether rubber-associated additives detected in human body fluids are derived from tire emissions, nontire rubber emissions and leaching, or other nonrubber uses in polymers.

Furthermore, the data set obtained in this study shows that excretion rates of tire-related chemicals are often higher compared to exposure and uptake rates of the same chemical (Table S7a–c). This observed discrepancy is likely due to the low number of data points and their high uncertainty and needs to be further explored before any sufficiently robust conclusions can be drawn.

This leads to the overall picture: there are shortcomings of the existing data set on human exposure resulting in a limited evaluation due to different analytes in most studies. No relation between PPD and PPD-Q was observed, and no conclusion can be drawn for the exposure to those substances as the results highly depend on the population group, population origin, and population activities as well as multiple sources of the chemical and geographical origin of the data. Finally, the question of where chemical exposure comes from has not been answered yet.

6. WHAT INFORMATION IS AVAILABLE TO CHARACTERIZE HUMAN HEALTH EFFECTS FROM TIRE EMISSIONS?

More than 103 toxicity studies were identified that characterized the potential human health hazard associated with tire emissions. Of these studies, 37 were associated with TWP or TRWP, and 66 were associated with tire-related chemicals.

Human Health Effect Information for TRWPs

Consistent with the conceptual exposure model developed in Müller et al. (2025)⁸ most literature regarding potential human health effects is associated with airborne TRWPs or artificially produced tire tread particles, such as cryo-milled tire tread (CMTT) (for definition, see Table 2) and the inhalation pathway. As a potential component of ambient air PM_{2.5} and PM₁₀ in traffic affected regions, it is logical to evaluate the potential for adverse health effects of TRWPs through the lens of airborne PM toxicity. The U.S. EPA and the World Health Organization (WHO) have stated that there is causal or likely to be causal relationships between exposure to PM_{2.5}, PM_{10–2.5} and ultrafine particulates (UFP) and various human health effects^{122,123} including cardiovascular disease, general mortality, respiratory and nervous system effects, as well as cancer. The bases for their conclusions included epidemiological data, controlled human exposure evaluations, and animal toxicological studies.

The U.S. EPA evaluated the biological plausibility of the adverse health effects observed in the epidemiology studies by examining the toxicology data for potential biological pathways or mechanisms underlying the observations. Of the potential biological pathways, several shared common initial effects despite differences in the observed health effects or the length of exposure. The initial effects included (1) activation of sensory nerves in respiratory tract, (2) respiratory tract injury, (3) respiratory tract inflammation, (4) respiratory tract oxidative stress, (5) translocation of particles and/or soluble components, and (6) olfactory transport. Additionally, 14 intermediate effects that follow the initial effects were evaluated to understand the biological plausibility including: modulation of the autonomic nervous system, local reflex responses/lung irritant responses, morphologic changes, allergic sensitization, altered host defense, upregulation of renin-angiotensin system, cardiac oxidative stress function, altered heart rate/heart rate variability, lung function decrements, respiratory symptoms, toll-like receptor mediated systemic inflammation, altered morphology and barrier function in nasal mucosa, airway remodeling, and increased airway responsiveness.

Since exposure to airborne TRWP does not occur in isolation but rather as a small fraction of the overall PM mixture, understanding the potential of TRWP to cause these effects and the relative potency of the particles is important. No epidemiological studies were identified that examine the connection, if any, between TRWP exposure and the potential for human health impacts. However, *in vitro* cellular-based studies and *in vivo* animal studies that evaluate potential effects of tire tread particles and TRWPs were identified. The available data are organized by biological system and initial or intermediate effects. Details, including test materials, test systems, and assays from the available literature are provided in Tables S8 and S9.

