Ref. Ares(2024)8936503 - 13/12/2024

Research and Innovation action

D6.2 — 955387 — LEON-T

LEON-T

Low particle Emissions and lOw Noise Tyres

Deliverable No.	D6.2	
Deliverable Title	Evaluation of future new policies and mitigation strategies on microplastics emissions	
Dissemination	PUBLIC	
Written by	Barouch Giechaskiel (JRC) Joris Quik (RIVM) Jos van Triel (RIVM) Miriam Gerlofs-Nijland (RIVM) Peter Tromp (TNO) Mats Gustafsson (VTI)	15/11/2024
Checked by	Theodoros Grigoratos (JRC)	25/11/2024
Approved by	Juan García (IDIADA)	30/11/2024
Issue date	30/11/2024	

This Project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement Nº 955397.
The content of this report reflects only the author´s view CINEA is not reponsible for any use that may be made of the information it contains.

Revision history

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
V1	11/11/2024	First version sent for internal review	BG (JRC) et al.
V2	25/11/2024	Revised version	BG (JRC) et al.
V3	30/11/2024	Final version	BG (JRC) et al.

1. Content

2. Executive summary

Task 6.2 aimed to assess the impact of microplastics emissions from tyres to the environment, public health and well-being of citizens, carrying out a cost benefit analysis. Information from **WP2** regarding abrasion rate and from **WP3** regarding the fate and quantification of tyre particles to different environmental compartments were used to (i) develop different policy scenarios aiming at the reduction of microplastics emissions from tyres (ii) evaluate the overall benefit of the different scenarios to the environment. Strengths and weaknesses of different scenarios were examined against the baseline scenario of no policy change in terms of economic, social and environmental impacts.

In this deliverable the fate of microplastics was examined according to the literature. A simplified model was developed to assess different mitigation strategies. The model assumes that tyre particles reach air, road or runoff. The road was assumed to be porous or non-porous with different trapping efficiencies. The runoff was assumed to be treated or not. The model was crosschecked with **D3.5** (Quantification of TWP in environmental compartments and comparison to other microplastics).
The cost of microplastics (year 2025) was assumed to be 13.8 EUR/kg for those ending up to the aquatic environment and 3.8 EUR/kg for those ending up in the soil. The cost estimates were based on cost estimates of plastics to the environment. To put the number into perspective PM_{10} has a cost of 29 EUR/kg, while $PM_{2.5}$ 160 EUR/kg in a city, and 495 EUR/kg in a metropole. The costs of mitigation measures, (runoff treatments) were based on the literature. The costs ranged from a few hundreds of thousands (ponds) to millions (wastewater treatment plants).

A few sample cases were examined:

1. Replacing non-porous with porous surfaces at highway roads.
2. Improving runoff treatment at highways.
3. Improving runoff treatment at urban areas.

For the first case, after full implementation of porous roads, a benefit of 460 million EUR per year is expected with expected investments recovery after 25-30 years.
For the second case, after implementation of higher efficiency highway runoff treatment, a benefit of 330 million EUR per year is expected, with a total net benefit of 6,000 million EUR in the 2025-2050 period. However, for this scenario the cost of tyre particles in the surface waters and those deposited was assumed to be equal to the cost in the marine environment. Upgrade of all wastewater treatment plants with tertiary treatment can result in annual benefits of 594 million EUR. However, upgrading the facilities has high costs, which would take longer than 30 to recover if only tyre particles benefits are considered.

The model can be used to assess other mitigation measures (e.g. tyre filters if they become available) or solutions for hot spots, or accelerated biodegradation which might have faster recuperation of the investments.

Comparing with **D6.1**, it is clear from the analysis that addressing the source is the most cost-effective approach with an order of magnitude higher cost effectiveness compared to treating tyre particles after they have been emitted to the environment. According to **D6.1** reduction of 10% of the tyres mean abrasion rate results in net savings of 7,400-14,000 million EUR in the 2025-2050 period, depending on the cost assumptions. Thus, measures reducing tyre wear should be prioritized (e.g. tyres with less wear rate, reduction of annual mileage and smoother driving, well maintained vehicle etc.).

3. List of abbreviations and acronyms

Abbreviation	Definition
BR	Butadiene rubber
CSO	Combined sewer overflow
D	Deliverable
EF	Emission factor
EU	European Union
MF	Manufacturer
MP	Microplastics
MS	Member State
NR	Natural rubber
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PTI	Periodic technical inspection
SBR	Styrene butadiene rubber
SUV	Sport utility vehicle
TPMS	Tyre pressure monitoring systems
TSS	Total suspended solids
UV	Ultraviolet
WFD	Water Framework Directive
WP	Work package
WWTP	Wastewater treatment plants

4. Introduction

The goal of **Work Package 6 (WP6)** is to synthesise the knowledge gained during the project's experimental activities into potential new policies and regulations and to evaluate their possible future impact for the public health and wellbeing of citizens, as well as the social acceptance of the economic impacts that could derive from the new policies and regulations. Possible future policy scenarios include tyre airborne particle emissions (**Deliverable 6.1** or **D6.1**), microplastics emissions (**Deliverable 6.2** or **D6.2**), and tyre noise emissions (**Deliverable 6.3** or **D6.3**). The final executive summary (**Deliverable 6.4** or **D6.4)** gathers the most relevant policy recommendations in all the three topics. This outcome may contribute to identifying guidelines for future policies and envisaging specific actions to mitigate tyre emissions. All tasks build on leading projects in the space of research, policy and regulations on the environmental and human health aspects of the tyre industry.

Task 6.2 aimed to assess the impact of microplastics emissions from tyres to the environment, public health and well-being of citizens, carrying out a cost benefit analysis. Information from **WP2** regarding abrasion rate and from **WP3** regarding the fate and quantification of tyre particles to different environmental compartments were used to (i) develop different policy scenarios aiming at the reduction of microplastics emissions from tyres (ii) evaluate the overall benefit of the different scenarios to the environment. Strengths and weaknesses of different scenarios were examined against the baseline scenario of no policy change in terms of economic, social and environmental impacts.

Initially, input from **WP3** allowed for a reliable estimate of the amount of microplastics emissions from tyres to different environmental compartments. Afterwards, a quantitative and qualitative baseline scenario was developed considering the possible evolution of the problem in a no policy change scenario. This baseline scenario considered the increasing penetration of new technologies and vehicles to the market and their influence on microplastics emissions. The definition of the objectives to be achieved at EU level followed, taking into account the developments in other on-going initiatives related to the topic. At a next level, prevailing future policy scenarios were developed based on the objectives, reduction measures, and developments on the abrasion rate method.

The impact of the proposed scenarios on public health and well-being of citizens along with a cost-benefit analysis was examined and compared to the baseline scenario. The Better Regulation toolbox of the Commission was applied for this purpose. Cost benefit analysis provided estimates of the costs and benefits to the society as whole but also for various stakeholders. As a final step, clear argumentation for rejecting some policy options was provided based on the results of the conducted analysis.

5. Tyre particles in the environment

Tyre particles are generated either by shear forces between the tread and the road pavement [1] or by volatilisation, which results in the generation of very small particles [2]. Some particles (the smaller ones) are emitted in the atmosphere. The majority (coarse size and larger) deposit on the road or nearby areas. Resuspension, wind and rain remobilise them. The majority of the particles will settle in the soil, however some will end up in the waters via drainage systems (with or without treatment). This chapter gives a short overview of the fate of particles in the environment.

5.1. Tyre particles generation

Studies estimated that, globally, 1.8-3.0 billion tyres are produced annually since 2017; 0.33-0.42 billion from of them are produced in Europe [3–7]. Among the newly sold tyres in EU [6]:

- 90% are for passenger cars (C1 tyres—tyres that are intended mainly for the M1 vehicle category plus O1 and O2) and light duty vehicles up to 3.5 t (C2 tyres—tyres that are intended mainly for the N1 vehicle category).
- 5% are for heavy-duty vehicles (either C2 tyres, tyres that are intended mainly for N2 vehicle category trucks plus O3 and O4, or C3 tyres, tyres that are intended mainly for M3 and N3 vehicle category trucks and buses plus O3 and O4).

An average tyre for a passenger car typically lasts for 40,000 km. Some data indicate that for premium tyres, the average service life is around 45,000 km, for mid-range tyres, it is around 40,000 km, and for budget tyres, it is around 30,000 km [8]. The treadwear index gives an estimation of the expected service life of a tyre [9]. Different tyres from the same manufacturer can have a wide range of variation in their treadwear indices. C2 tyres are expected to last 40,000–70,000 km [10] depending on the loads carried and the driving style. Finally, C3 tyres may last, on average, approximately 220,000 km before needing to be replaced or retreaded; in the second case, extending their service life to more than 600,000 km if the tire is retreaded two times [11]. Throughout its service life, a tyre sheds approximately 10% of its mass [12], (0.6–1.5 kg for a 7–12 kg tyre), depending on parameters such as tyre characteristics, vehicle characteristics, road surface characteristics, and vehicle operation [13,14]. Measurements in Korea found an 11% mass loss for passenger cars tyres and 18% for heavy-duty vehicles tyres [15]. Globally, tread abrasion from road tyres results in approximately 6000 kt of tyre rubber being emitted annually [16], equivalent to 0.80 kg per capita per year globally. A study reported that approximately 440 kt of tyre particles were emitted in China in 2008. The same study reported a significant increase, with more than 1500 kt of tyre particles emitted in 2018 [17]. The estimated mass of tyre abrasion generated in 2014 was 1120 kt for the United States and 1327 kt for the EU [18]. More conservative numbers have been reported for the EU (500 kt) [19,20]. In the

EU, passenger cars contribute around two- thirds to of the total release of microplastics from road transport [21]. However, the country specific contribution can vary significantly. For example, in the Netherlands, Denmark, and Norway, the contribution of passenger cars is estimated to be 62–71% [16], in Japan, China, and Brazil, the contribution is reported to be 46–48%, in the United States, it is estimated to be 33%, and in India and South Korea, it is only 20% [15,16]. In India and South Korea, the heavy-duty sector (trucks and buses) contributed >50% to the road transport tyre wear.

5.2. Properties of tyre particles

Tyre wear particles consist of tyre tread fragments incorporating materials from the road surface with a commonly cited ratio of 1:1 [22], which is also used in standards (e.g., ISO 20593:2017). However, many experimental studies have found that tyre constituents are the major contributor. A study found only a 25% contribution of from the encrusted particles [23]. Another study found that only 6% of the particles had a ratio of road to tyre fractions of 1:1 or higher [24]. The road contribution (in terms of volume) was as low as 6%. On the other hand, a laboratory study found a 70–80% contribution of the asphalt to the particles [25]. This ratio can vary depending on the road, tyre materials, and particle size. In **WP3** the contribution (percentage) of encrustations in tyre wear particles <100 µm in deposited dust samples at the road side was 29±12%, decreasing with decreasing size.

5.2.1. Physical characterisation of tyre particles

The size distribution of tyre wear particles spans over a wide range of sizes [26,27], with typical bimodal distribution [28]. **Figure 5.1** presents typical images of tyre particles collected at various sites. More images can be found in the literature [24,28–32]. Typically, based on road samples, the mass distribution peaks at 10–200 µm (mostly 50–100 µm) [28,33–38]. In the airborne sub-20 µm range, a peak in the 2–10 µm is also found in laboratory studies (see reviews [26,27,39]). In **WP3** road side soil, deposited dust and runoff samples had bimodal distribution with peaks at 5-25 µm and 50-200 µm. In general, due to the large particles generated, the total suspended matter and the PM_{10} and $PM_{2.5}$ fractions are considered low. In a few cases, a nucleation mode in the 10–50 nm range is measured due to localised high-temperature hot spots on the tyre tread [31,32,40–42].

Regarding morphology, the shape of the large particles is elongated, cylindrical, and “sausage-like”. Spherical or round particles are commonly seen, especially at in the lower size ranges. Some researchers report that the elongated/round shape particles appear with variable amounts of mineral encrustation from the road material [36]. Irregularly sized particles have also been reported. A recent laboratory study could detect two separate types of tyre wear particles, denoted as firm-elastic and sub-elastic, where the sub-elastic type was characterised by the commonly seen cigar shape and embedded mineral grains, while the firm-elastic type was more irregular and knobbly and with superficial mineral encrustations. In the laboratory, the sub-elastic type was vastly more common than the firm-elastic type [43]. The average aspect ratio of particles collected at from roadside or tunnel samples is around 1.65 [29,34].

The densities of the different materials typically found in tyres are 5.1 g/cm^3 for metallic particles, 2.7 g/cm^3 for minerals, and 1.2 g/cm^3 for rubber. Road constituents, such as bitumen have a density of 1.0 g/cm^3, and road coarse particles have a density of around 2.5 g/cm^3 [25]. Depending on the ratio of tread and road dust particles, different densities can be calculated for tyre wear particles. For a highway with low little road-encrusted material (<10%), a tyre wear particles a density of 1.26 g/cm^3 was estimated [24]. Tyre wear particles (sizes 63–500 µm) collected from road dust near a bus stop had densities in the range of 1.3–1.7 g/cm^3 [44]. Highway or parking lot particles (i.e., tyre wear and others) had densities between 1.55 and 1.94 g/cm^3 [45]. Recent studies found densities of 1.8–1.9 g/cm^3 for tyre wear particles [29,46], but higher values have been reported as well [25,44]. In **WP3** calculated densities of deposited tyre wear particles <100 µm collected at the roadside were in the range of 1.5-1.9 g/cm^3, with decreasing densities for smaller particles.

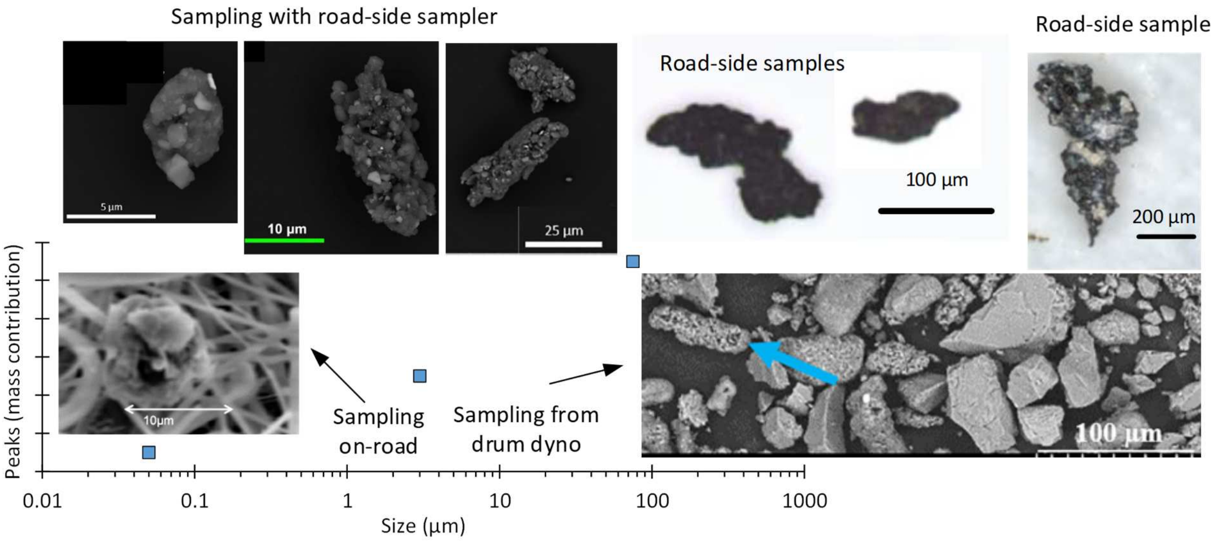


Figure 5.1. *Typical images of tyre wear particles collected on the road, from the roadside with sampler, from a drum dyno, or from roadside dust. Blue squares indicate typical mass size distribution peaks and their relative contributions to the total mass. Sources from smaller to larger particles (all open access articles) are:* [29,36,44,47–49]. *The blue arrow indicates a tyre wear particle to distinguish it from the stone particles in the same figure.*

5.2.2. Chemical composition

A typical tyre tread consists of approximately 40–60% rubber polymers, 20–45% reinforcing/filler agents (ratio 1:2), and 5–15% chemical additives. Two main types of rubber can be found in light-duty vehicle tyres: natural rubber (NR—polyisoprene $[C5H8]_n$) and synthetic rubbers, which include styrene butadiene rubber (SBR) and butadiene rubber (BR) [44,50]. NR is the preferred material for high-performance tyres used in aircraft, trucks, and buses [12]. In **WP2** it was found that there is a high variability of NR between brands of light-duty vehicles (16–41% of total rubber). In **WP3** this variability was also seen. Moreover, the percentage of NR increased with increase in freight traffic, in line with the belief that truck tires mainly consist of NR. It was also derived that the range of NR in tyres for light-duty vehicles was 5 - 15% NR. However, this has been was disputed recently; a study showed that SBR and BR are also present in heavy-duty vehicle tyres, sometimes even at higher concentrations than in some of the light-duty vehicle tyres [51]. A recent study also highlighted the high variability of natural and synthetic rubber between brands and models [51].

Overview studies [16,26,40,50,52] show that a variety of different compounds are added to improve the properties of tyres rubber. Sulphur (and other chemicals such as thiazoles, sulphenamides, selenium, tellurium, organic peroxides, nitro compounds, and azo compounds) are added to vulcanise the rubber and obtain a highly elastic material. Zinc oxide (also calcium, lead, or magnesium oxides) is added as a catalyst (an activator for the vulcanisation process), whereas carbon black is added as a filler and to make the tyre resistant. Over time, these additives have also been modified, e.g., carbon black has been partially replaced by silica to improve the rolling resistance of tyres. Furthermore, oils are added to make the tyre more flexible and control hardness. It should be highlighted that this is a simplistic view of tyre composition: a common-sized all season passenger tyre may contain 30 kinds of synthetic rubber, 8 kinds of natural rubber, 8 kinds of carbon black, and 40 different chemical additives [53]. More detailed information about the ingredients, their role, and their concentrations can be found in [54,55].
Metals in high concentrations are Si, S, Zn, Ca, Al, and Fe [28,30,56–60]. Zn is commonly used as a marker for tyre-wear emissions in ambient PM source apportionment studies [26,61,62]. However, the high concentrations of these metals may originate from the encrusted material from other sources. A commonly formulated criticism to this approach is that other sources of Zn from traffic sources such as corrosion of crash barriers, brake wear, and engine oil may influence the quality of the source apportionment studies by overestimating the contribution of tyre wear emissions [63].
Besides to inorganic compounds, tyre wear particles contain a large variety of organic chemicals. A recent study identified 214 different organic chemicals in tyres among which 145 were classified as leachable; thus, indicating a large potential for transport in the environment [64]. Examples of tyre-derived chemical compounds are benzothiazoles, N-(1,3-dimethylbutyl)-N'-phenyl-1,4-phenylenediamine (6-PPD), 1,3-diphenylguanidine (DPG), and a wide variety of polycyclic aromatic hydrocarbons (PAHs) [65,66]. In ISO standards for the determination of tyre– road wear particles, dipentene is used as a marker for natural rubber, and 4-vinylcyclohexene is used for

SBR and BR (e.g., ISO 20593:2017, ISO 21396:2017). However, these markers have been disputed by others because they were too unspecific or because of interferences with plant material [67,68]. Potential markers for tyre wear sources are discussed in relevant publications [18,61]. Older studies have found PAHs, in tyre wear emissions including phenanthrene, pyrene, ben-zo(a)pyrene, benzo(g,h,i)perylene, and indeno-1,2,3(c,d)pyrene, in tyre wear emissions [69,70]. In the EU, the concentrations of PAHs in tyre wear emissions declined since after January 2010 due to the implementation of EU Directive 2005/69/EC and European Regulation 1907/2006/EC (REACH), which that limit the sum of eight PAHs to 10 mg/kg [71]. Nevertheless, values higher than the limit values have also been measured [60,72].

5.1. Tyre particles to the environment

5.1.1. Tyre particles and microplastics

Plastics can be found everywhere: from packaging and clothing, to construction materials, electronic products, medical devices, furniture, toys, and vehicles, with a global production of more than 390 million tonnes in 2021 [73]. A fraction of these plastics can be released to the environment, sometimes as small particles. Although a commonly agreed-upon definition for microplastics does not exist, it is widely accepted that these are particles smaller than 5 mm in size. Of these, primary microplastics are those directly released into the environment, while secondary microplastics originate mostly from the degradation [74] of large plastic waste into smaller plastic fragments once exposed to the environment. The global release of primary microplastics into the environment was estimated at 3.2 to 6 million tonnes in 2017 [16,75]. Microplastics are recognised as an emerging global threat because of their potential health impacts on aquatic and terrestrial organisms, including humans, via multiple exposure pathways such as the food chain, drinking water, and air [76–79]. Microplastics releases to the oceans are projected to increase further unless action is taken [80]. Tyre particles are considered microplastics because of their size and their high content of synthetic polymers [81].

