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Review

Review: Mitigation measures to reduce tire and road wear particles

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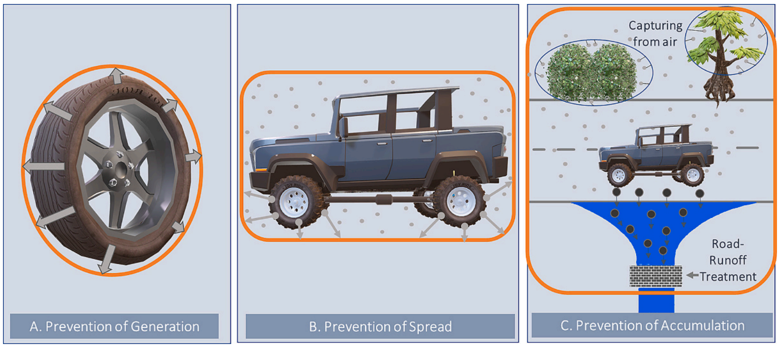
HIGHLIGHTS

- The state of knowledge of measures to mitigate TRWP is reviewed.
- Mitigation measures to prevent TRWP from generation, spread, and accumulation are identified, classified, and evaluated.
- Major knowledge gaps are analyzed, and fields of research are pointed out.
- Best-performing approaches comprise the combination of various mitigation measures and the implementation at hotspots.
- Future mobility trends (e-mobility, autonomous driving) are upcoming important issues in the context of TRWP mitigation.

GRAPHICAL ABSTRACT



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ABSTRACT

The generation of tire wear is an inevitable outcome of the friction between the road and the tire which is necessary for the safe operation of vehicles on roadways. Tire wear particles form agglomerates with road surface material. These agglomerates are called tire and road wear particles (TRWP). Due to their persistence in the environmental compartments and their potentially harmful effects, research on preventative and end-of-pipe mitigation strategies for TRWP is essential.

The major goal of this study is to summarize and assess the state of the art in science and technology of mitigation measures for TRWP as the basis for further research activities. Approximately 500 literature sources were found and analyzed in terms of the efficiency, maturity, implementation, and impact of the mitigation measures.

Generally, technological and management mitigation measures to reduce the generation of TRWP are beneficial since they prevent TRWP from entering the environment. Once released into environmental compartments, their mobility and dispersion would increase, making removing the particles more challenging.

Technological and management mitigation measures after the release of TRWP into the environment are mainly well established in industrialized countries. Street cleaning and wastewater technologies show good removal efficiencies for TRWP and microplastics.

In any case, no individual measure can solely solve the TRWP issue, but a set of combined measures could potentially be more effective.

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The absence of fully-developed and standardized methods for tire abrasion testing and measuring TRWP in the environment makes it impossible to reliably compare the tire abrasion behavior of different tire types, determine thresholds, and control mitigation actions.

Field tests and pilot studies are highly needed to demonstrate the effectiveness of the abatement measures under real conditions.

Abbreviations related to particle generation and emission

MP	microplastics; extremely small pieces of plastic in the environment that come from consumer products and industrial waste
NEE	non-exhaust emissions
PM	particulate matter: mixture of solid particles and liquid droplets found in the air
$PM_{0.1}$	ultra fine inhalable particulate matter <0.1 μm in diameter
$PM_{2.5}$	fine inhalable particulate matter <2.5 μm in diameter
PM_{10}	inhalable particulate matter <10 μm in diameter
TRWP	tire and road wear particles
TSS	total suspended solids
TWP	pure tire wear particles

1. Introduction

The following sections give a brief overview of the generation, characteristics, and pathways of TRWP related to the atmosphere, road runoff, and soil to clarify the complex, interrelated, and dynamic systems in which TRWP are generated, transported, transformed, and interact with the environment. These complex interrelationships must be thoroughly understood to derive suitable mitigation strategies for TRWP.