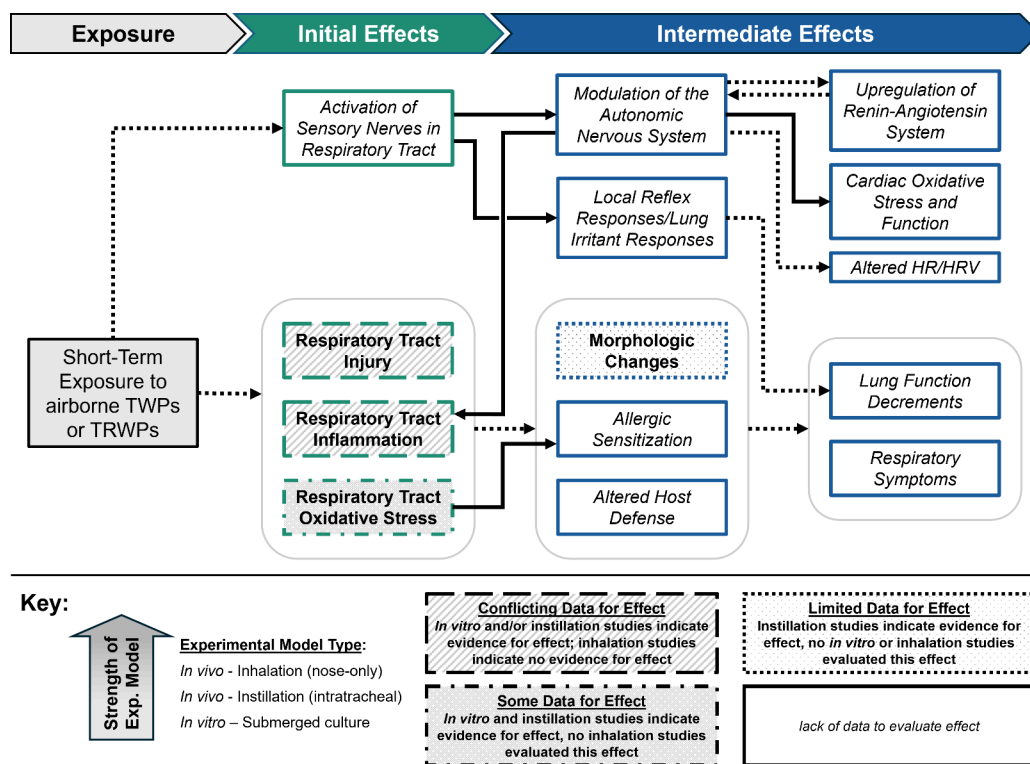


Figure 3. Mapping of available data following short-term airborne TWP or TRWP exposure to initial and intermediate effects of U.S. EPA's biological pathways for respiratory effects.²⁰ Solid arrows indicate that progression from the upstream to downstream effect occurs as a direct result of exposure, whereas dotted arrows denote a possible relationship between the effects. Adapted from ref 20.

Respiratory System. Two biological pathways are postulated for short-term exposure to PM_{2.5} including activation of sensory nerves in the respiratory tract and one or more initial effects including respiratory tract injury, inflammation, and oxidative stress. For long-term exposure, the pathway is postulated as an initial step of respiratory tract injury, inflammation, and oxidative stress.

More than 30 *in vitro* studies of tire tread particles and TRWPs have been used as a tool for assessing the impacts on the respiratory system (Table S8). Most of the *in vitro* studies conducted to date have used primary human bronchial epithelial cells^{124,125} or immortalized lung cell lines^{126–131} to evaluate effects of tire tread particles or TRWPs. Yet, human intestinal or mouse macrophage cell lines have also been used in several studies.^{132–135}

Of the six common initial effects identified for PM_{2.5}, only potential for oxidative stress^{124,125,130,134,135} and respiratory tract inflammation^{131,132,134–138} are potentially supported by the *in vitro* studies of tire tread particles and TRWPs. Although not specified as initial effects for the respiratory system, the available studies also provide insight into the potential for tire tread particles and TRWPs to induce cytotoxicity,^{124–129,131,132,134,136,138} DNA damage and/or alterations in gene expression^{128–132,137} or cell morphology.^{127,132}

Over the past decade, research has shown that airborne particles containing environmentally persistent free radicals (EPFR) are often associated with higher production of reactive oxygen species (ROS), which is an indicator of oxidative stress in a cell system or organism. However, to date, the concentration of EPFR has not been considered by regulatory agencies as a specific causal factor with respect to health outcomes from inhalation of ambient PM. A systematic review

by Kumar et al. (2025)¹³⁹ concluded that currently, there is insufficient exposure and epidemiological information to inform risk assessment. Nevertheless, EPFRs have been quantified in tire tread particles and TRWP *in vitro* toxicity testing following laboratory aging of the particles. The concentrations ranged from approximately $(1–4) \times 10^7$ spins/g, where 1 spin corresponds to 1 free radical.^{125,134} The concentration range is within the range reported for ambient air and indoor dust, but orders of magnitude less than that reported for coal combustion, automobile exhaust, and crop and firewood combustion residues.¹³⁹