Several studies identify tyre particles as the main source of microplastics emissions into the environment, with a share ranging between 11 and 93% (35–85% excluding the min-–max values) (**Table 5.1**). Some of the variation in the fraction of tyre wear comes from differences in the microplastics sources taken into account in each study. In many of these studies, the second contributing source accounted for 10 to 29% of the total microplastics emissions. For example: household dust and laundry 12% [82], rubber granules 10% [83], artificial turfs 18% [84], synthetic fibres, 29% [85], and pre-production plastics 12% [19]. Nevertheless, sources such as paints, pellets, packaging,

and agriculture are also considered important [20,86,87]. The European Commission completed a cost-benefit analysis on of policies for combating microplastics pollution in the EU. This study identified paints as similar contributor to microplastics emissions in the EU as tyres, with a percentage of approximately 36% [20].
Tyres have been found to also be the major contributor of microplastics also at a local level. For example, 53% at a stormwater detention reservoir in Sao Paulo, Brazil [88], or 41% based on particles captured by spider webs in a medium-sized city in Germany [89], 51% at a road in a German city [34], and 38–39% at medium- and high-traffic sites in the United States [47]. These studies used chemical markers to apportion particles to the source. A study in India in an urban- traffic site found a 31% contribution of tyres to road dust particles up to 75 µm [90]. Comparisons of road-deposited sediments at curves or traffic light spots have shown much higher concentrations of tyre wear particles compared to, e.g., parks [91]. More tyre wear particles were found within road-side drains where driving had required increased braking and accelerating than within the drains of roads with high traffic densities [92]. Another study demonstrated that a high traffic volume and high manoeuvring density resulted in higher brake, tyre, and road particles emissions compared to other types of sampling sites [93].

Table 5.1: *Tyres' contribution to microplastics (MP) pollution in various countries.*

Year	Ref.	Country	MP (kt)	Tyres / MP	Tyres fraction to water
2014	[82]	Norway	8.4	54%	50%
2015	[83]	Denmark	5.5-13.9	56%	12-26%
2016	[94,95]	Netherlands *	5.4-32.9	11-96%	10-18%
2017	[84]	Sweden	10.5-13.5	60-77%	42% **
2018	[96]	Germany	330	43%	22%
2018	[97]	Switzerland	87.8	93% ***	22%
2018	[19]	EU	787	64%	19%
2019	[85]	China	737	54%	10%
2019	[98]	Global	3000	47%	n/a
2022	[99]	Sweden	9.6	85%	n/a
2022	[87]	Netherlands	7.6	35%	9%
2023	[20]	EU	1250	36%	n/a
2023	[100]	Global	800	62%	14%

* ranges provide values from two studies; the high contribution from tyres in one study is because land-based litter fragmentation was not included.

** value of 42% reported in [96].

*** also includes end-of-life tyre losses, but not paints.

5.2. Tyre particles at the environmental compartments

The study of the fate of tyre microplastics emissions emitted into the environment has received increased attention over the last years. Some researchers found microplastics, including tyres, from the Alps to the Arctic [101]. **Figure 2** plots the modelled fate of tyre particles based on the concept of studies [94,102–105], but with additional data from [16,18,97,106]. The topic has been discussed in **D3.5**. Small particles, such as PM_{10} (<10μm), become airborne to a large extent. Most tyre particles accumulate on the road surface, especially on the edges of the road. Road sweeping can remove them. Precipitation can transport tyre particles to the nearest drainage system of that road, which can be treated or untreated.

The figure does not include the fate of end-of life tyres [107], which are discarded (scrap) non-reusable tyres. End-of life tyres in Europe in 2019 were 3500 kt; 55% of these tyres were treated through material recovery, while 40% went through energy recovery. Less than 5% (160 kt) were stocked or unknown (e.g., illegally landfilled) [108,109].

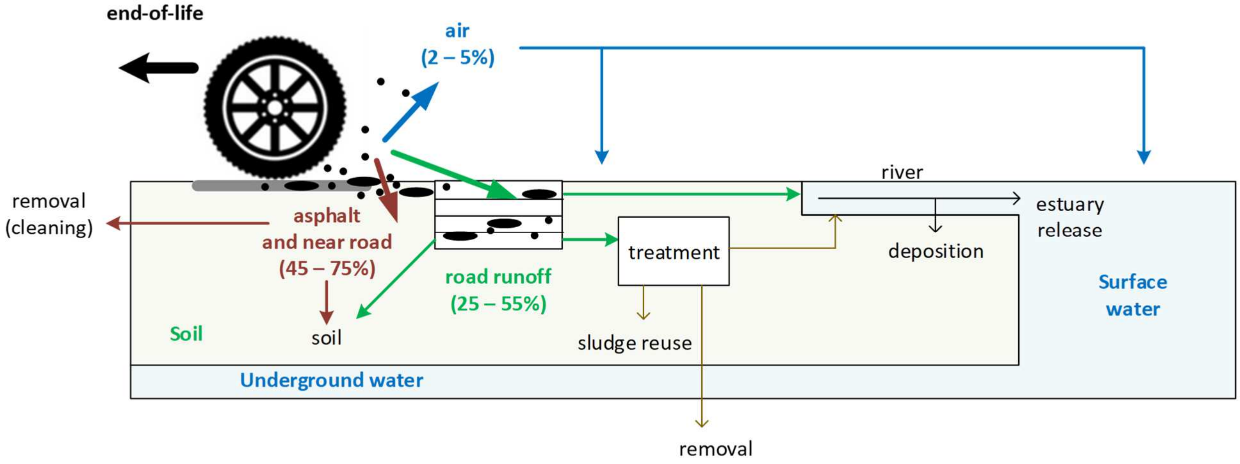


Figure 5.2. *Modelled source, release, and transportation of tyre particles in the environment based on* [94,102–104]*. Arrows indicate pathways of tyre particles release to environment*.

5.2.1. *Tyres particles and ambient PM*

Only a small amount of tyre becomes airborne (2–5%) [33,110], although other studies assume a much higher percentage (10%) [111]. Most tyre particles will deposit on the road or nearby surfaces. Small particles can be transported over long distances and enter the surface water (including marine) [111]. Recent work has highlighted the atmosphere's role in transporting microplastics to remote locations [112,113].

Overall, road transport is estimated to be responsible for 10–15% of particulate matter below 10 μm in diameter (PM_{10}) [114]. This percentage can be much higher in cities and near roads [115,116] or in closed environments such as tunnels [117,118]. Tyres contribute 5–31% to road transport PM_{10} (based on the overview table in [115]). Thus, based on the 10-15% contribution of road transport to PM_{10}, an overall contribution of tyres to the total PM_{10} of 0.3% to 4.5% can be calculated. A review found the contribution of tyres contribution to the total PM_{10} to be below 10% in most studies [119]. As the majority of particles is >10 μm, in addition to the size distribution of tyre particles, the cut-off size of the cyclone or impactor is important for the determined ratio PM_{10} to total wear mass. The contribution of tyre particles to ambient concentrations of $PM_{2.5}$ (particulate matter below 2.5 μm in diameter) has been estimated to vary between 1% and 10% by mass; however, these values are mostly based on data from 20 years old studies and on indirect calculations from only a few observational studies [119]. Source apportionment studies indicate a contribution from tyres to ambient PM_{10} of 5–6% and a contribution of 0.1–0.4% to ambient $PM_{2.5}$ at traffic sites [120]. Recently, the German Environment Agency (UBA) reported that in Germany, road traffic contributed an overall 13.8% to ambient PM_{10} in 2017, out of which tyres had a share of 3.1%. For $PM_{2.5}$, the respective numbers were 18.8% and 4.6% [121]. Similar estimations have also been published also by the Air Quality Expert Group for the UK [122]. The European Environmental Agency estimated a 4% contribution to PM_{10} and a 2% contribution to $PM_{2.5}$ from tyres [114].

In general, these estimates are in good agreement with field measurements for PM_{10}, whereas for $PM_{2.5}$, field measurements show contributions towards the lower end of the estimations. For example, measurements of airborne concentrations of tyre particles in urban and rural areas of France, Japan, and the United States found 0.6–22% contributions to PM_{10} [123]. Results from the same project (i.e., the Tire Industry Project, TIP) [124] indicated tyre particle contributions of 0.1–0.7% to ambient $PM_{2.5}$ concentrations in the same areas [125]. On-road and laboratory measurements in South Korea revealed that tyre particles accounted for 3–7% of $PM_{2.5}$ and PM_{10} [126]. Similar percentages for PM_{10} (4–6%) were measured in Stockholm (Sweden) [127]. The annual average mass fraction of tyres in PM_{10} was 1.8% at an urban background site in Switzerland and 10.5% at an urban kerbside site [29]. Road dust samples from a highway in Sweden contained more than 10% of tyre particles [128]. A study with a single particle aerosol mass spectrometer at the roadside of a port highway in China found a 6.6% contribution of tyres to the total PM [129]. In **WP3** the percentage of tyre wear to total PM, PM_{10} and $PM_{2.5}$ was found to be in the range of 0.2-5.5%, 0.1-1.9% and 0.1-0.9%, with the highest percentages in the city close to a busy intersection and the lowest percentages at a rural background location. Ambient total PM, PM_{10} and $PM_{2.5}$ concentrations were 0.05–1.4, 0.02-0.3 and 0.01-0.1 μg/m^3. Others found higher road ambient air tyre wear concentrations of about 0.4–11 μg/m^3 [130].

5.2.1. *Tyres particles to soil*

Most of the published studies base their results on modelling and report that the major part of tyre wear particles ends up in the soil near the road (rain, snow removal): [110]

(66-76%), [103] (25-75%). Concentrations of around 10 mg of tyre wear per gram of soil (mg/g) near roads have been reported, but the range is very wide between 0.7 and 210 mg/g [110,130,131]. Tyre wear enters the road side soil via atmospheric deposition and road surface runoff. The concentration in soil depends on the traffic intensity, the type of road surface/asphalt, the speed, and the presence of a runoff and drainage system. A significant part of tyre wear that was initially deposited on the road surface can be flushed into surface waters directly via road runoff (approximately 50 mg/g; range: 10–150 mg/g) [110] after precipitation. In **WP3** similar concentrations were found in road runoff, in the range of 8.8-100 mg/g. The concentration at the roadside and runoff also depends also on the number of days without rain [132]. The soil concentration of tyre particles decreases rapidly with the distance from the road (>80% at 30 m distance) [130,133]. This is in agreement with the results from **WP3**, where concentrations tyre wear 1 m from the road (1.9-13 mg/g) were much higher than concentrations further away from the road (10 m: 0.5-1.5 mg/g, 30-350 m: ~0.4 mg/g).

5.2.2. Tyres particles to water

The runoff of rural and highways roads typically enters lakes, rivers, and the marine environment without a previous treatment step. Urban road runoff is mostly connected to sewers through storm drains with some treatment. Estimations of tyre particle concentrations in sediments range from 0.3 to 155 mg/g d.w. [110,130]. Tyre wear within road surface runoff has been reported in the range of 12 to 179 mg/L ([130,131], but 1-2 orders of magnitude lower at river to sea water [110].The concentrations in **WP3** are consistent with these findings, with tyre wear in road runoff in the range of 1.9 to 52 mg/L and tyre wear in river surface water in the range of 0.6 to 30 µg/L.

Table 5.1 presents the estimated percentages from emitted tyres ending in the aquatic environment (9–50%). These percentages are in line with other studies. For example, a study found that 12–20% of the tyre particles in Germany are reaching surface waters [106]. A study in Switzerland reported 22% of tyre particles reaching surface waters [97]. Another study estimated that, worldwide, the tyre material ending up in the oceans is 28–46% [75]. A modelling study estimated that the proportion of tyre material transported by European rivers to seas was 42% of the total tyre abrasion [134]. A study estimated that 18% of the tyre particles reached the rivers, but only 2% reached the estuary due to deposition [103]. Reviews concluded that the relative contribution of tyre abrasion to the total global amount of plastics ending up in the oceans is 5–10% [16,18]. It should be added that around 34% of the airborne fraction (which is on the order of 5%) can reach oceans, suggesting that the direct deposition of airborne road microplastics is at least an equal source for the ocean as compared to the direct wash-out from the land [111,131].

6. Influencing parameters of tyre wear

In general, the tyres abrasion rate and the PM emissions depend on the following parameters [135]:

- Tyre characteristics,
- Vehicle characteristics,
- Road characteristics,
- Driving style, and
- Environmental conditions.

The factors with the highest impact other than the tyre, are:

- Lateral and longitudinal accelerations and decelerations (braking) [13]: With at least second-order functions, per force unit, the lateral acceleration is more important [25]. Comparison across different studies is not easy, as this information is rarely provided and not with a commonly agreed index. A proposal is to use the standard deviation of the accelerations over a trip. This is included in the proposed method for future tyre regulation to measure the abrasion rate of tyres [136].
- The road surface can have an impact by a factor of at least two [137,138].
- The load of the vehicle: A dedicated study with tyres of the same construction but different sizes and loads demonstrated a linear relationship [139]. This has also been confirmed by other experimental (e.g., [140,141]) and theoretical (e.g., [142]) studies of abrasion. A linear relationship has also been demonstrated for PM [140].
- Vehicle maintenance. The tyre industry estimated that incorrect wheel alignment may increase tyre wear by 10% [95]. If the tyre pressure is too low, internal heat generation occurs, which increases the wear [143]. Higher pressure gives lower wear in modelling. A cost-benefit analysis from the Netherlands found that adjusting to optimal air pressure led to a significant decrease in tyre wear [95]. A study estimated that tyre wear can be reduced by 14% if all Dutch vehicles not fitted with a tyre pressure monitor system, or with only an indirect system, were to install a direct system [95].
- The ambient temperature: Recent experimental studies showed a decrease in emissions with increasing temperature [144]. However, this is not always the trend [145]; sometimes it depends on the tyre type (summer or winter) [146]. Also road simulator results in **WP3** suggests otherwise, with increasing tyre mass loss with increasing temperatures for both summer and winter tyres. The complex effect of temperature was already discussed in the 1970s and was found to depend on how far the ambient/tyre temperature was from the glass transition temperature [147].

7. Mitigation Measures

In order to reduce the health and environmental risks of a pollutant, it is important to address its sources, release and emission pathways, and further fate and transport which, in the end, will determine the exposure effect [102]. The available options to mitigate tyre abrasion pollution can be broadly categorised as follows [39,52,95,148–152].

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

Another important aspect is the management of waste tyres [153–155]. On one hand, recycling waste vehicle tyres into crumb rubber has many applications (e.g., turf fields, playgrounds, or road asphalt pavement) [155]. On the other hand, there are concerns about the environmental and human health effects from some of the substances in waste tyres [156,157].

7.1. Preventing or reducing the formation of particles

A reduction in the formation of tyre abrasion particles can be achieved either with technological or management measures. In all cases, directly or indirectly, these measures aim to reduce one or more of the factors discussed in **Chapter 6**.

7.1.1. Tyre characteristics

An obvious measure is the development of materials with greater abrasion resistance and which are sustainable, more environmentally friendly, and less toxic [158–160] without compromising comfort and safety [161]. Improved tyres means using materials resulting in reduced abrasion, or the elimination of vent spews or even setup to reduce influencing factors (e.g. more efficient cooling) [39]. In EU a limit on tyre abrasion will be introduced from 2028 for C1 tyres and later for C2 and C3 tyres. Introduction of tyre wear labelling and encouraging car users to prefer low emitting tyres could also have a positive impact. However, most buyers value higher rolling resistance and (fuel saving) and tyre price, rather than the environmental impact. The introduction of low emitting tyres was examined in **D6.1**.

The tyre chemical composition is not covered in the Euro 7 regulation. Some studies indicate that some chemicals may be more harmful than others and thus should be limited. In EU chemicals are covered by REACH. Limits for PAHs already exist

(Directive 2005/69/EC): maximum 1 mg/kg BaP or 10 mg/kg of the sum of specific eight PAHs.

Winter and studded tyres have higher emissions than summer tyres. Banning winter tyres in summer, or limiting the use of studded tyres could have a positive impact. Non-studded winter tires are generally allowed all year round, while studded tires are only permitted in a specific period in the winter season and when required by weather or road surface conditions. This specific period varies somewhat between countries, but lasts typically from November to March/April. Taxation on studded tire usage or ban at some roads, are options that can discourage consumers from using studded tires (And18). Educating the drivers is of high importance.

7.1.2. Road characteristics

Road surface and design improvement can result in lower abrasion. However, a road surface can be optimised for tyre abrasion, but it could have a negative impact on road wear or even safety issues (i.e., less grip).
Reducing locations that result in high wear due to longitudinal or lateral accelerations, minimum radius of curvature or the use of roundabouts instead of traffic lights, thus reducing cornering and braking/accelerating can also result in reduced tyre wear. Improved road maintenance might also decrease areas with worn roads that could further increase road and tyre wear.

7.1.3. Vehicle load

The impact of load on tyre abrasion is well known (see **Chapter 6**), but the implementation is not straightforward since market trends currently favour heavier vehicles such as sport utility vehicles (SUVs) and electric vehicles. Any reduction of the load would have a positive impact to other non-exhaust emissions as well.

7.1.4. Speed limits

Speed limits are considered more suitable for roads with high speed and traffic volume in a dry climate with buildings close to the road [151]. The impact on PM is probably modest (from none up to 30% in a few cases, see studies in [152]).

7.1.5. Eco driving (Acceleration limits)

Longitudinal and lateral accelerations are a major factor of tyre abrasion. Smooth driving, either with better traffic control (e.g. with support of Driver Assistance Systems) or with acceleration indicators (or even limiters) to the driver (without compromising safety) may help. Smooth driving could also help reducing in general emissions from road transport.

7.1.6. Vehicle maintenance

Vehicle maintenance includes tyre pressure monitoring system for older cars, and wheel alignment. In the EU, tyre pressure monitoring systems (TPMS) are mandatory for new passenger cars registered from November 2014, according to the EU Directive 2010/48/EU. However, not all countries have implemented the Directive (e.g. Sweden). Future tyres might be integrated with sensors not only for safety but also for wear [162]. Controlling wheel alignment is part of mandatory periodic vehicle inspections in accordance with the EU Directive 2014/45/EU. The periodic safety inspection of passenger cars and vans could include control for uneven tyre abrasion [149]. Experts from the tyre industry estimate an impact of 10% on the abrasion from poor alignment [149]. A study with a misaligned vehicle found 3 mm tread depth reduction, while normally aligned vehicles have a 1 mm reduction every 10,000 km [163].

7.1.7. Reduced total km driven

Reduction of annual mileage could be achieved by using public transport, taxation to driven distance, road pricing. Although a reduction in vehicle-km travelled will reduce emissions, road transport activity is expected to increase [164].

7.2. Collecting particles upon emissions

This category includes solutions such as
- Tyre particle collectors [165]
- Constructing road surfaces as a trap for particles [166–170].

These measures reduce resuspension and particles reaching sewers and road runoff [63].

7.2.1. Particle collectors

Filters behind the wheel arch [165] or underbody of a vehicle [171] have been presented. Using a sucking device in combination with the particle filter can increase the filtration efficiency even if the vehicle is not moving. Recently an enclosed wheel was presented [172]. Another approach is using electrostatic attraction (The Tyre Collective). The collection devices are still at early development levels with lack of experimental data, in particular for long term efficiency and robustness (e.g. to whether conditions, mad, rain etc.).

A completely different approach is installing filters at the front-end of the vehicle, used to cool the engine compartment. Ambient air particles (tyre particles are typically 10-30%) can be filtered with efficiencies >50% [173].

7.2.2. Porous roads

The research on roads focuses mainly on materials [155,174,175] to increase the life span [176], reduce aqua planning and noise [177–179], and decrease the costs [180]. As non-exhaust emissions become more and more important, recent studies investigated the impact of road surface tyre and road wear [176].

Permeable pavements are all surfaces designed to allow water to pass through, and include pervious and porous pavements. However, not all permeable products have pores and therefore, cannot be called porous.

In general, retention efficiencies 60%-90% have been reported in the literature, but in the long term, lower efficiencies have been modelled, depending on the rain falls (<50%) [168]. A laboratory study found removal efficiencies at porous asphalt for coarse sediments (>62.5 μm), Pb, and Zn >98%, for total suspended solids at drains 93%, but for fine sediments (<62.5 μm) around 58% [167]. Another laboratory study with permeable asphalt found that > 85% of the particulate material (sizes 75 to 2000 μm) remained on the porous surface [166]. Another laboratory study with porous asphalt found >90% retention of oil and contaminants (<0.5 mm) [181].