Of the seven studies where animals were exposed to various forms of tire tread particles or TRWPs through inhalation or intratracheal instillation (*in vivo* studies), some showed evidence of impacts to the respiratory system, although none investigated or reported activation of the sensory nerves in the respiratory tract (Table S9). Three of the six common initial effects identified for PM_{2.5} have been potentially supported by the instillation studies including respiratory tract injury,^{140–142} respiratory tract inflammation,^{140–143} and respiratory oxidative stress.¹⁴³ With respect to morphologic changes in the lung, three of the instillation studies reported differences with exposure to tire tread particles or TRWPs including changes in airway and alveolar space, vessel wall thickness, and collagen deposition in lung tissue.^{140,142,143} In contrast, neither of the inhalation studies showed evidence of respiratory tract injury or inflammation.^{144,145} In the only *in vivo* study to examine nanosized particles, Li et al. (2022)¹⁴⁰ exposed mice in a single instillation to three doses of tire tread particles with a hydrodynamic diameter of approximately 100 nm. The effects observed included decrements in lung function, differential cell counts, pathological changes in the middle and high dose

groups and changes in mRNA expression. Figure 3 provides a summary of the research available to inform the biological pathways associated with respiratory system effects from exposure to tire tread particles or TRWP in the ambient air.

The relative potency of tire tread particles or TRWPs and other constituents of ambient air PM has been investigated in both *in vitro* and *in vivo* studies. One *in vitro* study reported a comparison between effects elicited from TRWP and that of diesel exhaust particulate (DEP).¹³¹ In this study, the researchers compared cytokine release (CXCL8, IL-1 α , IL-1 β , TNF α) and expression of genes linked to inflammation (CXCL8, IL1A, IL1B, COX2, IL6), xenobiotic metabolism (CYP1A1) and redox responses (HMOX1) in human bronchial epithelial cells (HBEC3-KT) and THP-1-derived macrophages after exposure to samples of TRWPs generated using studded tires at a road simulator (PM10 size fraction) and DEP. The results showed that TRWPs and DEP induced proinflammatory responses acting through different mechanisms and that the relative potency of TRWPs differed between cell types and end points, although the pro-inflammatory responses were similar to or greater than DEP.¹³¹

Two *in vivo* studies also compared the respiratory system impacts of TRWPs versus other constituents of ambient air PM.^{144,145} Kreider et al. (2012)¹⁴⁴ reported results from a comparative instillation toxicity study performed using TRWP and particles with known pro-inflammatory effects including DEP and crystalline silica. The study results showed that TRWPs were significantly less potent than either of those particle types and similar to the negative controls. Gerlofs-Nijland et al. (2019)¹⁴⁵ also performed a comparative toxicity study wherein adult mice were exposed via inhalation in an acute study to a single concentration of TRWPs (collected from a road simulator lab using studded tire and re-aerosolized particles <2.5 μm in size), four types of brake wear particles, wood smoke from an old-fashioned and a modern stove, diesel engine exhaust, and PM2.5 collected in a poultry farm housing unit. The authors reported no effects on cytotoxicity or oxidative stress from TRWPs or any of the other particles. Additionally, the TRWPs were less potent in terms of inflammatory effects than PM from the old fashion or modern wood stoves, diesel exhaust, two of the four types of brake wear particles and the poultry farm PM.

Cardiovascular System. For short-term exposures to PM2.5, it has been postulated that there are two biological pathways that may result in cardiovascular effects: (1) initial effects of activation of sensory nerves in the respiratory tract, translocation of particles or soluble components of particles, and respiratory tract inflammation (these are also considered a biological pathway for long-term exposure), and (2) modulation of the autonomic nervous system, although an initial effect leading to this has not been identified.

Although the studies were not specifically conducted to assess cardiovascular effects, as stated previously both *in vivo* and *in vitro* studies of tire tread particles or TRWPs showed indications of respiratory tract inflammation.^{131,132,134–138,140–145} Additionally, one *in vivo* instillation study showed translocation of metals from the particles.¹⁴¹

Nervous System. Two biological pathways have been postulated for long-term exposure to PM2.5 and adverse effects on the nervous system. The first pathway is associated with intermediate effects starting with upregulation of the renin-angiotensin stem, followed by activation of the sympathetic nervous system, which may then lead to hypertension and

metabolic syndrome and myocardial inflammation. The second pathway involves immediate effects starting with respiratory tract inflammation, translocation of particles, and/or soluble components and olfactory transport. These initial effects are then proposed to trigger a cascade of intermediate effects, resulting in neurologic disorders.

None of the literature for TRWPs evaluated the pathways related to nervous system end points and no studies reported olfactory transport. As stated previously, in the discussion of respiratory system impacts, *in vivo* and *in vitro* studies of tire tread particles and TRWPs showed indications of respiratory tract inflammation.^{131,132,134–138,140–145}

Cancer Incidence and Mortality. Epidemiological studies of populations exposed to PM2.5 have associated exposure with lung cancer, but associations with other cancers such as breast, brain, liver, ovarian, bladder, and leukemias have been found to be inconsistent. Two biological pathways have been postulated for lung cancer: (1) genotoxicity via systemic inflammation and (2) epigenetic mechanism that alter gene expression, cell growth, and cell regulation as precursors to tumor initiation, promotion, and progression. However, after describing the pathways for the development of cancer, the U.S. EPA (2019)²⁰ organized its discussion of PM2.5 exposure and cancer using the hallmarks of cancer and the key characteristics of carcinogens,¹⁴⁶ and not the potential biological pathways.

None of the *in vivo* studies for tire tread particles or TRWPs examined cancer as an end point specifically, although two of the ten key characteristics of carcinogens, namely oxidative stress and genotoxicity have been reported in the *in vitro* literature for tire tread particles and TRWPs.^{131,132,134–138,140–145} The potential for oxidative stress was examined and found to be increased with tire tread particles and TRWPs compared to nonexposed cells.^{124,130,134,135,140} Genotoxicity was assessed through several *in vitro* studies, although inconsistent results have been reported. Cells exposed to material from tire particles indicated genotoxicity in three studies,^{128,132,137} but not in a fourth study.¹⁴⁷ These differences might reflect the source of the particles, the amount of material to which the cells were exposed, or other factors.

Uncertainties. The literature revealed conflicting results among the *in vivo* and *in vitro* studies, which are likely a result of study design factors including particle source, particle size, animal model, and specific end points (Tables S8 and S9). The myriads of test materials used in the toxicity research are identified for each study in Tables S8 and S9. The test materials have included particles manually made from abraded tire tread (e.g., CMTT), PM10 collected at roadside near busy streets, cryomilled recycled crumb rubber, as well as TRWP generated at road simulator laboratories where different pavements and different types of tires have been used. In particular, several of the studies involved the use of studded tires in road simulators, which generate significantly more pavement wear than nonstudded tires and have an unknown influence on the study results.^{131,135,137,138,148,149} Further, although most of the size fractions included those in the respirable range, one study was specifically focused on nanometer-sized particles.¹⁴⁰ Finally, the animal or cell line varied as well as the route of exposure for *in vivo* studies. Animal models included 3 different strains of mice, including both male and female, and three different types of rats including male and female. Methods of exposure for the *in vivo*

studies included nose-only inhalation, intratracheal instillation of particles in saline, and instillation of aerosolized suspensions using a hand-held liquid aerosol lung delivery device.

Overall, it is not possible to draw definitive conclusions from *in vitro* studies of tire tread particles or TRWPs due to several study design limitations involving test concentrations. For example, effects reported at concentrations that are also cytotoxic are not generally considered reliable for data integration because it cannot be determined whether the effects are due to cytotoxicity. Noncytotoxic test concentrations should be used for the measurement of end points that are not related to cell death. In addition, several of the studies examining the toxicological effects of tire tread particles or TRWPs tested only one or two concentrations. It is difficult to identify concentration-responsive effects with only two test concentrations, and the dose spacing was not always appropriate. Given these limitations, confidence in the studies to determine the *in vitro* toxicological effects of tire tread particle and TRWP exposure is low. Moreover, these study design limitations preclude the ability to evaluate potential differences in the toxicological potency of tire tread particles and TRWPs versus other airborne PMs because none used positive or negative test controls. With the large number of different test conditions, it is impossible to directly compare results in the different studies or draw conclusions about the reason for positive findings in one study compared to another. Although it is desirable to test multiple animal species or cell lines, to generate a weight of evidence, at a minimum, the tests need to use the same test substance. Additional studies with robust study designs are needed to confirm the effects reported in the *in vitro* tire tread particle or TRWP studies.

What Are the Hazard Profiles for the Tire-Related Chemicals Measured in Human Fluids?

Chemicals used as tire materials (excluding the transformation products) are included on national chemical inventories around the world and registered as appropriate in the different jurisdictions (e.g., EU REACH). It is beyond the scope of this review to discuss the available data for each chemical and relevant toxicity end points. Nevertheless, human health hazard data is generally available for all of the chemicals listed on Table S5 (except for the PPD-Qs), although the data varies in completeness and reliability in terms of the various toxicity end points. Summarized hazard information may be obtained through publicly available databases (e.g., EU C&L Inventory,¹⁵⁰ ECHA CHEM,¹⁵¹ and USEPA CompTox¹⁵²).