In **WP3** it was confirmed that asphalt surface has an influence on emission rate (and particle size distribution of tyre wear particles): stone mastic asphalt had more fine tyre particle, while open-graded (porous) asphalt more coarse tyre particles. Both asphalts had approximately three times lower road side soil concentrations than regular dense-graded asphalt. For the open-graded asphalt also the concentration of tyre wear in road runoff was considerable lower.

Regarding ambient air PM_{10}, reductions on the order of 50% were measured with a Double Layered Porous Asphalt compared to non-porous stone mastic asphalt [169,179]. However, such reductions have not been confirmed by other studies with porous asphalt [182].

It should be mentioned that porous asphalt might increase PM_{10} levels of tyre wear particles because the road surface has a coarser structure. Air monitoring studies along highways with open-graded asphalt are contradictory. However due to its trapping capabilities the net impact to the environment will be positive [95].

Porous surfaces have also a positive effect on noise pollution and on road safety (lower risk of aquaplaning). Porous roads, due to the higher percentage of hollow spaces, are less suitable for use in curves, exits, and crossings as it would tend to break down more quickly in such situations [95]. Porous asphalt is less suitable for Nordic and alpine areas because frost damages the road surface [94,183].

In the NL, approximately 95% of the highways are surfaced with porous asphalt (ZOAB) and 5% with non-porous asphalt (DAB). Replacing asphalt take time: In the NL it took 35 year to replace 95% of the roads [94]. DAB is assumed to have a usable lifetime of 40-50 years. Therefore, 2% of the roads should be replaced per year [95]. It is also recommended to clean the road at least twice per year to maintain its draining, noise and particles reduction efficiencies [94]. This was probably the reason why in **WP3** the reduction of the road side soil concentration next to the open-graded asphalt road A2 was less then the typical reduction factor of 20.

7.3. Treating Particles

This category includes measures such as:

- Street cleaning (e.g., sweeping or washing with water or chemical dust suppressants at increased frequency) [184], Street cleaning also has the potential to reduce resuspension and consequently ambient PM levels [185].
- Treating road runoff (e.g., adding and improving retention basins or wastewater treatment plants) [186]. Sweeping the material collected in, e.g., gutters or streets, will reduce the concentration arriving in the soil and aquatic environment.
- Accelerating microbiological degradation (adding micro-organisms to drainage gutters, retention basins and/or road side soil). Environmental degradation of tyre wear particles in road side soil was already in 1980 [187], with degradation rates of 0.09 – 0.15 d^{-1} (half-life around 16 months). Recently accelerated biodegradation in a laboratory setup with activated sludge inoculum was demonstrated [188]. In **WP3** both ultraviolet (UV) degradation rates and biodegradation rates were determined with accelerated laboratory tests. Derived environmental degradation rates were in the order of 0.035 d^{-1} for both UV and biodegradation. Adding special funghi or activated sludge to road side soil, drainage gutters a/o retention basins has the potential to increase biodegradation rates and reduce road side concentrations in soil and runoff.

7.3.1. Street cleaning

Street cleaning includes sweeping, washing, sediment removal and dust suppressants [39]. The most common types of sweeping vehicles are mechanical broom sweepers, regenerative-air sweepers and vacuum sweepers [189]. Mechanical sweepers are more effective in removing coarser particles (>100 to 125 µm), whereas vacuum- and regenerative air sweepers perform better at removing finer sediments [184].
The studies can be divided into those investigating street cleaning to reduce the concentrations of PM_{10} and $PM_{2.5}$ in air, those focusing on stormwater quality, and those that describe the efficiency of individual street sweeping machines for removal of particles from the road surface.

Reviews [184,189] concluded that sweeping in general did not affect ambient air PM or any reductions or increases were short lived. Sweeping combined with washing was found to reduce ambient PM 15% up to three days, but only at roads that transport contribution to ambient PM was significant [190]. Others have also found positive impact of combined sweeping with washing [185].
The removal of large particles was typically 20-50% for mechanical broom systems, but >50% for vacuum sweepers, and regenerative-air systems in between [191,192]. With water flushing the removal efficiencies are typically >50% for all sizes [184]. However, if cleaning is not performed often, the final reduction of run-off concentration will be low (<10%). Nevertheless, a study found up to 84% less dissolved phosphorous and nitrogen in stormwater with street cleaning and leaf collection [193]. A study found that compared to cleaning all roads once per week, the 3-fold cleaning of either only the main roads or only the intersections reduced the tire abrasion input into the sewer by 42 and 36%, respectively [91].

The efficiency of cleaning depends on many parameters (e.g., road configuration, the machine used, and amounts of deposited dust). In addition, frequency and weather (rain) impact the final result. A study estimated that cleaning could reach a maximum value of 8% under ideal conditions. For urban roads, with often cleaning an expected value is close to 4-5%, while for highways with infrequent cleaning the efficiency is <1%. Thus, it could be performed in streets with a high dust load (e.g., near construction sites, high traffic roads that are not connected to the sewer, tunnels). It should be also noted that particle collection or trapping does not necessarily solve the primary problem of material release into the environment: bad practices (e.g., methods of disposal which are not environmentally friendly) will decrease the benefits. Finally, street cleaning management needs to be flexible for specific local conditions such as weather, and season variability, which impacts the tyre particles remaining on and near the road.

A topic recently discussed is the adverse impact of the wear of plastic brushes [194]. By weighing mass loss of used brushes and combine with yearly consumption of brushes in a medium sized municipality and interpolating the results to the Swedish municipal street network, a rough estimate of about 20 tonnes of plastic brush material worn per year, was calculated. In **WP2**, test track field experiments with a closed wheel approach indicated significant emissions due to the presence of brushes at the wheel housing edge.

Dust binding (suppressants) efficiently reduces the amount of dust being whirled up but does not remove the dust from the system. Instead, it is transported into the stormwater.

7.3.2. Treating runoff

A recent study differentiated the following treatment categories: (1) decentralized road runoff treatment, (2) semi-centralized road runoff treatment, and (3) centralized road runoff treatment (WWTP) [150,195]. The first two categories are considered separate systems, while the last one combined systems.

(1) Decentralized road runoff treatment,

This treatment is typically for rural areas. It includes:

- 1a: Roadside gully pots, which have retention efficiency for solid particles 20-50% (at the low range for smaller particles and high flow rates) [152].
- 1b: Subsurface treatment units, such as vortex separators (up to 50% removal of TSS), or more advanced such as wet basins and lamella basins, infiltration chambers, ballasted flocculation, cartridge filters and media filters (such as sand, olivine, aluminum silicate, calcite, zeolite, and filtralite) (typically 80% of total suspended solids - TSS). Assessments of filters showed that some filter techniques were able to separate 61–98% of microplastic particles in stormwater in sizes from 14 to 125 µm. The separation efficiencies for tyre particles larger than 125 µm were 78–98%.

(2) semi-centralized road runoff treatment.

These systems are used for the treatment of highly-polluted road runoff, which is drained and collected along frequently-used rural roads, urban streets, and/or highways.

- 2a: Retention basins or wet ponds (removal around 75-80%). High separation efficiencies of 90–100% for microplastic particles >20 µm have also been demonstrated [151].
- 2b: Detention basin, infiltration ponds or dry ponds (removal around 85-90%).
- 2c: Constructed wetland (removal around 55%, but much higher 85% have also been reported [19,151,196].
- 2d: Biofilters (bio-retention cells) (30-90%, closer to 80% [168]).
- 2e: Roadside swales (70-80%) [152,168].

(3) Centralized measures (wastewater treatment plants)

- 3a: Wastewater treatment plants (WWTP) (80-95%, even higher for sizes >300 µm) [151,197,198]: for smaller particles 20-300 µm the removal efficiency varied between 70 and 90%, above 99% for particles in sizes between 10 and 500 µm. In the event of exceptional rainfall, stormwater may be diverted from the WWTP because of capacity problems. This quantity is typically <5%, but can be up to 20%.
- 3b: Treatment of sewage sludge (50%). Around 50% of all sewage sludge from WWTP is recycled and used as agricultural fertilizers in Europe and North America [199].

At primary treatment, sewage is pumped into settlement tanks where heavy solids are removed (efficiencies 17-78%). Secondary treatment includes biological processes to remove dissolved and suspended compounds (efficiencies 29-98%). Tertiary treatment removes chemicals before effluent is discharged to the water. WWTPs with tertiary treatment can achieve efficiencies >99% (efficiencies 72-99.7%). Around 55% of the population is connected to tertiary treatment and 77% are connected to secondary or higher treatments [19].

Indicative efficiencies of treatment systems are given in **Table 7.1** in function of particle size [151]:

Table 7.1: *Retention efficiencies of various runoff treatment facilities. Adapted from* [151]*: M=medium, H=High.*

Facility	**<0.45 µm**	**0.45-10 µm**	**10-125 µm**	**125-5,000 µm**	**>5 mm**
Sediment trap				L	M
Underground retention basin			M	H	M
Stormwater pond			M	M	
Swale			H	H	
Infiltration facility	M	M	M		
Biocell	M	H	M		
Membrane filter	M	M			

Countries have their own rules for assessing the construction of treatment facilities. Most countries normally rely on a fixed benchmark for traffic density. However, traffic density can predict only around 30% of the variation between different sites. Other parameters play also an important role, e.g. road design, rain characteristics (frequency, volume, duration), use of de-icing salts [200]. In Germany the treatment decision is based on whether the area is an ecosystem, the expected annual load of suspended solids smaller than 63 µm (AFS63), and the annual average daily traffic intensity [151]. In UK, HAWRAT is used: an evidence-based risk assessment tool that takes into account biological and ecological considerations in combination with hydraulics and traffic characteristics. Other countries use their own tools, but application to other areas and countries does not necessarily predict the pollution [201].

Some measures that can improve the overall efficiency of current systems:

- Primary sludge could be incinerated or landfilled, while quality secondary sludge could still be used as fertiliser.
- Application of filters for road run-off water at verified hot spots. Greater use and better maintenance of existing filtering techniques, such as disc sieve filter system, drum cloth filtering system, retention soil filter, etc. is recommended.

- Retention basins are artificial lakes used to manage stormwater runoff. Retention ponds have good capacity to remove urban particulate pollution and improve the quality of surface runoff thanks to sedimentation. Sediments need to be removed on a regular basis and disposed in an appropriate way.
- Water storage underground: In a combined sewer system, stormwater runoff is combined in a single pipe with wastewater from homes, businesses, and industry. In case of exceptionally intense rainfalls, this untreated wastewater can exceed the capacity of the collection system and overflow in the environment, the so called combined sewage overflow (CSO). This percentage is typically estimated to be 5% [19]. To prevent CSO, and therefore the transportation of TRWP to surface waters, water storage underground and compact urban drainage systems could be an option.

Costs

Advanced separate treatment systems cost 100,000-150,000 EUR and the annual operating costs are 5,000 EUR. Changing filters (every 30 years) costs 20,000-40,000 EUR [95].

A wet ponds costs 18-30 EUR/m^2 with maintenance costs 0.7-1.8 EUR/m^2 or 5% per year [202]. For Norway costs were estimated approximately 430-850,000 EUR. An infiltration basin costs 12-18 EUR/m^2 with maintenance costs 0.1-0.4 EUR/m^2. For Norway costs were estimated approximately 650-1,300,000 EUR (sedimentation step plus infiltration).

A centralised treatment plant is on the order of 5 million EUR [151]. For EU, upgrading all WWTP facilities with at least tertiary systems would cost on average 1.5 billion EUR per year. This value was calculated assuming a 0.08-0.20 EUR/m^3 of wastewater treated per year and considering that there are between 10 and 16 billion m^3 of wastewater that would benefit from the upgrade [19].

Water storage underground and compact urban drainage systems have cost around €0.06/m^3 [19].

7.4. Reducing Exposure

This category includes measures such as planting vegetation [168]. For example, increasing the distance between cycle lanes and traffic can reduce cyclists' exposure [203], or vegetation barriers can reduce roadside concentrations [204].

Sustainable drainage systems for managing road runoff start to become popular as they offer many benefits such as flood prevention, pollution prevention, increase attractiveness of the place [202].

7.5. Summary of mitigation measures

Table 7.2 summarises mitigation measures, along with expected time frame and interactions with other regulations. The columns give:

- Reduction potential / effectiveness,
- Cost (effectiveness),
- Implementation time,
- Interactions with other policy instruments,
- Comments regarding positive and negative side effects (an increase or decrease in other environmental impacts, road safety, or costs), feasibility (technical or legal barriers), and any other significant factors that may influence the assessment, and thereby the decision.

Note: The table refers only to tyre particles. The advantages for other particles or microplastics is not included.

Table 7.2: *Measures, reduction potential, costs and interactions.*

Measure	Reduction *	Cost	Time	Interactions	Comment
Tyre	10-30%	Tyre MF	<5 years	Euro 7	
Road maintenance	unknown	MS	continuous		
Vehicle load	proportional	Vehicle MF	continuous	CO_2	Market trends opposite
Smooth driving	Not well quantified	none	Will impact only traffic cases		Positive to environ.
Vehicle maintenance	10% or more	Included in PTI	Every 1-2 years	PTI directives	Unknown percentage of misaligned cars
Reduced km (public transport)	proportional	Low (assuming no increase of public transport means)			Activity is expected to increase
Particle collectors	Expected 30%	Vehicle MF	More than 5 years, new cars	Not included in Euro 7	robustness
Porous roads	85%	MS	2% of roads per year	Road regulations	Cleaning needed
Street cleaning	Up to 8%	MS	Immediate		Weather impact
Runoff treatment (separate)	See **7.3.2** (and **Table 7.1**): 50%	200 kEUR (simple)	2 years	Zero pollution. WFD. Countries have rules	maintenance
Runoff treatment (combined)	See **7.3.2**: 80%	5 million (centralised)	5 years	Zero pollution. WFD. Countries have rules	overflow

* Reduction refers to microplastics

MF=manufacturer, MS=Member State

8. Health and environmental impact

There are studies that have examined the impact of tyre particles on health and environment. However, based on a few review studies, there are no clear conclusions and more research is needed. Nevertheless, some key messages from the literature are:

- From the hundreds of chemicals present in tyres, Zn can be toxic to living organisms [205,206], butadiene is considered carcinogenic to humans [207], benzothiazoles and derivatives are carcinogens and genotoxicants [208], and PAHs are toxic [209] and carcinogenic [210]. Recently, a transformation product of 6-PPD was linked to the acute mortality of coho salmon [211], and the same chemical was shown to shorten the lifespan and health span of Caenorhabditis elegans an in- vitro study [212,213].
- Some tyre substances become more toxic when exposed to UV radiation. In **WP2** and **WP3** it was shown that UV aging results in degradation and fragmentation of rubber and oxidation of chemical additives. An example of such an oxidation product is 6-PPD quinone [211]. In general, oxygenated species are more toxic; this was also shown in **WP2** by a higher oxidative potential in UV aged particulate matter. Because oxygenated species are more soluble in water, these transformed substances will also leach more easily.
- Studies that spiked tyre particles into sediments showed fewer adverse effects than those using tyre particles in water [7,151].

There are no studies estimating the cost of tyre (or even microplastics) particles to the society. For this reason, we focused on plastics and PM costs (**Figure 8.1**). The values were converted to EUR in year 2025.

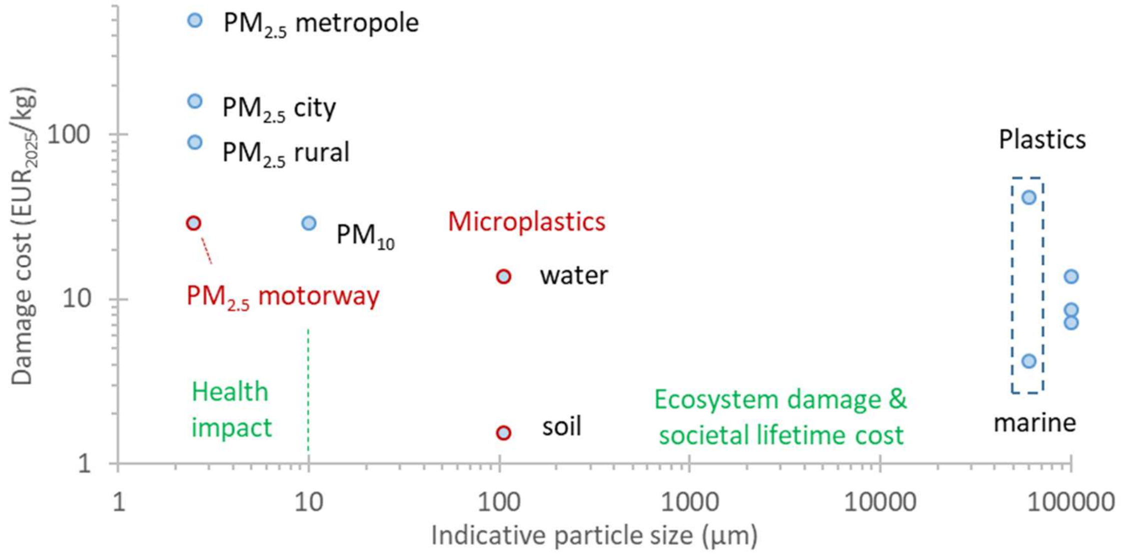


Figure 8.1: *Cost of PM, microplastics and plastics.*

The cost of PM is given in the Handbook of costs [214]. The costs for plastics are based on a few studies in the literature. One of them [215] focused only on the costs to the marine ecosystem (range 4.2 to 41.7 Euros per kg of plastics). The other two [216,217] estimated the cost of plastics to be 8.7 to 13.7 EUR/kg, with estimations for the aquatic environment as well. The mean cost of plastics to the marine ecosystems from these studies is 13.8 EUR/kg. It should be emphasized that the studies took into account pollution from production of plastics, waste management, but not impacts on health, terrestrial ecosystems or aquatic organisms. Thus, it could be that the actual cost to the society is higher.

One study [216] reported that around 1.5 trillion USD per year are lost due to plastics' impact to the oceans, and another 730 billion USD due to GHG, release of toxics to the soil. Thus, the ratio of plastics costs to the oceans and to the soil is 2:1, or that the marine costs are 67% of the total plastics costs (i.e. 5.8 EUR/kg from the total 8.7 EUR/kg). Another study [217] estimated 3100 billion USD costs of plastic pollution on marine systems, but only 200 billion USD due to GHG release (no cost to terrestrial ecosystems was calculated). In that study, the marine costs were 84% of the total costs (including also the costs of the raw plastics) (6.0-11.5 EUR/kg), thus we can derive a ratio of 84%/16% or 5.2:1 (oceans to soil cost). Another study estimated 1.8 to 3.7 USD/kg for ocean clean up, but only 0.2 USD/kg from exposure to hazardous chemicals from dumpsite or 0.5 USD/kg from burning (but 16.5 USD/kg from dioxins) [218]. Depending on which cost is assumed for soil microplastics, different rations can be derived. Based on the estimated ratios of damage to water and to soil, we can assume a 3.6 times lower cost of soil pollution from microplastics (the average of the two first studies above). This results in a 3.8 EUR/kg cost of tyres deposited to the soil.

9. Model and cost-benefit evaluation

9.1. Overview

The model that was developed was based on the previous chapters and the published models [19,97,103,106,219] but with many simplifications. The schematic is presented in **Figure 9.1**. The input is the amount of wear (typically in mass per year) (from **D6.1**), the share to the different environmental compartments and the retaining efficiencies at these compartments or other mitigation solutions. The details of each parameter and typical values are given in **Table 9.1**. In general, there is lack of evidence of actual removal efficiencies of tyre particles by existing treatment facilities. For this reason, the numbers are indicative in order to estimate cost-efficient solutions.

Although the model is very simplistic, some pathways remained: It is assumed that some tyre particles will reach directly surface waters (direct emissions or via the soil). WWTP sludge that is used for agriculture will result in tyre particles in the soil. The model also assumes some mass loss due to degradation. This value is considered the same in the soil and in the aquatic environment. Although this assumption needs to be confirmed in the future, a study showed similar values for plastics [220].

On the other hand, there are many pathways not considered in this simplified model. For example, the water treatment is divided only in two categories: treated or not treated. Particles at roofs and house walls are not considered (it is assumed that they will reach soil or runoff after rain events). There is no distinction between tyre particles reaching the soil next to the road or further away. The model estimates tyre particles in the environmental compartments and their fate from there by adding processes such as biodegradation and transfer to waters, but the approach is too simplistic and does not fully capture the procedures taking place (see **D3.5**).

Furthermore, the model does not take into account end-of-life tyres. The wear input of the model represents typically 10-30% of the tyres tread. The rest 70-90% is recycled, goes for energy recovery, retreaded, or incinerated. However, around 5% of this amount is landfilled (illegally). Thus, the cost to the environment could be multiplied by this factor to have an estimate of this impact.

After calculation of the tyre mass at the various compartments, the masses of the tyre particles at the different compartments are multiplied with their cost to the environment (values in **Chapter 8**). In this simplified model only two compartments are considered: soil and aquatic (see **Chapter 8**). Note that the cost of particles in ‘water’ although they might be deposited, it was assumed to be the cost of the marine compartment, and not the soil. This assumption will have to be re-examined in the future.

The cost of mitigation measures is estimated from the literature. The cost of the mitigation measure an the saved costs by reduced tyre particles in the environmental compartments are compared for a period of 25-35 years. The analysis does not take into account the future money value (i.e. inflation and discount rates are considered equal). Based on **D6.1** the impact would be that 1 EUR in 2025 would worth 40% less in 2050. As all investments are assumed to take place in the first 5-10 years, the impact should be small and resulting in overestimation of the cost of the infrastructure investments (<20%). Furthermore, the analysis takes into account only the tyre particles at the different compartments. Most facilities treating particles would treat also other particles (e.g. fibres from textiles, brake particles, road wear particles etc.). Thus, the benefits are by treating particles are underestimated.

It should be recalled that the tyre wear was taken from **D6.1**: 985 kt in 2025 and 1270 kt in 2050 (and constant afterwards). This increase is due to 0.7% fleet increase per year and increase of the electrified (heavier) vehicles. We also assumed that highway and rural emission factors are 25% lower from the average, while urban emission factors 50% higher [221].

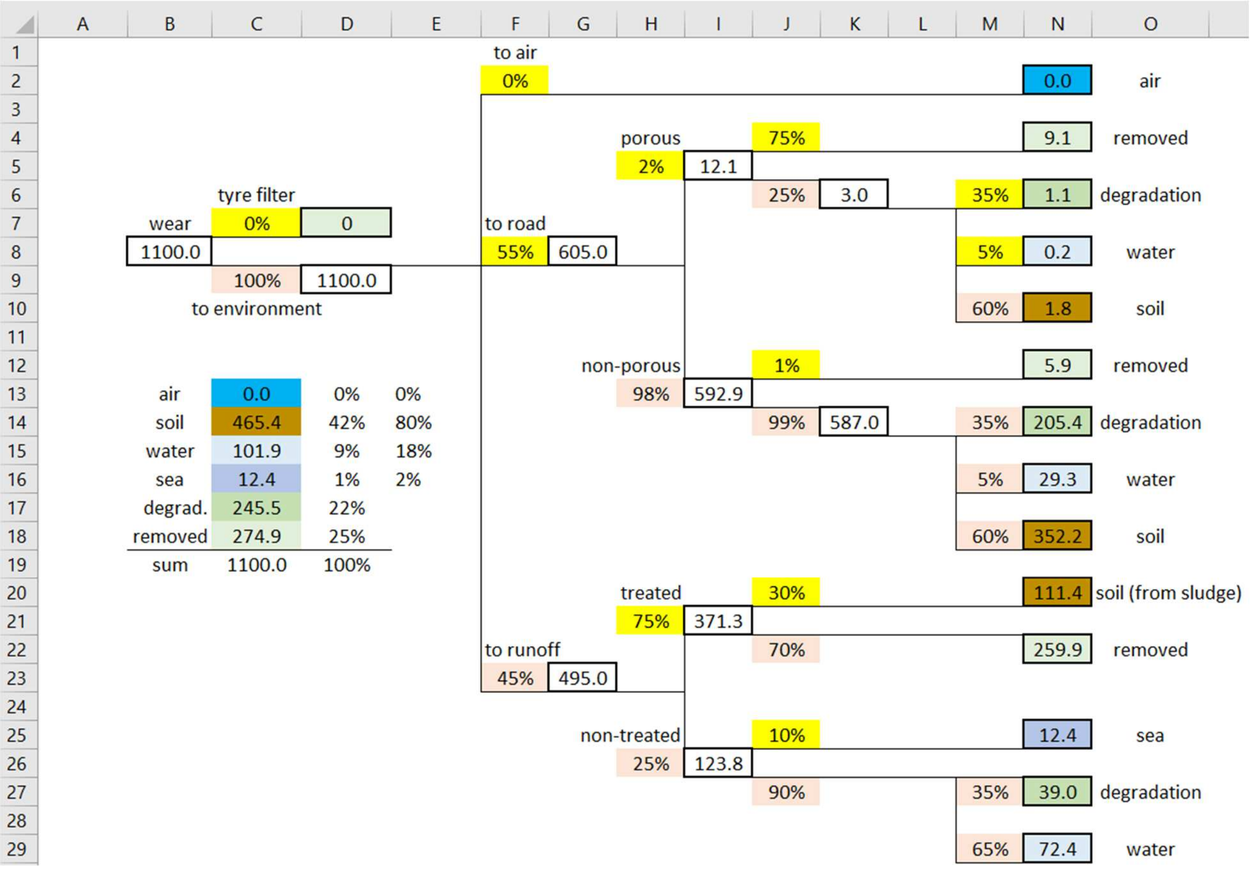


Figure 9.1: *Schematic representation of the simplified model in Excel.*

Table 9.1: *Explanation of parameters of the simplified model.*

Cell	Name	Units	Comments
B8	Tyre wear	mass	Depends on the scenario. Input from **D6.1**. We assumed 34% urban, 33% rural and 33% highway. The EFs of urban were considered higher by a factor of 1.5 and of highway and rural by a factor 0.75 compared to average.
C7	Wheel dust collector efficiency	%	Considering also the distance from the wheel 30% seems a realistic value. The impact is expected at PM mainly. This case was not examined in this **D6.2**.
C9	To environment	%	Calculated (1-C7)
F2	To air	%	Values around 5%. However it was set to 0% as the interest of this **D6.2** is microplastics and not PM.
F8	To road	%	Values around 35% (urban) to 85% (highway)
F23	To runoff	%	Calculated (1-F2-F8)
H5	Porous roads	%	Low coverage in most countries except NL. Assumed 5% at EU highways.
H13	Non porous roads	%	Calculated (1-H5)
J4	Efficiency porous	%	Typically 80-95%
J12	Efficiency non porous	%	Typical values closer to 5% with often cleaning. High impact of rain.
N6 & N14	Degradation	%	Decreases mass of tyres in soils. Assumed to be 35% but could be higher with microbiological degradation.
N8 & N16	To water	%	Direct emissions to surface waters (lakes, rivers) or via the soil. Values lower than 10%.
N10 & N18	To soil	%	Calculated (1-N6-N8) or (1-N16-N18).
H21	Efficiency treatment	%	See **7.3.2**: Depends on country and urban or not. For urban areas it should be >75%. Should also exclude CSO which is 5-20%.
H26	Not treated	%	Calculated (1-H21)
J20	Sludge to soil	%	Typical values around 30-70%.
J25	Waters to sea	%	Tyre particles reaching sea waters and remaining in the water. A 10-15% of the surface waters particles was assumed to reach the sea. The rest most likely will deposit or degradate.

Examples of application of various mitigation measures are discussed in the following paragraphs. To put the results into perspective, it should be reminded that a 10% reduction of the tyres abrasion rate resulted in approximately 34 kt less $PM_{2.5}$ with 3400 million EUR savings and 82 kt less PM_{10} with 1700 million EUR savings over the 2025-2050 period. It also resulted in 2150 kt less tyre wear with 10,850 million EUR savings. The net savings were 7,400-14,000 million EUR, depending on the cost assumptions. It should also be highlighted again that the following solutions do not address only tyre particles but other particles as well (road wear, exhaust tailpipe wear, brake wear, dust suppressants etc. at soil and stormwater, fibres from textiles or microbeads from personal care or cleaning products in waste water), thus the net benefit will be much higher than the calculated one as only tyre particle mass at the different compartments was considered.

Figure 9.2 (urban), **Figure 9.3** (rural), **Figure 9.4** (highway) summarise the values that were considered as baseline for the various scenarios. As an example, the expected tyre wear in year 2036 is plotted, assuming no reduction of current emissions (i.e. baseline of **D6.1**). Due to Euro 7 future tyre abrasion limits, some reduction is expected. However, at the moment this reduction is unknown.

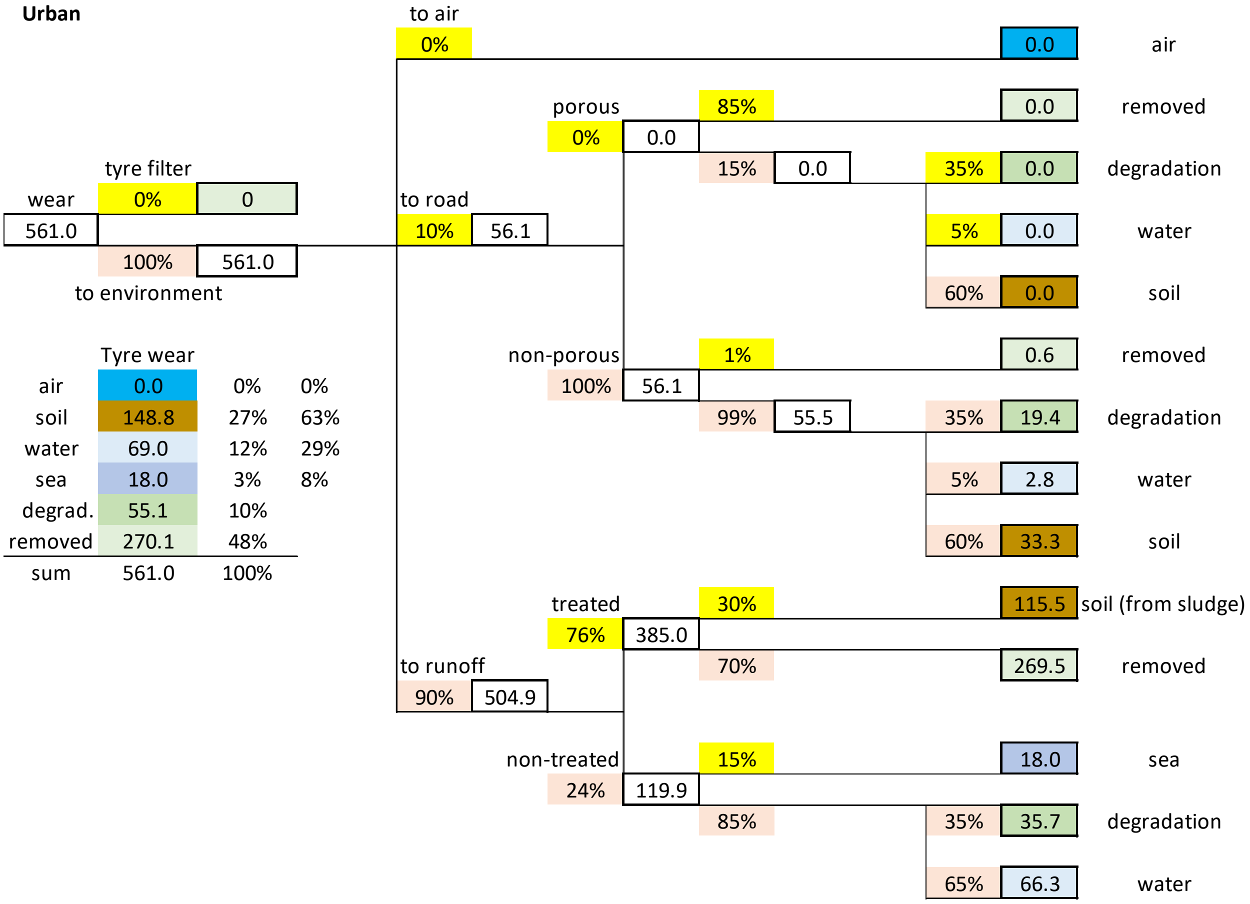
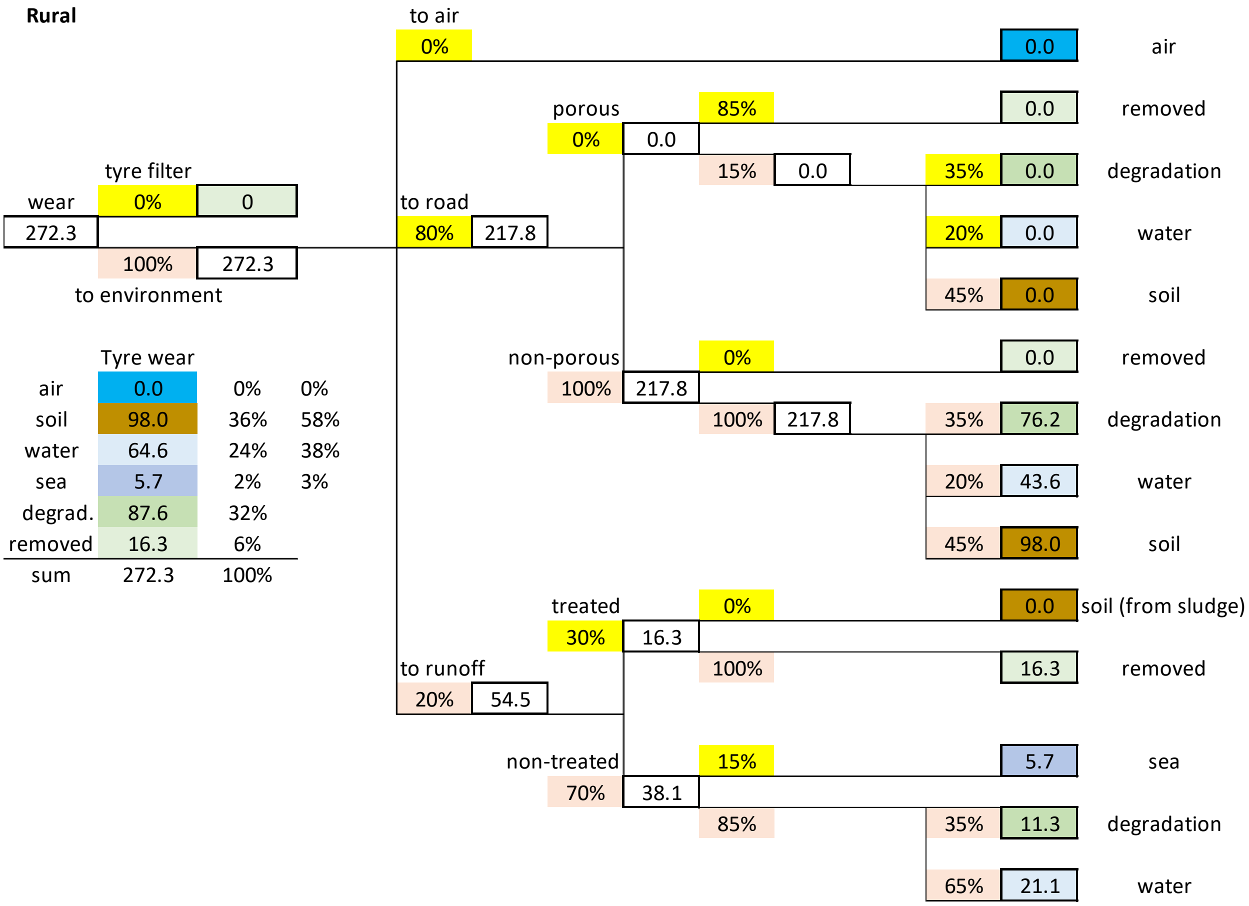


Figure 9.2: *Flow chart for urban roads (baseline example year 2036).*



	Tyre wear		
air	0.0	0%	0%
soil	98.0	36%	58%
water	64.6	24%	38%
sea	5.7	2%	3%
degrad.	87.6	32%	
removed	16.3	6%	
sum	272.3	100%	

Figure 9.3: *Flow chart for rural roads (baseline example year 2036).*

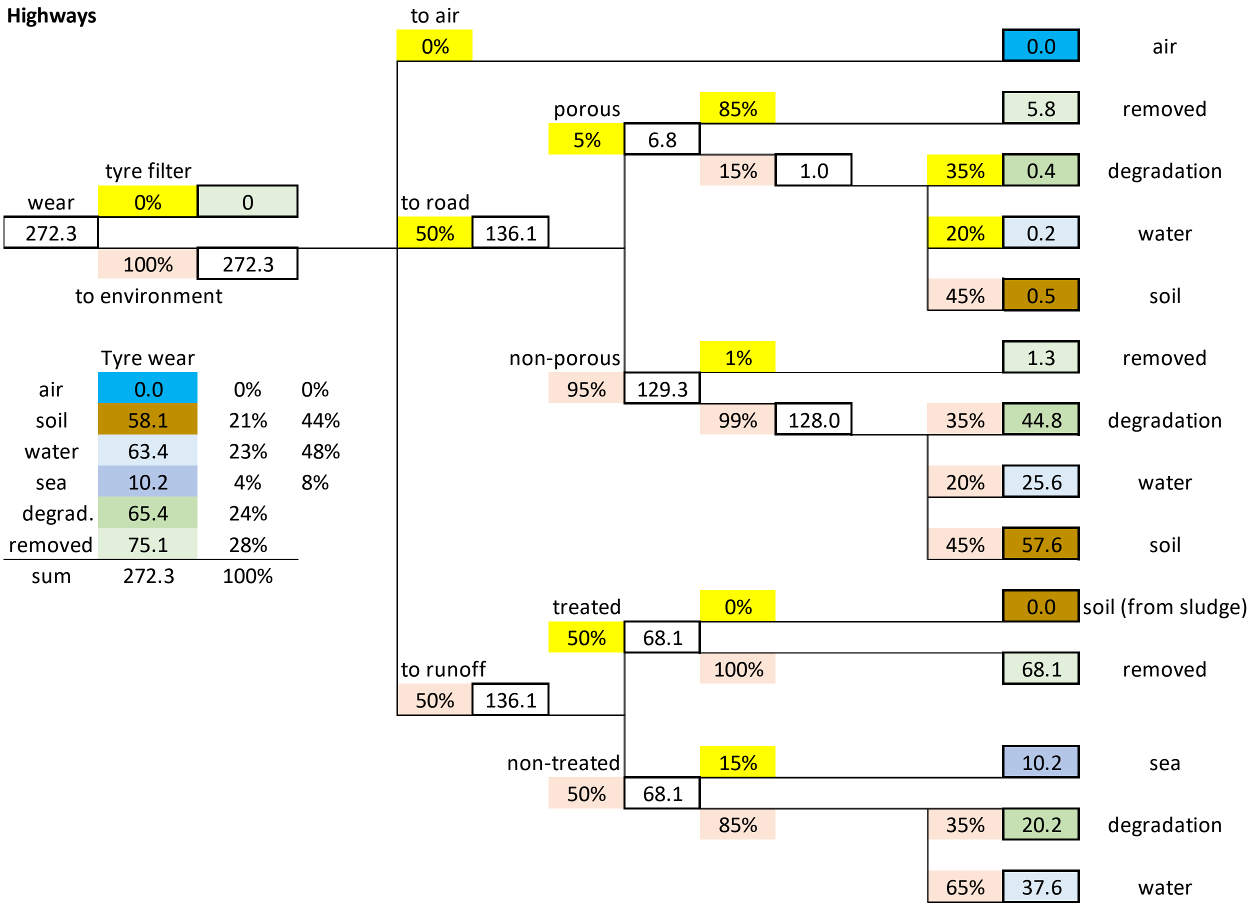


Figure 9.4: *Flow chart for highway roads (baseline example year 2036).*

The weighted cost of microplastics in the above cases is 7.5 EUR/kg (urban), 9.4 EUR/kg (rural), 8.0 EUR/kg (highway) and 8.1 EUR/kg (whole EU); in all cases above 7.2 EUR/kg assumed in **D6.1**.

9.2. EU highways: porous roads

For this case we assumed that non-porous highway roads (from 5%) were converted to porous roads (95% of the highway roads) (**Figure 9.5**). The trapping efficiency of the porous roads was assumed to be 85%. The percentage to runoff was assumed to be 50%.