Human health toxicity data for substances in the PPD-Q category is limited. Nevertheless, 6PPD-Q has been investigated the most and the research includes nearly 60 toxicity related studies. The research is dominated by 31 *in vitro* assays^{22,26,75,96,97,99,100,153–176} followed by 20 *in vivo* rodent studies,^{97,100,101,156,157,177–191} 10 *in silico* evaluations,^{157–160,181,182,192–195} and seven epidemiology studies based on biomonitoring^{83,85,87,92–95} (see Table S10). In general, the *in vivo* studies available for 6PPD-Q are quite limited in their utility for human health risk assessment because they employ inappropriate study design (i.e., irrelevant exposure route, single and/or high dose levels), lack transparency in methodology and/or reporting of results or are focused on toxicokinetic endpoints. Thus, despite the recent surge in toxicity studies for this chemical, there is insufficient data currently available to develop reliable health-based guidelines.

7. WHAT CONCLUSION CAN WE REACH ON THE IMPACT OF TIRE EMISSIONS ON HUMAN HEALTH?

The lack of comparable data sets, due to differences in sampling and analytical methodology that often reflect different research questions and target different particle populations, prevents reliable comparison and interpretation of the available exposure and hazard data for human health risk assessment. Harmonization requires not only standardized methods but also clearer operational definitions of what particle populations are being measured and for what purpose.

Detection of tire-related chemicals in human body fluids cannot be related directly to tire emissions or to a certain exposure pathway since these chemicals are also used for applications other than tires and exposure routes remain to be elucidated. Therefore, there is a need to identify the potential sources of these chemicals and quantify their individual contribution to human exposure. Based on the available literature regarding exposure and hazard data for airborne TRWPs, the following conclusions can be drawn, along with some research suggestions:

- Human exposure shows high uncertainty of concentration data due to different sampling and detection methods. This complicates and limits the exposure data interpretation.
- The available concentration data suggest that TRWPs contribute to overall PM₁₀ and PM_{2.5} on average <5 wt %.
- However, the investigation of human exposure to concentrations of TRWP and TRWPs is scarce, and for what is available, the findings are questionable. While there are studies reporting the presence of tire-related chemicals in various human body fluids, their exposure pathways remain inconclusive. It is also noted that human exposure to tire-related chemicals should be conducted for cohorts representing the average urban and suburban populations for different regions worldwide.
- Sampling of food, dust, and water is important to rule in or out of these media as sources of chemicals used in tires and detected in human fluids. In addition, physiologically based pharmacokinetic and toxicokinetic–toxicodynamic modeling may be conducted to examine plausibility of tire-related chemicals in human body fluids being from airborne TRWPs.
- The hazard data lack harmonized study design and are dominated by *in vitro* studies, resulting in a data set where comparison between studies is not possible. Overall, the data do not imply higher toxicity of TRWPs to humans compared to that of overall airborne PM. There is insufficient hazard data on the effects of some tire-related chemicals on humans.
- It is recommended to confirm potential exposure pathways for humans and to determine TRWPs and tire chemical hazard, with relevant end points, e.g., chronic end points, under realistic exposure conditions.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.estlett.6c00153>.

Additional global PM_{2.5} and PM₁₀ concentrations; detailed airborne tire wear particle concentration, and the used sampling techniques and detection/quantification methods; substance name abbreviations; airborne tire chemical concentrations; experimental details and observed effects of *in vitro* and *in vivo* studies for particulate tire wear emissions (PDF)

Literature list; tire chemical concentrations in human body fluids and their excretion, intake, and exposure rates; details of 6PPD-Q hazard studies (XLSX)

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Author Contributions

K.M.: conceptualization, visualization, writing—original draft, writing—review and editing. J.P.: conceptualization, writing—original draft, writing—review and editing. K.M.U.: conceptualization, visualization, writing—original draft, writing—review and editing. S.W.: funding acquisition, conceptualization, writing—original draft, writing—review and editing, project administration.

Notes

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with a mission to anticipate, understand, and address global environmental, social, and governance issues relevant to the tire industry and its value chain. TIP acts by commissioning independent research of the highest standards, collaborating on sectoral solutions, and engaging with external stakeholders. TIP currently brings together 10 leading tire companies that represent more than 60% of the world's tire manufacturing capacity.

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