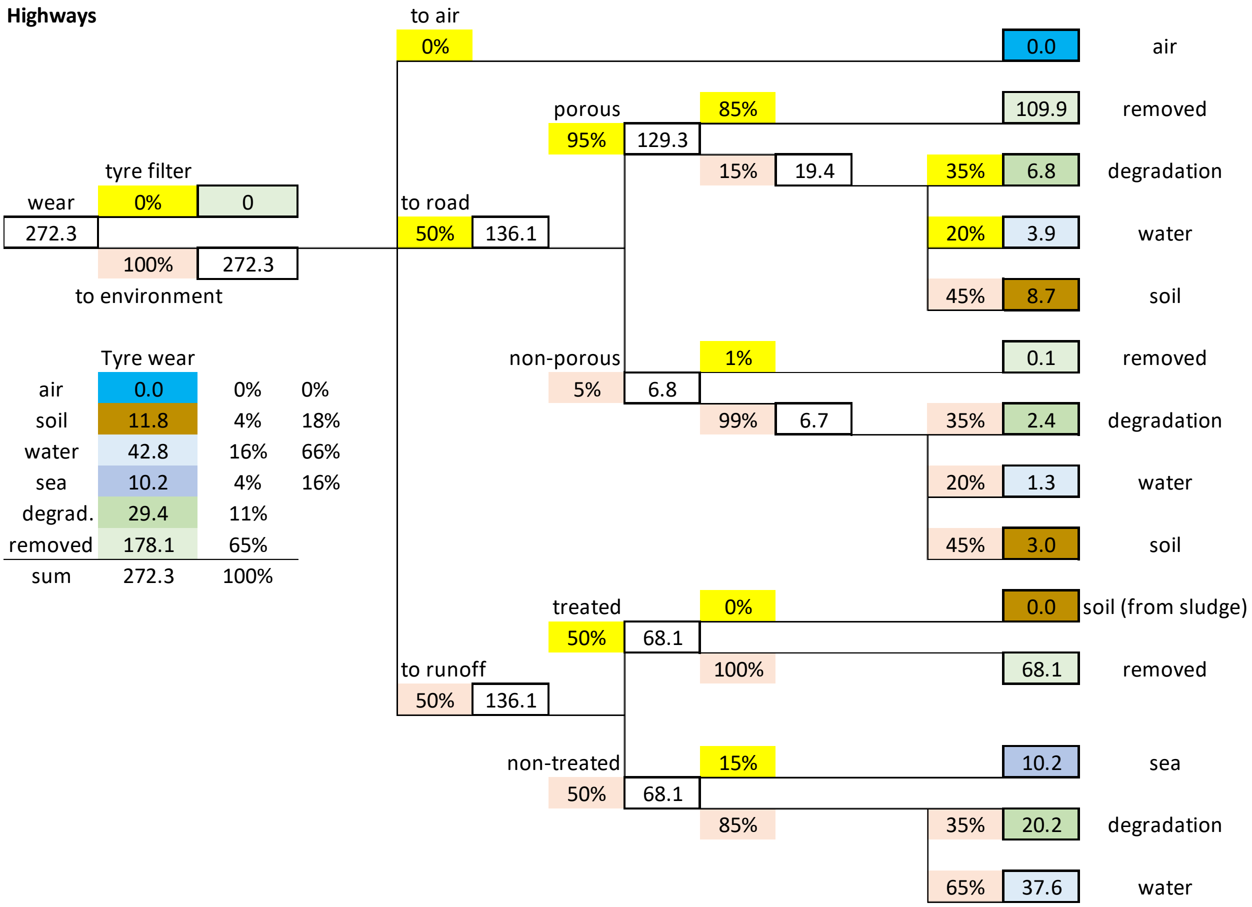


Figure 9.5: *Highways with 95% porous roads (example year 2036).*

The analysis shows that approximately 100 kt of tyre wear could be trapped and cleaned at the porous roads (in year 2036), but due to the lower mass at the soil, less would result degradation, with a net benefit of 67 kt (**Table 9.2**). This translates to approximately 460 million EUR savings annually after full implementation of the porous roads. Assuming 3% replacement of roads, which is a reasonable value for typical life span of roads of 30 years, it would take 30 years to reach 95% porous roads from 5%.

Table 9.2: *Cost and benefits of applying porous roads at the highways (example year 2036).*

	Highway Baseline	porous 5-->95%	Reduction kt	Savings mEUR
air	0.0	0.0	0.0	
soil	58.1	11.8	-46.3	176
water	63.4	42.8	-20.6	284
sea	10.2	10.2	0.0	0
degrad.	65.4	29.4	-36.0	
removed	75.1	178.1	102.9	
sum	272.3	272.3		460

The investment costs (including maintenance) in EU road infrastructure were around 55,500 million Euros. Highways are <5% of total roads (around 75,000 km), thus <2,800 million were invested in highways. Assuming 10% higher cost of porous roads would translate to additional 280 million EUR. Similar order of costs is calculated assuming 4 EUR/m^2 increased cost for porous roads (10% of 40 EUR/m^2). For a 6-lane road the cost would be 800 EUR/m. For 75,000 km, replaced 3% per year, the additional cost would be 180 million EUR. Both estimations (180-280) are at the same order (but lower) as the benefit (460 million EUR).

Figure 9.6 summarises the results. It will take almost 13 years to reach a net positive balance, but after 30 years, when the replacement of the roads will have been completed and the costs will be only maintenance, the net benefit will become high. After approximately 25-30 years the sum over the years will become positive.

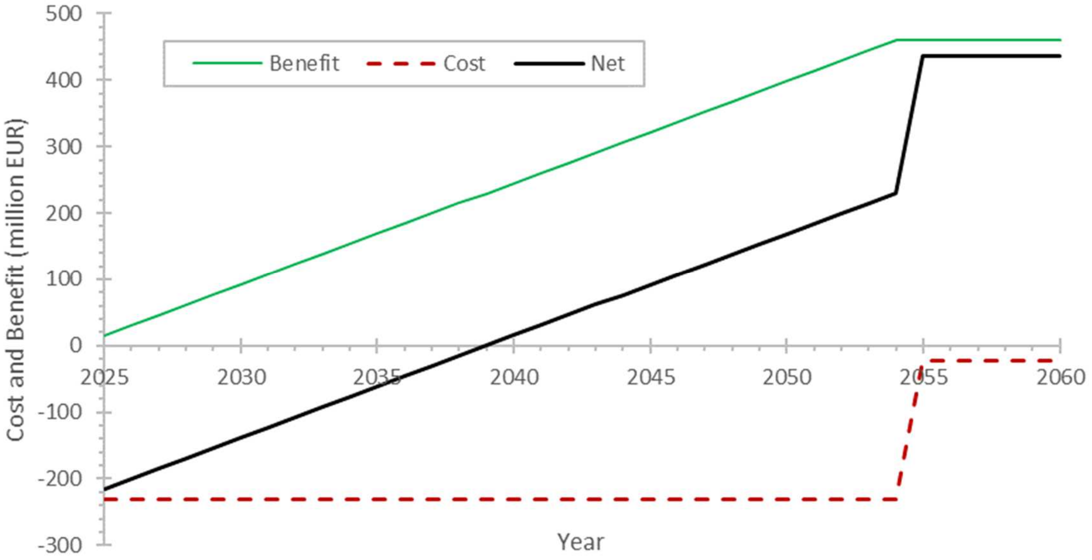


Figure 9.6: *Overview of costs and benefits of case applying porous roads at the EU highways.*

9.3. EU highways: better runoff treatment

In this case we assumed that the highway treated runoff efficiency increased from 50% to 75%. This would result in 34 kt less to the aquatic environment (example year 2036), or 24 kt after considering degradation. Due to the higher cost compared to soil, it is expected that savings would be 330 million EUR per year after full implementation (**Table 9.3**). Note that the cost of tyre particles in the surface waters and those deposited was assumed to be equal to the cost in the marine environment.

The higher percentage of treatments would need improvements of the current installations. The increased efficiency could be achieved by better maintenance, and addition of secondary treatment. The time frame is on the order of 5 years for such interventions.

Ponds with forebays or forebays with soil filters cost around 25,000 EUR (including maintenance) per decade. Assuming that there are ponds every 3 km of highway road (75,000/3) the improvement and maintenance cost around 625 million EUR. **Figure 9.7** shows an example that takes 10 years to improve the existing ponds, and then the costs remain the same (not 10% of the initial investment). The net benefit becomes positive only after a few years, and in the time frame 2025-2050 almost 6,000 million EUR can be saved.

Table 9.3: *Cost and benefits of applying higher efficiency treatment at the highways (example year 2036).*

	Highway Baseline	treatment 50-->75%	Reduction kt	Savings mEUR
air	0.0	0.0	0.0	
soil	58.1	58.1	0.0	0
water	63.4	44.6	-18.8	259
sea	10.2	5.1	-5.1	70
degrad.	65.4	55.3	-10.1	
removed	75.1	109.2	34.0	
sum	272.3	272.3		330

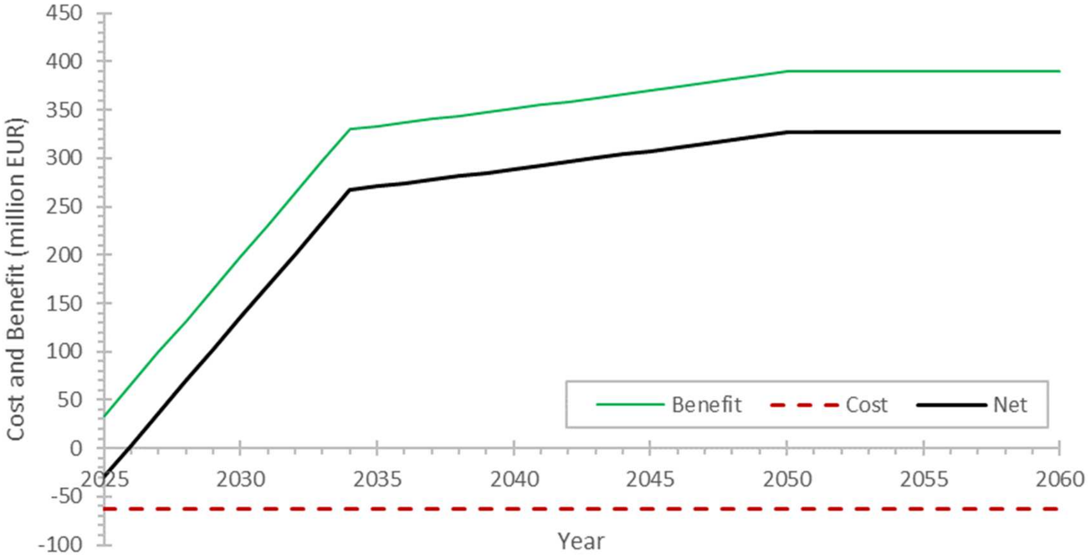


Figure 9.7: *Overview of costs and benefits of case applying higher efficiency treatment at the EU highways.*

9.4. EU urban

For this case we assume that at urban areas only 10% reaches the soil, while the rest reaches the sewers. The urban treatment consists of combined and separate systems, with assumed ratios of 75% and 25%. For example, combined systems consist 70% or

higher in some countries (NL, FR, UK), 40% in some others (DE, DK), or even lower [19]. We also assumed efficiencies of 85% and 50% for combined and separate systems respectively. The 85% efficiency includes also a 5% of CSO. Thus, the weighted efficiency is 76% (**Figure 9.8**).
For the improved case we assume 95% efficiency of the combined systems and 75% of the separate with a weighted efficiency of 90%. These assumptions need to be re-examined in the future when current facilities will be evaluated with standardized methods [222].

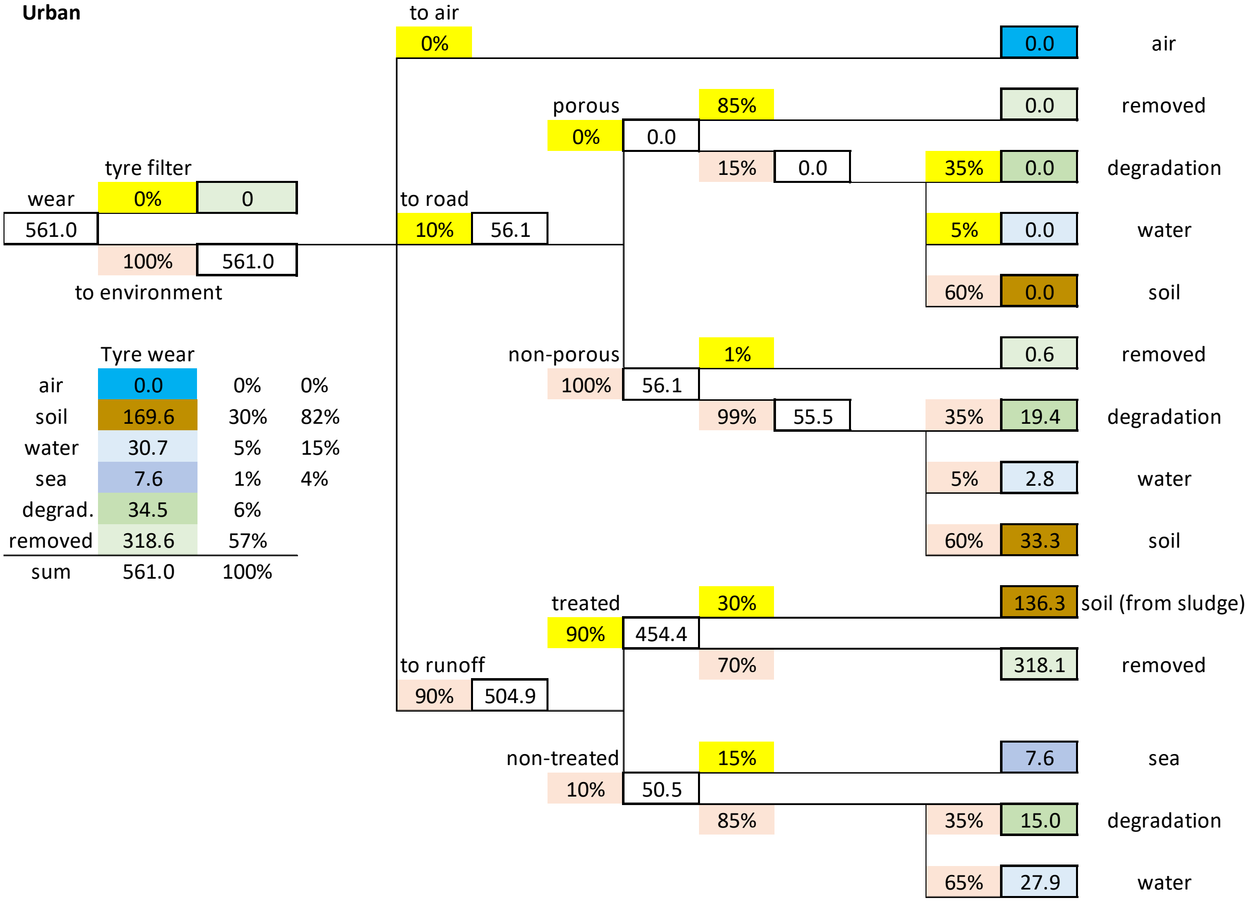
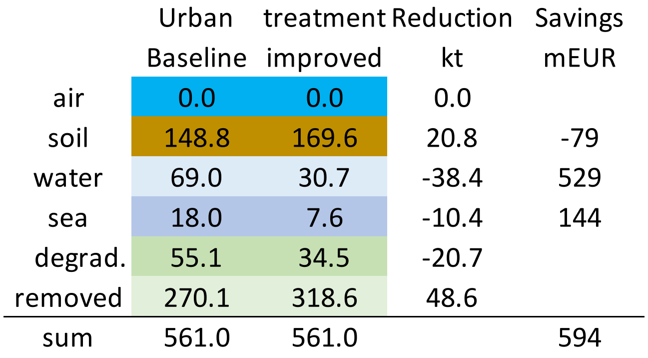


Figure 9.8: *Urban areas with runoff consisting 75% combined systems with efficiency 95% (instead of 80%) and separate systems with efficiency 75% (instead of 50%) (example year 2036).*

The efficiency improvement results in 48 kt less tyre mass, but a considerable amount is returned to the soil via the sludge (**Table 9.4**). Thus, the total savings are 594 million EUR annually. If the annual cost is1.5 billion Euros for the first 10 years and 10% afterwards, as presented in **Figure 9.9**, the investment will hardly recover even after 30 years. However, it should be reminded that other benefits (e.g. from textile fibres) have not been taken into account.

Table 9.4: *Cost and benefits of applying higher efficiency treatment at the urban areas (example year 2036).*



	Urban Baseline	treatment improved	Reduction kt	Savings mEUR
air	0.0	0.0	0.0	
soil	148.8	169.6	20.8	-79
water	69.0	30.7	-38.4	529
sea	18.0	7.6	-10.4	144
degrad.	55.1	34.5	-20.7	
removed	270.1	318.6	48.6	
sum	561.0	561.0		594

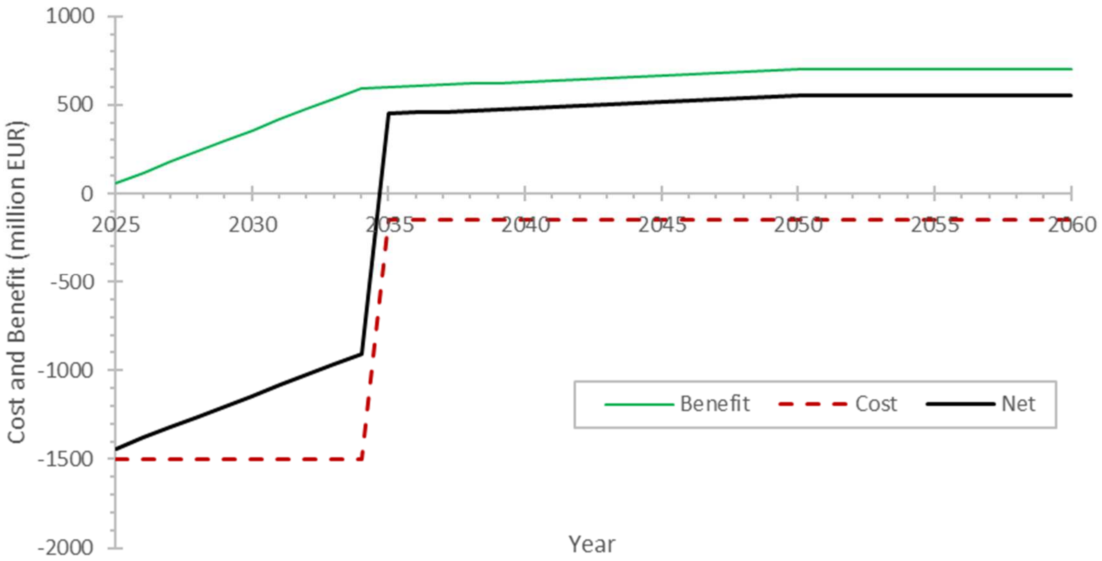


Figure 9.9: *Overview of costs and benefits of case applying higher efficiency treatment at the EU urban areas.*

9.5. Other measures

Other measures that have not been examined due to difficulties in implementation are:

- Avoiding microplastics from becoming part of sewage sludge or returning them to the agriculture soil.
- Street cleaning due to the overall efficiency uncertainties
- Installation of tyre filters due to the difficulty in installation and lack of robustness evidence.
- Solutions at rural roads due to the high length of the roads
- Biodegradation. It seems a promising solution with low cost.

10. Summary

In this deliverable the fate of microplastics was examined. A simplified model was developed to assess different mitigation strategies. The model assumes that tyre particles reach air, road or runoff. The road was assumed to be porous or non-porous with different trapping efficiencies. The runoff was assumed to be treated or not. The cost of microplastics (year 2025) was assumed to be 13.8 EUR/kg for those ending up to the aquatic environment and 3.8 EUR/kg for those ending up in the soil. The cost estimates were based on cost estimates of plastics to the environment. To put the number into perspective PM_{10} has a cost of 29 EUR/kg, while $PM_{2.5}$ 160 EUR/kg in a city, and 495 EUR/kg in a metropole. The costs of mitigation measures, (runoff treatments) were based on the literature.

A few sample cases were examined:

- Replacing non-porous with porous surfaces at highway roads.
- Improving runoff treatment at highways.
- Improving runoff treatment at urban areas.

The cost-benefit analysis showed a net benefit with improvement of highways runoff. Porous roads could be efficient but it would take almost 30 years to see the net benefit. Upgrading of all WWTP with tertiary treatment has high costs, which would hardly recover after 30 years if only tyre particles benefits are considered. Nevertheless, hot spots might have faster recuperation of the investments. Accelerated biodegradation seems also a promising cost-effective solution.

Comparing with **D6.1**, it is clear from the analysis that addressing the source is the most cost-effective approach with an order of magnitude higher cost effectiveness compared to treating tyre particles after they have been emitted to the environment. Thus, measures reducing tyre wear should be prioritized (e.g. tyres with less wear rate, reduction of annual mileage and smoother driving, well maintained vehicle etc.).

11. Bibliography

1. Fukahori, Y.; Gabriel, P.; Liang, H.; Busfield, J.J.C. A New Generalized Philosophy and Theory for Rubber Friction and Wear. *Wear* **2020**, *446–447*, 203166, doi:10.1016/j.wear.2019.203166.
2. Park, I.; Lee, J.; Lee, S. Laboratory Study of the Generation of Nanoparticles from Tire Tread. *Aerosol Science and Technology* **2017**, *51*, 188–197, doi:10.1080/02786826.2016.1248757.
3. IMARC *Europe Tire Market: Industry Trends, Share, Size, Growth, Opportunity and Forecast 2023-2028. Available Online at: Https://Www.Imarcgroup.Com/Europe-Tire-Market#:~:text=The%20Europe%20tire%20market%20size,3.11%25%20during%202023%2D2028*; IMARC: London, UK, 2022;
4. Luo, Z.; Zhou, X.; Su, Y.; Wang, H.; Yu, R.; Zhou, S.; Xu, E.G.; Xing, B. Environmental Occurrence, Fate, Impact, and Potential Solution of Tire Microplastics: Similarities and Differences with Tire Wear Particles. *Science of The Total Environment* **2021**, *795*, 148902, doi:10.1016/j.scitotenv.2021.148902.
5. Michelin *Results 2022. Available Online at: Https://Www.Michelin.Com/En/Finance/Results-and-Presentations/Results-and-Sales/*; Michelin: Clermont Ferrand, France, 2022;
6. ETRMA *European Tyre & Rubber Industry. Statistics*; European Tyre & Rubber Manufacturers Association (ETRMA): Brussels, Belgium, 2021;
7. Mayer, P.M.; Moran, K.D.; Miller, E.L.; Brander, S.M.; Harper, S.; Garcia-Jaramillo, M.; Carrasco-Navarro, V.; Ho, K.T.; Burgess, R.M.; Thornton Hampton, L.M.; et al. Where the Rubber Meets the Road: Emerging Environmental Impacts of Tire Wear Particles and Their Chemical Cocktails. *Science of The Total Environment* **2024**, *927*, 171153, doi:10.1016/j.scitotenv.2024.171153.
8. Anadón, R. Study on Tyres Abrasion Test Method Durability Investigation. Document TA-01-05. Available Online at: Https://Wiki.Unece.Org/Display/Trans/TF+TA+session+1. 2022.
9. CFR (Code of Federal Regulations) 49 CFR § 575.104 - Uniform Tire Quality Grading Standards. Available on Line at: Https://Www.Law.Cornell.Edu/Cfr/Text/49/575.104 2023.
10. Russian Federation Particulate Matter Emissions by Tyres. Informal Document GRPE-65-20. Available Online at: Https://Unece.Org/DAM/Trans/Doc/2013/Wp29grpe/GRPE-65-20e.Pdf 2013.
11. Mugnier, E.; Farhangi, C.; Kley, S.; Aurez, V.; Chhang, A. *The Socio-Economic Impact of Truck Tyre Retreading in Europe. The Circular Economy of Tyres in Danger. Available Online at: Https://Www.Etrma.Org/Wp-Content/Uploads/2019/09/201611-Ey_retreading_lr.Pdf*; EY: Paris, France, 2016;
12. Camatini, M.; Crosta, G.F.; Dolukhanyan, T.; Sung, C.; Giuliani, G.; Corbetta, G.M.; Cencetti, S.; Regazzoni, C. Microcharacterization and Identification of Tire Debris in Heterogeneous Laboratory and Environmental Specimens. *Materials Characterization* **2001**, *46*, 271–283, doi:10.1016/S1044-5803(00)00098-X.
13. Boulter, P.G. *A Review of Emission Factors and Models for Road Vehicle Non-Exhaust Particulate Matter*; TRL Limited: Berkshire, UK, 2005;

14. Lorenčič, V. The Effect of Tire Age and Anti-Lock Braking System on the Coefficient of Friction and Braking Distance. *Sustainability* **2023**, *15*, 6945, doi:10.3390/su15086945.
15. Lee, H.; Ju, M.; Kim, Y. Estimation of Emission of Tire Wear Particles (TWPs) in Korea. *Waste Management* **2020**, *108*, 154–159, doi:10.1016/j.wasman.2020.04.037.
16. Kole, P.J.; Löhr, A.J.; Van Belleghem, F.; Ragas, A. Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment. *IJERPH* **2017**, *14*, 1265, doi:10.3390/ijerph14101265.
17. Zhou, X.; Luo, Z.; Wang, H.; Luo, Y.; Yu, R.; Zhou, S.; Wang, Z.; Hu, G.; Xing, B. Machine Learning Application in Forecasting Tire Wear Particles Emission in China under Different Potential Socioeconomic and Climate Scenarios with Tire Microplastics Context. *Journal of Hazardous Materials* **2023**, *441*, 129878, doi:10.1016/j.jhazmat.2022.129878.
18. Wagner, S.; Hüffer, T.; Klöckner, P.; Wehrhahn, M.; Hofmann, T.; Reemtsma, T. Tire Wear Particles in the Aquatic Environment - A Review on Generation, Analysis, Occurrence, Fate and Effects. *Water Research* **2018**, *139*, 83–100, doi:10.1016/j.watres.2018.03.051.
19. Hann, S.; Sherrington, C.; Jamieson, O.; Hickman, M.; Kershaw, P.; Bapasola, A.; Cole, G. *Investigating Options for Reducing Releases in the Aquatic Environment of Microplastics Emitted by (but Not Intentionally Added in) Products. Report for DG Environment of the European Commission*; Eunomia Research & Consulting Ltd: Bristol, UK, 2018;
20. European Commission *Combating Microplastic Pollution in the European Union. Impact Assessment Report for the Proposal for a Regulation of the European Parliament and of the Council on Preventing Plastic Pellet Losses to Reduce Microplastic Pollution. Available Online at: Eur-Lex.Europa.Eu/Legal-Content/EN/TXT/PDF/?uri=CONSIL:ST_14248_2023_ADD_5&qid=1697535311916*; Brussels, Belgium, 2023;
21. Quantis; EA *Plastic Leak Project: Methodological Guidelines. Available Online at: Quantis-Intl.Com/Plastic-Leak-Project-Guidelines*; Zürich, Switzerland, 2020;
22. Unice, K.M.; Kreider, M.L.; Panko, J.M. Comparison of Tire and Road Wear Particle Concentrations in Sediment for Watersheds in France, Japan, and the United States by Quantitative Pyrolysis GC/MS Analysis. *Environ. Sci. Technol.* **2013**, 130710100101002, doi:10.1021/es400871j.
23. Klöckner, P.; Seiwert, B.; Weyrauch, S.; Escher, B.I.; Reemtsma, T.; Wagner, S. Comprehensive Characterization of Tire and Road Wear Particles in Highway Tunnel Road Dust by Use of Size and Density Fractionation. *Chemosphere* **2021**, *279*, 130530, doi:10.1016/j.chemosphere.2021.130530.
24. 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*, 2014–2028, doi:10.4209/aaqr.2018.03.0099.
25. 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* **2023**, *14*, 1780, doi:10.3390/atmos14121780.
26. Grigoratos, T.; Martini, G. *Non-Exhaust Traffic Related Emissions - Brake and Tyre Wear PM: Literature Review.*; Publications Office: LU, 2014;
27. 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.; et al. A Review of Road

Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures. *Environ. Sci. Technol.* **2022**, *56*, 6813–6835, doi:10.1021/acs.est.2c01072.

28. 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. *Science of The Total Environment* **2010**, *408*, 652–659, doi:10.1016/j.scitotenv.2009.10.016.
29. Rausch, J.; Jaramillo-Vogel, D.; Perseguers, S.; Schnidrig, N.; Grobéty, 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. *Science of The Total Environment* **2022**, *803*, 149832, doi:10.1016/j.scitotenv.2021.149832.
30. Kim, G.; Lee, S. Characteristics of Tire Wear Particles Generated by a Tire Simulator under Various Driving Conditions. *Environ. Sci. Technol.* **2018**, *52*, 12153–12161, doi:10.1021/acs.est.8b03459.
31. Park, I.; Kim, H.; Lee, S. Characteristics of Tire Wear Particles Generated in a Laboratory Simulation of Tire/Road Contact Conditions. *Journal of Aerosol Science* **2018**, *124*, 30–40, doi:10.1016/j.jaerosci.2018.07.005.
32. 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. *Atmospheric Environment* **2006**, *40*, 1314–1323, doi:10.1016/j.atmosenv.2005.10.029.
33. Järlskog, I.; Jaramillo-Vogel, D.; Rausch, J.; Gustafsson, M.; Strömvall, A.-M.; Andersson-Sköld, Y. Concentrations of Tire Wear Microplastics and Other Traffic-Derived Non-Exhaust Particles in the Road Environment. *Environment International* **2022**, *170*, 107618, doi:10.1016/j.envint.2022.107618.
34. Kovochich, M.; Parker, J.A.; Oh, S.C.; Lee, J.P.; Wagner, S.; Reemtsma, T.; Unice, K.M. Characterization of Individual Tire and Road Wear Particles in Environmental Road Dust, Tunnel Dust, and Sediment. *Environ. Sci. Technol. Lett.* **2021**, *8*, 1057–1064, doi:10.1021/acs.estlett.1c00811.
35. Worek, J.; Badura, X.; Białas, A.; Chwiej, J.; Kawoń, K.; Styszko, K. Pollution from Transport: Detection of Tyre Particles in Environmental Samples. *Energies* **2022**, *15*, 2816, doi:10.3390/en15082816.
36. Kovochich, M.; Liong, M.; Parker, J.A.; Oh, S.C.; Lee, J.P.; Xi, L.; Kreider, M.L.; Unice, K.M. Chemical Mapping of Tire and Road Wear Particles for Single Particle Analysis. *Science of The Total Environment* **2021**, *757*, 144085, doi:10.1016/j.scitotenv.2020.144085.
37. Klöckner, P.; Seiwert, B.; Eisentraut, P.; Braun, U.; Reemtsma, T.; Wagner, S. Characterization of Tire and Road Wear Particles from Road Runoff Indicates Highly Dynamic Particle Properties. *Water Research* **2020**, *185*, 116262, doi:10.1016/j.watres.2020.116262.
38. Kovochich, M.; Oh, S.C.; Lee, J.P.; Parker, J.A.; Barber, T.; Unice, K. Characterization of Tire and Road Wear Particles in Urban River Samples. *Environmental Advances* **2023**, *12*, 100385, doi:10.1016/j.envadv.2023.100385.
39. Piscitello, A.; Bianco, C.; Casasso, A.; Sethi, R. Non-Exhaust Traffic Emissions: Sources, Characterization, and Mitigation Measures. *Science of The Total Environment* **2021**, *766*, 144440, doi:10.1016/j.scitotenv.2020.144440.
40. 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. *Atmospheric Environment* **2023**, *297*, 119597, doi:10.1016/j.atmosenv.2023.119597.

41. Mathissen, M.; Scheer, V.; Vogt, R.; Benter, T. Investigation on the Potential Generation of Ultrafine Particles from the Tire–Road Interface. *Atmospheric Environment* **2011**, *45*, 6172–6179, doi:10.1016/j.atmosenv.2011.08.032.
42. Foitzik, M.-J.; Unrau, H.-J.; Gauterin, F.; Dörnhöfer, J.; Koch, T. Investigation of Ultra Fine Particulate Matter Emission of Rubber Tires. *Wear* **2018**, *394–395*, 87–95, doi:10.1016/j.wear.2017.09.023.
43. Wilkinson, T.; Järlskog, I.; De Lima, J.A.; Gustafsson, M.; Mattsson, K.; Andersson Sköld, Y.; Hassellöv, M. Shades of Grey—Tire Characteristics and Road Surface Influence Tire and Road Wear Particle (TRWP) Abundance and Physicochemical Properties. *Front. Environ. Sci.* **2023**, *11*, 1258922, doi:10.3389/fenvs.2023.1258922.
44. Jung, U.; Choi, S.-S. Classification and Characterization of Tire-Road Wear Particles in Road Dust by Density. *Polymers* **2022**, *14*, 1005, doi:10.3390/polym14051005.
45. Kayhanian, M.; McKenzie, E.R.; Leatherbarrow, J.E.; Young, T.M. Characteristics of Road Sediment Fractionated Particles Captured from Paved Surfaces, Surface Run-off and Detention Basins. *Science of The Total Environment* **2012**, *439*, 172–186, doi:10.1016/j.scitotenv.2012.08.077.
46. Klöckner, P.; Reemtsma, T.; Eisentraut, P.; Braun, U.; Ruhl, A.S.; Wagner, S. Tire and Road Wear Particles in Road Environment – Quantification and Assessment of Particle Dynamics by Zn Determination after Density Separation. *Chemosphere* **2019**, *222*, 714–721, doi:10.1016/j.chemosphere.2019.01.176.
47. Gao, Z.; Cizdziel, J.V.; Wontor, K.; Clisham, C.; Focia, K.; Rausch, J.; Jaramillo-Vogel, D. On Airborne Tire Wear Particles along Roads with Different Traffic Characteristics Using Passive Sampling and Optical Microscopy, Single Particle SEM/EDX, and µ-ATR-FTIR Analyses. *Front. Environ. Sci.* **2022**, *10*, 1022697, doi:10.3389/fenvs.2022.1022697.
48. Tonegawa, Y.; Sasaki, S. Development of Tire-Wear Particle Emission Measurements for Passenger Vehicles. *Emiss. Control Sci. Technol.* **2021**, *7*, 56–62, doi:10.1007/s40825-020-00181-z.
49. Mattsson, K.; De Lima, J.A.; Wilkinson, T.; Järlskog, I.; Ekstrand, E.; Sköld, Y.A.; Gustafsson, M.; Hassellöv, M. Tyre and Road Wear Particles from Source to Sea. *Micropl.&Nanopl.* **2023**, *3*, 14, doi:10.1186/s43591-023-00060-8.
50. Luhana, L.; Sokhi, R.S.; Warner, L.; Mao, H.; Boulter, P.; McCrae, I.; Wright, J.; Osborn, D. *Measurement of Non-Exhaust Particulate Matter*; 2004;
51. Rauert, C.; Rødland, E.S.; Okoffo, E.D.; Reid, M.J.; Meland, S.; Thomas, K.V. Challenges with Quantifying Tire Road Wear Particles: Recognizing the Need for Further Refinement of the ISO Technical Specification. *Environ. Sci. Technol. Lett.* **2021**, *8*, 231–236, doi:10.1021/acs.estlett.0c00949.
52. 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*; European Topic Centre on Air pollution, transport, noise and industrial pollution: Kjeller, Norway, 2021;
53. Evans, A.; Evans, R. *The Composition of a Tyre: Typical Components*; The Waste & Resurces Action Programme, 2006;
54. Rodgers, B. *Tire Engineering: An Introduction*; CRC press: Boca Raton, 2020; ISBN 978-1-00-302296-1.

55. Rodgers, B.; Tallury, S.S.; Klingensmith, W. Rubber Compounding. In *Kirk-Othmer Encyclopedia of Chemical Technology*; Kirk-Othmer, Ed.; Wiley, 2023; pp. 1–65 ISBN 978-0-471-48494-3.
56. Councell, T.B.; Duckenfield, K.U.; Landa, E.R.; Callender, E. Tire-Wear Particles as a Source of Zinc to the Environment. *Environ. Sci. Technol.* **2004**, *38*, 4206–4214, doi:10.1021/es034631f.
57. Li, J.; Zhang, M.; Ge, Y.; Wen, Y.; Luo, J.; Yin, D.; Wang, C.; Wang, C. Emission Characteristics of Tyre Wear Particles from Light-Duty Vehicles. *Atmosphere* **2023**, *14*, 724, doi:10.3390/atmos14040724.
58. Jeong, Y.; Lee, S.; Woo, S.-H. Chemical Leaching from Tire Wear Particles with Various Treadwear Ratings. *IJERPH* **2022**, *19*, 6006, doi:10.3390/ijerph19106006.
59. Güney, B. Investigation of Physical and Chemical Properties of Particulate Matter Caused by Vehicle Tire Wear. *Int. J. Environ. Sci. Technol.* **2023**, doi:10.1007/s13762-023-05261-5.
60. Guo, Q.; Men, Z.; Liu, Z.; Niu, Z.; Fang, T.; Liu, F.; Wu, L.; Peng, J.; Mao, H. Chemical Characteristics of Fine Tire Wear Particles Generated on a Tire Simulator. *Environmental Pollution* **2023**, *336*, 122399, doi:10.1016/j.envpol.2023.122399.
61. 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. *Atmospheric Environment* **2021**, *262*, 118592, doi:10.1016/j.atmosenv.2021.118592.
62. Rødland, E.S.; Gustafsson, M.; Jaramillo-Vogel, D.; Järlskog, I.; Müller, K.; Rauert, C.; Rausch, J.; Wagner, S. Analytical Challenges and Possibilities for the Quantification of Tire-Road Wear Particles. *TrAC Trends in Analytical Chemistry* **2023**, *165*, 117121, doi:10.1016/j.trac.2023.117121.
63. CEDR *MICROPROOF (Micropollutants in Road RunOff). Measurements of Organic Micropollutants, Microplastics and Associated Substances from Road Transport. Deliverable 6.6. Available Online at: Https://Www.Cedr.Eu/Download/Other_public_files/Research_programme/Call_2016/Call_2016_water_quality/Microproof/Microproof-D6.6-Measurements-of-Organic-Micropollutants-Microplastics-and-Associated-Substances-from-Road-Transport.Pdf*; Transnational Road Research Programme: The Netherlands, 2019;
64. Müller, K.; Hübner, D.; Huppertsberg, S.; Knepper, T.P.; Zahn, D. Probing the Chemical Complexity of Tires: Identification of Potential Tire-Borne Water Contaminants with High-Resolution Mass Spectrometry. *Science of The Total Environment* **2022**, *802*, 149799, doi:10.1016/j.scitotenv.2021.149799.
65. Halsband, C.; Sørensen, L.; Booth, A.M.; Herzke, D. Car Tire Crumb Rubber: Does Leaching Produce a Toxic Chemical Cocktail in Coastal Marine Systems? *Front. Environ. Sci.* **2020**, *8*, 125, doi:10.3389/fenvs.2020.00125.
66. Seiwert, B.; Klöckner, P.; Wagner, S.; Reemtsma, T. Source-Related Smart Suspect Screening in the Aqueous Environment: Search for Tire-Derived Persistent and Mobile Trace Organic Contaminants in Surface Waters. *Anal Bioanal Chem* **2020**, *412*, 4909–4919, doi:10.1007/s00216-020-02653-1.
67. Eisentraut, P.; Dümichen, E.; Ruhl, A.S.; Jekel, M.; Albrecht, M.; Gehde, M.; Braun, U. Two Birds with One Stone—Fast and Simultaneous Analysis of

Microplastics: Microparticles Derived from Thermoplastics and Tire Wear. *Environ. Sci. Technol. Lett.* **2018**, *5*, 608–613, doi:10.1021/acs.estlett.8b00446.

68. Duemichen, E.; Eisentraut, P.; Celina, M.; Braun, U. Automated Thermal Extraction-Desorption Gas Chromatography Mass Spectrometry: A Multifunctional Tool for Comprehensive Characterization of Polymers and Their Degradation Products. *Journal of Chromatography A* **2019**, *1592*, 133–142, doi:10.1016/j.chroma.2019.01.033.
69. Aatmeeyata; Sharma, M. Polycyclic Aromatic Hydrocarbons, Elemental and Organic Carbon Emissions from Tire-Wear. *Science of The Total Environment* **2010**, *408*, 4563–4568, doi:10.1016/j.scitotenv.2010.06.011.
70. Sadiktsis, I.; Bergvall, C.; Johansson, C.; Westerholm, R. Automobile Tires—A Potential Source of Highly Carcinogenic Dibenzopyrenes to the Environment. *Environ. Sci. Technol.* **2012**, *46*, 3326–3334, doi:10.1021/es204257d.
71. Hoyer, S.; Kroll, L.; Lippert, K.; Seidel, A. A Long-Term Study on the Content of Polycyclic Aromatic Hydrocarbons in Rubber from End-of-Life Tires of Passenger Cars and Trucks. *Materials* **2022**, *15*, 7017, doi:10.3390/ma15197017.
72. 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. *Atmospheric Environment* **2020**, *224*, 117252, doi:10.1016/j.atmosenv.2019.117252.
73. Plastics Europe AISBL *Plastics - The Facts 2022. Available Online at: Https://Plasticseurope.Org/Knowledge-Hub/Plastics-the-Facts-2022/*; Plastics Europe AISBL: Brussels, Belgium;
74. Zhang, K.; Hamidian, A.H.; Tubić, A.; Zhang, Y.; Fang, J.K.H.; Wu, C.; Lam, P.K.S. Understanding Plastic Degradation and Microplastic Formation in the Environment: A Review. *Environmental Pollution* **2021**, *274*, 116554, doi:10.1016/j.envpol.2021.116554.
75. Boucher, J.; Friot, D. *Primary Microplastics in the Oceans: A Global Evaluation of Sources*; IUCN International Union for Conservation of Nature, 2017; ISBN 978-2-8317-1827-9.
76. Jiang, B.; Kauffman, A.E.; Li, L.; McFee, W.; Cai, B.; Weinstein, J.; Lead, J.R.; Chatterjee, S.; Scott, G.I.; Xiao, S. Health Impacts of Environmental Contamination of Micro- and Nanoplastics: A Review. *Environ Health Prev Med* **2020**, *25*, 29, doi:10.1186/s12199-020-00870-9.
77. Campanale; Massarelli; Savino; Locaputo; Uricchio A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *IJERPH* **2020**, *17*, 1212, doi:10.3390/ijerph17041212.
78. Sana, S.S.; Dogiparthi, L.K.; Gangadhar, L.; Chakravorty, A.; Abhishek, N. Effects of Microplastics and Nanoplastics on Marine Environment and Human Health. *Environ Sci Pollut Res* **2020**, *27*, 44743–44756, doi:10.1007/s11356-020-10573-x.
79. Osman, A.I.; Hosny, M.; Eltaweil, A.S.; Omar, S.; Elgarahy, A.M.; Farghali, M.; Yap, P.-S.; Wu, Y.-S.; Nagandran, S.; Batumalaie, K.; et al. Microplastic Sources, Formation, Toxicity and Remediation: A Review. *Environ Chem Lett* **2023**, *21*, 2129–2169, doi:10.1007/s10311-023-01593-3.
80. Lebreton, L.; Egger, M.; Slat, B. A Global Mass Budget for Positively Buoyant Macroplastic Debris in the Ocean. *Sci Rep* **2019**, *9*, 12922, doi:10.1038/s41598-019-49413-5.
81. Hartmann, N.B.; Hüffer, T.; Thompson, R.C.; Hassellöv, M.; Verschoor, A.; Daugaard, A.E.; Rist, S.; Karlsson, T.; Brennholt, N.; Cole, M.; et al. Are We

Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris. *Environ. Sci. Technol.* **2019**, *53*, 1039–1047, doi:10.1021/acs.est.8b05297.

82. Sundt, P.; Schulze, P.-E.; Syversen, F. *Sources of Microplastics-Pollution to the Marine Environment*; Norway, 2014;
83. Lassen, C.; Hansen, S.F.; Magnusson, K.; Hartmann, N.B.; Rehne Jensen, P.; Torkel, G.; Brinch, A. *Microplastics: Occurrence, Effects and Sources of Releases to the Environment in Denmark*; Danish Environmental Protection Agency., 2015;
84. Magnusson, K.; Eliasson, K.; Fråne, A.; Haikonen, K.; Hultén, J.; Olshammar, M.; Stadmark, J.; Voisin, A. *Swedish Sources and Pathways for Microplastics to the Marine Environment: A Review of Existing Data*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2016;
85. Wang, T.; Li, B.; Zou, X.; Wang, Y.; Li, Y.; Xu, Y.; Mao, L.; Zhang, C.; Yu, W. Emission of Primary Microplastics in Mainland China: Invisible but Not Negligible. *Water Research* **2019**, *162*, 214–224, doi:10.1016/j.watres.2019.06.042.
86. Turner, A. Paint Particles in the Marine Environment: An Overlooked Component of Microplastics. *Water Research X* **2021**, *12*, 100110, doi:10.1016/j.wroa.2021.100110.
87. Urbanus, J.H.; Brunner, A.; Boersma, A.; Henke, S.; Kooter, I.; Lensen, S.; Parker, L.; Schwarz, A.; Imhof, P.; Dortmans, A.; et al. Microplastics Are Everywhere: 70% Reduction Achievable. Available Online at: File:///C:/Users/Giechba/Downloads/TNO-2022-Microplastics-Eng.Pdf 2022.
88. Goehler, L.O.; Moruzzi, R.B.; Tomazini Da Conceição, F.; Júnior, A.A.C.; Speranza, L.G.; Busquets, R.; Campos, L.C. Relevance of Tyre Wear Particles to the Total Content of Microplastics Transported by Runoff in a High-Imperviousness and Intense Vehicle Traffic Urban Area. *Environmental Pollution* **2022**, *314*, 120200, doi:10.1016/j.envpol.2022.120200.
89. Goßmann, I.; Süßmuth, R.; Scholz-Böttcher, B.M. Plastic in the Air?! - Spider Webs as Spatial and Temporal Mirror for Microplastics Including Tire Wear Particles in Urban Air. *Science of The Total Environment* **2022**, *832*, 155008, doi:10.1016/j.scitotenv.2022.155008.
90. Kumar, A.; Elumalai, S.P. Influence of Road Paving on Particulate Matter Emission and Fingerprinting of Elements of Road Dust. *Arch Environ Contam Toxicol* **2018**, *75*, 424–435, doi:10.1007/s00244-018-0546-6.
91. Venghaus, D.; Neupert, J.W.; Barjenbruch, M. Tire Wear Monitoring Approach for Hotspot Identification in Road Deposited Sediments from a Metropolitan City in Germany. *Sustainability* **2023**, *15*, 12029, doi:10.3390/su151512029.
92. Knight, L.J.; Parker-Jurd, F.N.F.; Al-Sid-Cheikh, M.; Thompson, R.C. Tyre Wear Particles: An Abundant yet Widely Unreported Microplastic? *Environ Sci Pollut Res* **2020**, *27*, 18345–18354, doi:10.1007/s11356-020-08187-4.
93. Kunze, M.; Feißel, T.; Ivanov, V.; Bachmann, T.; Hesse, D.; Gramstat, S. Analysis of TRWP Particle Distribution in Urban and Suburban Landscapes, Connecting Real Road Measurements with Particle Distribution Simulation. *Atmosphere* **2022**, *13*, 1204, doi:10.3390/atmos13081204.
94. Verschoor, A.; de Poorter, L.; Dröge, R.; Kuenen, J.; de Valk, E. *Emission of Microplastics and Potential Mitigation Measures: Abrasive Cleaning Agents, Paints and Tyre Wear*; National Institute for Public Health and the Environment (RIVM), 2016;

95. Verschoor, A.J.; De Valk, E. Potential Measures against Microplastic Emissions to Water. **2018**, doi:10.21945/RIVM-2017-0193.
96. Bertling, J.; Hamann, L.; Bertling, R. Kunststoffe in Der Umwelt. **2018**, doi:10.24406/UMSICHT-N-497117.
97. Sieber, R.; Kawecki, D.; Nowack, B. Dynamic Probabilistic Material Flow Analysis of Rubber Release from Tires into the Environment. *Environmental Pollution* **2020**, *258*, 113573, doi:10.1016/j.envpol.2019.113573.
98. Ryberg, M.W.; Hauschild, M.Z.; Wang, F.; Averous-Monnery, S.; Laurent, A. Global Environmental Losses of Plastics across Their Value Chains. *Resources, Conservation and Recycling* **2019**, *151*, 104459, doi:10.1016/j.resconrec.2019.104459.
99. Unsbo, H.; Rosengren, H.; Olshammar, M. *Indicators for Microplastic Flow. Available Online at: Https://Smed.Se/Vatten/5321*; 2022;
100. Schwarz, A.E.; Lensen, S.M.C.; Langeveld, E.; Parker, L.A.; Urbanus, J.H. Plastics in the Global Environment Assessed through Material Flow Analysis, Degradation and Environmental Transportation. *Science of The Total Environment* **2023**, *875*, 162644, doi:10.1016/j.scitotenv.2023.162644.
101. Bergmann, M.; Mützel, S.; Primpke, S.; Tekman, M.B.; Trachsel, J.; Gerdts, G. White and Wonderful? Microplastics Prevail in Snow from the Alps to the Arctic. *Sci. Adv.* **2019**, *5*, eaax1157, doi:10.1126/sciadv.aax1157.
102. Rutgers, M.; Faber, M.; Waaijers-van der Loop, S.; Quik, J. *Microplastics in Soil Systems, from Source to Path to Protection Goals. State of Knowledge on Microplastics in Soil*; Rijksinstituut voor Volksgezondheid en Milieu RIVM, 2022;
103. Unice, K.M.; Weeber, M.P.; Abramson, M.M.; Reid, R.C.D.; Van Gils, J.A.G.; Markus, A.A.; Vethaak, A.D.; Panko, J.M. Characterizing Export of Land-Based Microplastics to the Estuary - Part I: Application of Integrated Geospatial Microplastic Transport Models to Assess Tire and Road Wear Particles in the Seine Watershed. *Science of The Total Environment* **2019**, *646*, 1639–1649, doi:10.1016/j.scitotenv.2018.07.368.
104. European TRWP Platform *Way Forward Report*; 2019;
105. Quik, J.T.K.; Meesters, J.A.J.; Koelmans, A.A. A Multimedia Model to Estimate the Environmental Fate of Microplastic Particles. *Science of The Total Environment* **2023**, *882*, 163437, doi:10.1016/j.scitotenv.2023.163437.
106. Baensch-Baltruschat, B.; Kocher, B.; Kochleus, C.; Stock, F.; Reifferscheid, G. Tyre and Road Wear Particles - A Calculation of Generation, Transport and Release to Water and Soil with Special Regard to German Roads. *Science of The Total Environment* **2021**, *752*, 141939, doi:10.1016/j.scitotenv.2020.141939.
107. Prenner, S.; Allesch, A.; Staudner, M.; Rexeis, M.; Schwingshackl, M.; Huber-Humer, M.; Part, F. Static Modelling of the Material Flows of Micro- and Nanoplastic Particles Caused by the Use of Vehicle Tyres. *Environmental Pollution* **2021**, *290*, 118102, doi:10.1016/j.envpol.2021.118102.
108. ETRMA In Europe 95% of All End of Life Tyres Were Collected and Treated in 2019. Available Online at: Https://Www.Etrma.Org/Wp-Content/Uploads/2021/05/20210520_ETRMA_PRESS-RELEASE_ELT-2019.Pdf 2021.
109. EuRIC AISBL *Mechanical Tyre Recycling Fact Sheet. Available Online at: Https://Euric.Org/Resource-Hub/Reports-Studies/Mechanical-Tyre-Recycling-Factsheet*; Brussels, Belgium, 2022;

110. 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. *Science of The Total Environment* **2020**, *733*, 137823, doi:10.1016/j.scitotenv.2020.137823.
111. Evangeliou, N.; Grythe, H.; Klimont, Z.; Heyes, C.; Eckhardt, S.; Lopez-Aparicio, S.; Stohl, A. Atmospheric Transport Is a Major Pathway of Microplastics to Remote Regions. *Nat Commun* **2020**, *11*, 3381, doi:10.1038/s41467-020-17201-9.
112. Allen, S.; Allen, D.; Phoenix, V.R.; Le Roux, G.; Durántez Jiménez, P.; Simonneau, A.; Binet, S.; Galop, D. Atmospheric Transport and Deposition of Microplastics in a Remote Mountain Catchment. *Nat. Geosci.* **2019**, *12*, 339–344, doi:10.1038/s41561-019-0335-5.
113. Brahney, J.; Hallerud, M.; Heim, E.; Hahnenberger, M.; Sukumaran, S. Plastic Rain in Protected Areas of the United States. *Science* **2020**, *368*, 1257–1260, doi:10.1126/science.aaz5819.
114. European Environment Agency *Air Quality in Europe: 2019 Report.*; 2019; ISBN 978-92-9480-088-6.
115. Matthaios, V.N.; Lawrence, J.; Martins, M.A.G.; Ferguson, S.T.; Wolfson, J.M.; Harrison, R.M.; Koutrakis, P. Quantifying Factors Affecting Contributions of Roadway Exhaust and Non-Exhaust Emissions to Ambient PM10–2.5 and PM2.5–0.2 Particles. *Science of The Total Environment* **2022**, *835*, 155368, doi:10.1016/j.scitotenv.2022.155368.
116. Amato, F.; Alastuey, A.; Karanasiou, A.; Lucarelli, F.; Nava, S.; Calzolai, G.; Severi, M.; Becagli, S.; Gianelle, V.L.; Colombi, C.; et al. AIRUSE-LIFE+: A Harmonized PM Speciation and Source Apportionment in Five Southern European Cities. *Atmos. Chem. Phys.* **2016**, *16*, 3289–3309, doi:10.5194/acp-16-3289-2016.
117. Marinello, S.; Lolli, F.; Gamberini, R. Roadway Tunnels: A Critical Review of Air Pollutant Concentrations and Vehicular Emissions. *Transportation Research Part D: Transport and Environment* **2020**, *86*, 102478, doi:10.1016/j.trd.2020.102478.
118. De Vito, S.; Del Giudice, A.; D'Elia, G.; Esposito, E.; Fattoruso, G.; Ferlito, S.; Formisano, F.; Loffredo, G.; Massera, E.; Bellucci, P.; et al. Correlating Air Pollution Concentrations and Vehicular Emissions in an Italian Roadway Tunnel by Means of Low Cost Sensors. *Atmosphere* **2023**, *14*, 679, doi:10.3390/atmos14040679.
119. Panko, J.; Kreider, M.; Unice, K. Review of Tire Wear Emissions. In *Non-Exhaust Emissions*; Elsevier, 2018; pp. 147–160 ISBN 978-0-12-811770-5.
120. OECD *Non-Exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge*; OECD, 2020; ISBN 978-92-64-45244-2.
121. Umweltbundesamtes (UBA) Schwerpunkt. Gesunde Luft (Healthy Air). (in German). Available Online at: Https://Www.Umweltbundesamt.de/Sites/Default/Files/Medien/2546/Publikationen/Sp_1-2019_web.Pdf. *UBA* 2019.
122. Air Quality Expert Group (AQEG) *Non-Exhaust Emissions from Road Traffic. Available Online at: Https://Uk-Air.Defra.Gov.Uk/Assets/Documents/Reports/Cat09/1907101151_20190709_Non_Exhaust_Emissions_typeset_Final.Pdf*; UK, 2019;
123. 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. *Atmospheric Environment* **2013**, *72*, 192–199, doi:10.1016/j.atmosenv.2013.01.040.

124. World Business Council for Sustainable Development Tire Industry Project. Available Online: Https://Www.Wbcsd.Org/Sector-Projects/Tire-Industry-Project 2005.
125. Panko, J.; Hitchcock, K.; Fuller, G.; Green, D. Evaluation of Tire Wear Contribution to PM2.5 in Urban Environments. *Atmosphere* **2019**, *10*, 99, doi:10.3390/atmos10020099.
126. Kwak, J.; Kim, H.; Lee, J.; Lee, S. Characterization of Non-Exhaust Coarse and Fine Particles from on-Road Driving and Laboratory Measurements. *Science of The Total Environment* **2013**, *458–460*, 273–282, doi:10.1016/j.scitotenv.2013.04.040.
127. Svensson, N.; Engardt, M.; Gustafsson, M.; Andersson-Sköld, Y. Modelled Atmospheric Concentration of Tyre Wear in an Urban Environment. *Atmospheric Environment: X* **2023**, *20*, 100225, doi:10.1016/j.aeaoa.2023.100225.
128. Järlskog, I.; Jaramillo-Vogel, D.; Rausch, J.; Perseguers, S.; Gustafsson, M.; Strömvall, A.-M.; Andersson-Sköld, Y. Differentiating and Quantifying Carbonaceous (Tire, Bitumen, and Road Marking Wear) and Non-Carbonaceous (Metals, Minerals, and Glass Beads) Non-Exhaust Particles in Road Dust Samples from a Traffic Environment. *Water Air Soil Pollut* **2022**, *233*, 375, doi:10.1007/s11270-022-05847-8.
129. Zhang, Q.; Liu, J.; Wei, N.; Song, C.; Peng, J.; Wu, L.; Mao, H. Identify the Contribution of Vehicle Non-Exhaust Emissions: A Single Particle Aerosol Mass Spectrometer Test Case at Typical Road Environment. *Front. Environ. Sci. Eng.* **2023**, *17*, 62, doi:10.1007/s11783-023-1662-8.
130. Wik, A.; Dave, G. Occurrence and Effects of Tire Wear Particles in the Environment – A Critical Review and an Initial Risk Assessment. *Environmental Pollution* **2009**, *157*, 1–11, doi:10.1016/j.envpol.2008.09.028.
131. Parker-Jurd, F.N.F.; Napper, I.E.; Abbott, G.D.; Hann, S.; Thompson, R.C. Quantifying the Release of Tyre Wear Particles to the Marine Environment via Multiple Pathways. *Marine Pollution Bulletin* **2021**, *172*, 112897, doi:10.1016/j.marpolbul.2021.112897.
132. Kang, H.; Park, S.; Lee, B.; Kim, I.; Kim, S. Concentration of Microplastics in Road Dust as a Function of the Drying Period—A Case Study in G City, Korea. *Sustainability* **2022**, *14*, 3006, doi:10.3390/su14053006.
133. Cadle, S.H.; Williams, R.L. Gas and Particle Emissions from Automobile Tires in Laboratory and Field Studies. *Journal of the Air Pollution Control Association* **1978**, *28*, 502–507, doi:10.1080/00022470.1978.10470623.
134. Siegfried, M.; Koelmans, A.A.; Besseling, E.; Kroeze, C. Export of Microplastics from Land to Sea. A Modelling Approach. *Water Research* **2017**, *127*, 249–257, doi:10.1016/j.watres.2017.10.011.
135. Jekel, M. *Scientific Report on Tyre and Road Wear Particles, TRWP, in the Aquatic Environment*; European TRWP platform: Berlin, Germany, 2019;
136. TF TA Proposal for Supplement 02 to the 04 Series of Amendments to UN Regulation No. 117 (Tyre Rolling Resistance, Rolling Noise and Wet Grip). Available Online at: Https://Unece.Org/Transport/Documents/2023/11/Working-Documents/Tfta-Proposal-Supplement-02-04-Series-Amendments-Un-1 2023.
137. Lowne, R.W. The Effect of Road Surface Texture on Tyre Wear. *Wear* **1970**, *15*, 57–70, doi:10.1016/0043-1648(70)90186-9.

138. Chang, X.; Huang, H.; Jiao, R.; Liu, J. Experimental Investigation on the Characteristics of Tire Wear Particles under Different Non-Vehicle Operating Parameters. *Tribology International* **2020**, *150*, 106354, doi:10.1016/j.triboint.2020.106354.
139. ETRTO Tyre Abrasion Vehicle Load Normalization. Presented at the TF TA 7th session, Online, 2022.
140. 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. *Science of The Total Environment* **2022**, *842*, 156961, doi:10.1016/j.scitotenv.2022.156961.
141. Liang, R.; Wang, W.; Wang, G. Research on The Key Influencing Factors of Road Wear for Battery Electric Vehicles Tyres. In Proceedings of the 2021 9th International Conference on Traffic and Logistic Engineering (ICTLE); IEEE: Macau, China, August 9 2021; pp. 93–101.
142. Tong, G.; Jin, X.X. Study on the Simulation of Radial Tire Wear Characteristics. *WSEAS Transactions on Systems* **2012**, *11*, 419–429.
143. Li, Y.; Zuo, S.; Lei, L.; Yang, X.; Wu, X. Analysis of Impact Factors of Tire Wear. *Journal of Vibration and Control* **2012**, *18*, 833–840, doi:10.1177/1077546311411756.
144. Yan, H.; Zhang, L.; Liu, L.; Wen, S. Investigation of the External Conditions and Material Compositions Affecting the Formation Mechanism and Size Distribution of Tire Wear Particles. *Atmospheric Environment* **2021**, *244*, 118018, doi:10.1016/j.atmosenv.2020.118018.
145. Sjödin, Å.; Ferm, M.; Björk, A.; Rahmberg, M.; Gudmundsson, A.; Swietlick, E.; Johansson, C.; Gustafsson, M.; Blomqvist, G. *Wear Particles from Road Traffic - a Field, Laboratory and Modelling Study*; IVL Swedish Environmental Research Institute: Göteborg, Sweden, 2010;
146. Schläfle, S.; Unrau, H.-J.; Gauterin, F. Influence of Load Condition, Tire Type, and Ambient Temperature on the Emission of Tire–Road Particulate Matter. *Atmosphere* **2023**, *14*, 1095, doi:10.3390/atmos14071095.
147. Kienle, R.N.; Grosch, K.A.; Scott, C.E. Material Properties Affecting Traction and Wear of Passenger Tires.; February 1 1972; p. 720161.
148. Williams, H.; Landeg-Cox, C.; Levine, J.G.; Pope, F.D. Non-Exhaust Emissions from Road Transport - Policy Briefing Note Produced by the TRANSITION Clean Air Network. **2022**, doi:10.25500/EPAPERS.BHAM.00004108.
149. Johannesson, M.; Lithner, D. *Potential Policy Instruments and Measures against Microplastics from Tyre and Road Wear: Mapping and Prioritisation*; VTI: Stockholm, Sweden, 2022;
150. Gehrke, I.; Schläfle, S.; Bertling, R.; Öz, M.; Gregory, K. Review: Mitigation Measures to Reduce Tire and Road Wear Particles. *Science of The Total Environment* **2023**, *904*, 166537, doi:10.1016/j.scitotenv.2023.166537.
151. Andersson, J.; Mácsik, J.; van der Nat, D.; Norström, A.; Albinsson, M.; Åkerman, S.; Hernefeldt, P.; Jönsson, R. *Reducing Highway Runoff Pollution (REHIRUP). Sustainable Design and Maintenance of Stormwater Treatment Facilities.*; Trafikverket: Sweden, 2018;
152. Skumlien Furuseth, I.; Støhle Rødland, E. *Reducing the Release of Microplastic from Tire Wear: Nordic Efforts*; Nordic Council of Ministers, 2020;

153. Valentini, F.; Pegoretti, A. End-of-Life Options of Tyres. A Review. *Advanced Industrial and Engineering Polymer Research* **2022**, *5*, 203–213, doi:10.1016/j.aiepr.2022.08.006.
154. Trudsø, L.L.; Nielsen, M.B.; Hansen, S.F.; Syberg, K.; Kampmann, K.; Khan, F.R.; Palmqvist, A. The Need for Environmental Regulation of Tires: Challenges and Recommendations. *Environmental Pollution* **2022**, *311*, 119974, doi:10.1016/j.envpol.2022.119974.
155. Bressi, S.; Fiorentini, N.; Huang, J.; Losa, M. Crumb Rubber Modifier in Road Asphalt Pavements: State of the Art and Statistics. *Coatings* **2019**, *9*, 384, doi:10.3390/coatings9060384.
156. Fořt, J.; Kobetičová, K.; Böhm, M.; Podlesný, J.; Jelínková, V.; Vachtlová, M.; Bureš, F.; Černý, R. Environmental Consequences of Rubber Crumb Application: Soil and Water Pollution. *Polymers* **2022**, *14*, 1416, doi:10.3390/polym14071416.
157. Armada, D.; Llompart, M.; Celeiro, M.; Garcia-Castro, P.; Ratola, N.; Dagnac, T.; De Boer, J. Global Evaluation of the Chemical Hazard of Recycled Tire Crumb Rubber Employed on Worldwide Synthetic Turf Football Pitches. *Science of The Total Environment* **2022**, *812*, 152542, doi:10.1016/j.scitotenv.2021.152542.
158. Li, M.; Wang, K.; Xiong, Y. Multiple Intermolecular Interaction to Improve the Abrasion Resistance and Wet Skid Resistance of Eucommia Ulmoides Gum/Styrene Butadiene Rubber Composite. *Materials* **2021**, *14*, 5246, doi:10.3390/ma14185246.
159. Araujo-Morera, J.; Hernández Santana, M.; Verdejo, R.; López-Manchado, M.A. Giving a Second Opportunity to Tire Waste: An Alternative Path for the Development of Sustainable Self-Healing Styrene–Butadiene Rubber Compounds Overcoming the Magic Triangle of Tires. *Polymers* **2019**, *11*, 2122, doi:10.3390/polym11122122.
160. Ayar, M.; Dalkiran, A.; Kale, U.; Nagy, A.; Karakoc, T.H. Investigation of the Substitutability of Rubber Compounds with Environmentally Friendly Materials. *Sustainability* **2021**, *13*, 5251, doi:10.3390/su13095251.
161. Papaioannou, G.; Jerrelind, J.; Drugge, L. Multi-Objective Optimisation of Tyre and Suspension Parameters during Cornering for Different Road Roughness Profiles. *Applied Sciences* **2021**, *11*, 5934, doi:10.3390/app11135934.
162. Sallusti, M. The Role of the Connected Tyre in the Future Mobility. Presentation at the Conference Towards the Sustainable Vehicle Era. 8 Nov 2024, Milan, Italy. Milano, Italy, 2024.
163. Leu, A.I.V.; Arghir, M. Lateral Force Variation Tire Testing. *Acta Technica Napocensis* **2013**, *56*, 497–508.
164. European Commission. Joint Research Centre. *The Future of Road Transport: Implications of Automated, Connected, Low Carbon and Shared Mobility.*; Publications Office: LU, 2019;
165. Dong, J.; Huang, H.; Pei, J.; Xu, Y.; Cao, J. A Methodology for Capturing Tire Wear Particles: Computational Particle Fluid Dynamics Modelling and Experimental Verification. *Powder Technology* **2021**, *384*, 176–185, doi:10.1016/j.powtec.2021.02.016.
166. Marchioni, M.; Fedele, R.; Raimondi, A.; Sansalone, J.; Becciu, G. Permeable Asphalt Hydraulic Conductivity and Particulate Matter Separation With XRT. *Water Resour Manage* **2022**, *36*, 1879–1895, doi:10.1007/s11269-022-03113-4.

167. Jayakaran, A.; Knappenberger, T.; Stark, J.; Hinman, C. Remediation of Stormwater Pollutants by Porous Asphalt Pavement. *Water* **2019**, *11*, 520, doi:10.3390/w11030520.
168. Dutta, A.; Torres, A.S.; Vojinovic, Z. Evaluation of Pollutant Removal Efficiency by Small-Scale Nature-Based Solutions Focusing on Bio-Retention Cells, Vegetative Swale and Porous Pavement. *Water* **2021**, *13*, 2361, doi:10.3390/w13172361.
169. Svensson, N.; Lundberg, J.; Janhäll, S.; Kulovuori, S.; Gustafsson, M. Effects of a Porous Asphalt Pavement on Dust Suspension and PM10 Concentration. *Transportation Research Part D: Transport and Environment* **2023**, *123*, 103921, doi:10.1016/j.trd.2023.103921.
170. Rasmussen, L.A.; Lykkemark, J.; Andersen, T.R.; Vollertsen, J. Permeable Pavements: A Possible Sink for Tyre Wear Particles and Other Microplastics? *Science of The Total Environment* **2023**, *869*, 161770, doi:10.1016/j.scitotenv.2023.161770.
171. Streuff, S.; Schmid, P.; Kolczyk, M.; Keller, F. Mehr Nachhaltigkeit Und Weniger Feinstaub Im Urbanen Lieferverkehr. *ATZ* **2022**, *124*, 38–43.
172. Löber, M.; Bondorf, L.; Grein, T.; Reiland, S.; Wieser, S.; Epple, F.; Philipps, F.; Schripp, T. Investigations of Airborne Tire and Brake Wear Particles Using a Novel Vehicle Design. *Environ Sci Pollut Res* **2024**, *31*, 53521–53531, doi:10.1007/s11356-024-34543-9.
173. Thébault, E.; Raimbault, V.; Junginger, B.; Dos Santos Ascensao, M.; Montaigne, Q.; Chalet, D.; Opperbeck, G.; Keller, F. Towards an Emission-Neutral Vehicle by Integrating a Particulate Filter System into the Frontend. In *22. Internationales Stuttgarter Symposium*; Bargende, M., Reuss, H.-C., Wagner, A., Eds.; Proceedings; Springer Fachmedien Wiesbaden: Wiesbaden, 2022; pp. 371–386 ISBN 978-3-658-37010-7.
174. Porto, M.; Caputo, P.; Loise, V.; Eskandarsefat, S.; Teltayev, B.; Oliviero Rossi, C. Bitumen and Bitumen Modification: A Review on Latest Advances. *Applied Sciences* **2019**, *9*, 742, doi:10.3390/app9040742.
175. Yue, Y.; Abdelsalam, M.; Luo, D.; Khater, A.; Musanyufu, J.; Chen, T. Evaluation of the Properties of Asphalt Mixes Modified with Diatomite and Lignin Fiber: A Review. *Materials* **2019**, *12*, 400, doi:10.3390/ma12030400.
176. Scholz, M.; Grabowiecki, P. Review of Permeable Pavement Systems. *Building and Environment* **2007**, *42*, 3830–3836, doi:10.1016/j.buildenv.2006.11.016.
177. Liu, M.; Huang, X.; Xue, G. Effects of Double Layer Porous Asphalt Pavement of Urban Streets on Noise Reduction. *International Journal of Sustainable Built Environment* **2016**, *5*, 183–196, doi:10.1016/j.ijsbe.2016.02.001.
178. Frolova, O.; Salaiová, B.; Olexa, T.; Mandula, J. Using Crumb Rubber from Waste Tires to Reduce Road Traffic Noise. *MATEC Web Conf.* **2016**, *73*, 04022, doi:10.1051/matecconf/20167304022.
179. *26th International Congress on Sound and Vibration: 7-11 July 2019, Montreal*; International Institute of Acoustics and Vibration, Canadian Acoustical Association, Eds.; International Institute of Acoustics and Vibration (IIAV): Auburn, AL, USA, 2019; ISBN 978-1-9991810-0-0.
180. Jung, H.; Oli, T.; Nam, J.; Yun, K.; Kim, S.; Park, C. Life-Cycle Cost Analysis on Application of Asphalt and Concrete Pavement Overlay. *Applied Sciences* **2022**, *12*, 5098, doi:10.3390/app12105098.

181. Charlesworth, S.; Beddow, J.; Nnadi, E. The Fate of Pollutants in Porous Asphalt Pavements, Laboratory Experiments to Investigate Their Potential to Impact Environmental Health. *IJERPH* **2017**, *14*, 666, doi:10.3390/ijerph14060666.
182. Lundberg, J.; Gustafsson, M.; Janhäll, S.; Eriksson, O.; Blomqvist, G.; Erlingsson, S. Temporal Variation of Road Dust Load and Its Size Distribution—a Comparative Study of a Porous and a Dense Pavement. *Water Air Soil Pollut* **2020**, *231*, 561, doi:10.1007/s11270-020-04923-1.
183. Barr, B.C.; Andradóttir, H.Ó.; Thorsteinsson, T.; Erlingsson, S. Mitigation of Suspendable Road Dust in a Subpolar, Oceanic Climate. *Sustainability* **2021**, *13*, 9607, doi:10.3390/su13179607.
184. Amato, F.; Querol, X.; Johansson, C.; Nagl, C.; Alastuey, A. A Review on the Effectiveness of Street Sweeping, Washing and Dust Suppressants as Urban PM Control Methods. *Science of The Total Environment* **2010**, *408*, 3070–3084, doi:10.1016/j.scitotenv.2010.04.025.
185. Lin, S.-L.; Deng, Y.; Lin, M.-Y.; Huang, S.-W. Do the Street Sweeping and Washing Work for Reducing the Near-Ground Levels of Fine Particulate Matter and Related Pollutants? *Aerosol Air Qual. Res.* **2023**, *23*, 220338, doi:10.4209/aaqr.220338.
186. Liu, Y.; Engel, B.A.; Flanagan, D.C.; Gitau, M.W.; McMillan, S.K.; Chaubey, I. A Review on Effectiveness of Best Management Practices in Improving Hydrology and Water Quality: Needs and Opportunities. *Science of The Total Environment* **2017**, *601–602*, 580–593, doi:10.1016/j.scitotenv.2017.05.212.
187. Cadle, S.H.; Williams, R.L. Environmental Degradation of Tire-Wear Particles. *Rubber Chemistry and Technology* **1980**, *53*, 903–914, doi:10.5254/1.3535066.
188. Nielsen, A.F.; Polesel, F.; Ahonen, T.; Palmqvist, A.; Baun, A.; Hartmann, N.B. Assessing the Biodegradability of Tire Tread Particles and Influencing Factors. *Enviro Toxic and Chemistry* **2024**, *43*, 31–41, doi:10.1002/etc.5757.
189. Kang, J.-H.; Debats, S.R.; Stenstrom, M.K. Storm-Water Management Using Street Sweeping. *J. Environ. Eng.* **2009**, *135*, 479–489, doi:10.1061/(ASCE)0733-9372(2009)135:7(479).
190. Kryłów, M.; Generowicz, A. Impact of Street Sweeping and Washing on the PM10 and PM2.5 Concentrations in Cracow (Poland). *Rocznik Ochrona Środowiska* **2019**, *21*, 691–711.
191. Hixon, L.F.; Dymond, R.L. State of the Practice: Assessing Water Quality Benefits from Street Sweeping. *J. Sustainable Water Built Environ.* **2018**, *4*, 04018007, doi:10.1061/JSWBAY.0000860.
192. Das, S.; Wiseman, C.L.S. Examining the Effectiveness of Municipal Street Sweeping in Removing Road-Deposited Particles and Metal(Loid)s of Respiratory Health Concern. *Environment International* **2024**, *187*, 108697, doi:10.1016/j.envint.2024.108697.
193. Selbig, W.R. Evaluation of Leaf Removal as a Means to Reduce Nutrient Concentrations and Loads in Urban Stormwater. *Science of The Total Environment* **2016**, *571*, 124–133, doi:10.1016/j.scitotenv.2016.07.003.
194. Gustafsson, M.; Polukarova, M.; Blomqvist, G.; Järlskog, I.; Andersson Sköld, Y. *Street Sweeping: A Source to, or Measure against,Microplastic Emissions?*; VTI: Stockholm, Sweden, 2023;
195. Mooselu, M.G.; Liltved, H.; Hindar, A.; Amiri, H. Current European Approaches in Highway Runoff Management: A Review. *Environmental Challenges* **2022**, *7*, 100464, doi:10.1016/j.envc.2022.100464.

196. Qian, G.; Wang, C.; Gong, X.; Zhou, H.; Cai, J. Design of Constructed Wetland Treatment Measures for Highway Runoff in a Water Source Protection Area. *Sustainability* **2022**, *14*, 5951, doi:10.3390/su14105951.
197. Sun, J.; Dai, X.; Wang, Q.; Van Loosdrecht, M.C.M.; Ni, B.-J. Microplastics in Wastewater Treatment Plants: Detection, Occurrence and Removal. *Water Research* **2019**, *152*, 21–37, doi:10.1016/j.watres.2018.12.050.
198. Simon, M.; Van Alst, N.; Vollertsen, J. Quantification of Microplastic Mass and Removal Rates at Wastewater Treatment Plants Applying Focal Plane Array (FPA)-Based Fourier Transform Infrared (FT-IR) Imaging. *Water Research* **2018**, *142*, 1–9, doi:10.1016/j.watres.2018.05.019.
199. Nizzetto, L.; Futter, M.; Langaas, S. Are Agricultural Soils Dumps for Microplastics of Urban Origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779, doi:10.1021/acs.est.6b04140.
200. Huber, M.; Helmreich, B. Stormwater Management: Calculation of Traffic Area Runoff Loads and Traffic Related Emissions. *Water* **2016**, *8*, 294, doi:10.3390/w8070294.
201. Barbosa, A.E.; Fernandes, J.N. Review of Tools for Road Runoff Quality Prediction and Application to European Roads. *Water Science and Technology* **2021**, *84*, 2228–2241, doi:10.2166/wst.2021.427.
202. Vogelsang, C.; Lusher, A.L.; Dadkhah, M.; Sundvor, I.; Umar, M.; Ranneklev, S.; Eidsvoll, D.; Meland, S. *Microplastics in Road Dust – Haracteristics, Pathways and Measures*; Norwegian Institute for Water Research: Norway, 2020;
203. MacNaughton, P.; Melly, S.; Vallarino, J.; Adamkiewicz, G.; Spengler, J.D. Impact of Bicycle Route Type on Exposure to Traffic-Related Air Pollution. *Science of The Total Environment* **2014**, *490*, 37–43, doi:10.1016/j.scitotenv.2014.04.111.
204. Kumar, P.; Druckman, A.; Gallagher, J.; Gatersleben, B.; Allison, S.; Eisenman, T.S.; Hoang, U.; Hama, S.; Tiwari, A.; Sharma, A.; et al. The Nexus between Air Pollution, Green Infrastructure and Human Health. *Environment International* **2019**, *133*, 105181, doi:10.1016/j.envint.2019.105181.
205. Cuajungco, M.; Ramirez, M.; Tolmasky, M. Zinc: Multidimensional Effects on Living Organisms. *Biomedicines* **2021**, *9*, 208, doi:10.3390/biomedicines9020208.
206. Hussain, S.; Khan, M.; Sheikh, T.M.M.; Mumtaz, M.Z.; Chohan, T.A.; Shamim, S.; Liu, Y. Zinc Essentiality, Toxicity, and Its Bacterial Bioremediation: A Comprehensive Insight. *Front. Microbiol.* **2022**, *13*, 900740, doi:10.3389/fmicb.2022.900740.
207. Chen, W.-Q.; Zhang, X.-Y. 1,3-Butadiene: A Ubiquitous Environmental Mutagen and Its Associations with Diseases. *Genes and Environ* **2022**, *44*, 3, doi:10.1186/s41021-021-00233-y.
208. Liao, C.; Kim, U.-J.; Kannan, K. A Review of Environmental Occurrence, Fate, Exposure, and Toxicity of Benzothiazoles. *Environ. Sci. Technol.* **2018**, *52*, 5007–5026, doi:10.1021/acs.est.7b05493.
209. Honda, M.; Suzuki, N. Toxicities of Polycyclic Aromatic Hydrocarbons for Aquatic Animals. *Int J Environ Res Public Health* **2020**, *17*, 1363, doi:10.3390/ijerph17041363.
210. Bauer, A.; Siegrist, K.; Wolff, M.; Nield, L.; Brüning, T.; Upham, B.; Käfferlein, H.; Plöttner, S. The Carcinogenic Properties of Overlooked yet Prevalent Polycyclic Aromatic Hydrocarbons in Human Lung Epithelial Cells. *Toxics* **2022**, *10*, 28, doi:10.3390/toxics10010028.

211. Tian, Z.; Zhao, H.; Peter, K.T.; Gonzalez, M.; Wetzel, J.; Wu, C.; Hu, X.; Prat, J.; Mudrock, E.; Hettinger, R.; et al. A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon. *Science* **2021**, *371*, 185–189, doi:10.1126/science.abd6951.
212. Hua, X.; Wang, D. Exposure to 6-PPD Quinone at Environmentally Relevant Concentrations Inhibits Both Lifespan and Healthspan in *C. Elegans*. *Environ. Sci. Technol.* **2023**, acs.est.3c05325, doi:10.1021/acs.est.3c05325.
213. Hua, X.; Wang, D. Tire-Rubber Related Pollutant 6-PPD Quinone: A Review of Its Transformation, Environmental Distribution, Bioavailability, and Toxicity. *Journal of Hazardous Materials* **2023**, *459*, 132265, doi:10.1016/j.jhazmat.2023.132265.
214. European Commission. Directorate General for Mobility and Transport.; CE Delft. *Handbook on the External Costs of Transport: Version 2019 – 1.1.*; Publications Office: LU, 2020;
215. Beaumont, N.J.; Aanesen, M.; Austen, M.C.; Börger, T.; Clark, J.R.; Cole, M.; Hooper, T.; Lindeque, P.K.; Pascoe, C.; Wyles, K.J. Global Ecological, Social and Economic Impacts of Marine Plastic. *Marine Pollution Bulletin* **2019**, *142*, 189–195, doi:10.1016/j.marpolbul.2019.03.022.
216. Forrest, A.; Giacovazzi, L.; Dunlop, S.; Reisser, J.; Tickler, D.; Jamieson, A.; Meeuwig, J.J. Eliminating Plastic Pollution: How a Voluntary Contribution From Industry Will Drive the Circular Plastics Economy. *Front. Mar. Sci.* **2019**, *6*, 627, doi:10.3389/fmars.2019.00627.
217. DeWit, W.; Towers Burns, E.; Guinchard, J.-C. *Plastics: The Costs to the Society, the Environment and the Economy. A Report for WWF by Dalberg*; World Wide Fund for Nature (WWF): Gland, Switxerland, 2021;
218. United Nations Environment Programme *Turning Off the Tap: How the World Can End Plastic Pollution and Create a Circular Economy*; United Nations: Erscheinungsort nicht ermittelbar, 2023; ISBN 978-92-807-4024-0.
219. Hoeke, S.; Van Wijnen, J.; Krikke, H.; Löhr, A.; Ragas, A.M.J. Mapping the Tire Supply Chain and Its Microplastics Emissions Using a Multi-Stakeholder Approach. *Resources, Conservation and Recycling* **2024**, *203*, 107389, doi:10.1016/j.resconrec.2023.107389.
220. Chamas, A.; Moon, H.; Zheng, J.; Qiu, Y.; Tabassum, T.; Jang, J.H.; Abu-Omar, M.; Scott, S.L.; Suh, S. Degradation Rates of Plastics in the Environment. *ACS Sustainable Chem. Eng.* **2020**, *8*, 3494–3511, doi:10.1021/acssuschemeng.9b06635.
221. Giechaskiel, B.; Grigoratos, T.; Li, L.; Zang, S.; Lu, B.; Lopez, D.; García, J.J. Tyre Wear under Urban, Rural, and Motorway Driving Conditions at Two Locations in Spain and China. *Lubricants* **2024**, *12*, 338, doi:10.3390/lubricants12100338.
222. Neupert, J.W.; Lau, P.; Venghaus, D.; Barjenbruch, M. Development of a New Testing Approach for Decentralised Technical Sustainable Drainage Systems. *Water* **2021**, *13*, 722, doi:10.3390/w13050722.