1.1. Generation and characteristics of TRWP

Tire wear and abrasion are inevitable outcomes of friction between the tires of vehicles and the road. The rate at which tire tread is abraded depends on several parameters (Stalnaker et al., 1996; ChemRisk and DIK Inc, 2008; Allen and Kaloush, 2006; Baensch-Baltruschat et al., 2020; Thorpe and Harrison, 2008; Grigoratos and Martini, 2014):

- tire characteristics (e.g., size, tread depth, construction, composition, age, mileage, and tire pressure)
- road surface characteristics (e.g., material, macro and micro texture, binder, wet/dry, porosity, temperature)
- road topography and design (e.g., steepness, curvature)
- vehicle operation (e.g., velocity, linear, and radial acceleration rate)
- vehicle characteristics (e.g., type of vehicle, vehicle weight, suspension, steering alignment)

Due to road-tire-interactions, TRWP are spontaneously formed as aggregates of abraded tire tread and road surface material including embedded pavement particles and minerals from the road as well as brake dust (Rogge et al., 1993; Kreider et al., 2010).

TRWP have been considered microplastics (MP) due to their polymer-based structure, size, and insolubility (Eisentraut et al., 2018; Hartmann et al., 2019). In Europe, approximately 1.327 million metric tons of tire wear particles (TWP) were released into the environment in 2014 and 1.120 million metric tons of TWP were generated in the U.S. in 2010 (Wagner et al., 2018) making tires one of the largest emissions sources for microplastics (Baensch-Baltruschat et al., 2020; Lassen et al., 2015; Magnusson et al., 2016; Sherrington et al., 2016; Sundt et al., 2014).

Electron microscopy (see Fig. 1) reveals that TRWP have typically an elongated cylindrical shape with incrustations of materials from road surface abrasion and other sources (Adachi and Tainosho, 2004; Klöckner et al., 2021; Kovochich et al., 2021b; Kreider et al., 2010; Panko et al., 2018). Depending on the road surface and its characteristics, temperature, speed, age, and composition of the tire (Boulter et al., 2006; Gustafsson et al., 2008; Kreider et al., 2010; Mathissen et al., 2011; Smolders and Degryse, 2002) as well as the vehicle weight, and braking intensity (Oroumiyeh and Zhu, 2021) the TRWP emissions feature large-size (> 20 μm) particles as well as coarse airborne ($PM_{2.5–10}$) and ultra-fine (nanoscale) particles (Kreider et al., 2010; Kumar et al., 2013; Mathissen et al., 2011; Panko et al., 2013).

Wagner et al. (2018) with reference to Boulter et al. (2006); Barlow et al. (2007); Panko et al. (2013), and Wik and Dave (2009) also divide TRWP into coarse (PM_{10}), fine ($PM_{2.5}$), and ultrafine ($PM_{0.1}$) particles and include most particles in the coarse size fraction. The small, airborne TRWP (<10 μm) make up <10 % by weight of tire wear emissions (Barlow et al., 2007; Panko et al., 2013).

According to recent studies, the density of TRWP is significantly higher than for water varying between 1.5 and 2.2 g/cm^3 (Baensch-Baltruschat et al., 2020 referring to Kayhanian et al., 2012; Rhodes et al., 2012), so the particles settle relatively fast in the aquatic environment.

1.2. Pathways and fate

After initial emission and deposition, particles that are not cleaned from the road will remain in place or be transported in natural or engineered environmental systems. The interconnected environmental and engineered compartments into and through which the particles flow are: road surface, atmosphere, adjacent surfaces, stormwater or combined sewers, surface water and groundwater, and sediments (Kole et al., 2017; Kumata et al., 2000; Kumata et al., 2002; Parker-Jurd et al., 2021; Prenner et al., 2021; Sieber et al., 2020; Sommer et al., 2018; Wik and Dave, 2009).

1.2.1. Transport and deposition via the atmosphere

Initially emitted into the air, particles can be transported or deposited on surfaces by settling or rain. However, most tire wear particles are coarse size or larger, settle rapidly from the air, and are deposited on the roadways or nearby surfaces. Once settled, TRWP can be remobilized from surfaces to the air by traffic-induced turbulence, and turbulence from wind (Amato et al., 2012; Gnecco et al., 2005; Järlskog et al., 2021). Particles in the fine and ultrafine size ranges can be transported over long distances (Allen et al., 2019; Evangeliou et al., 2020). For these airborne TRWP atmospheric deposition may be a pathway for microplastics to enter the surface water (including marine) environments (Brahney et al., 2021; Evangeliou et al., 2020).

1.2.2. Transport and sedimentation via road runoff

Stormwater runoff can intermittently remobilize TRWP from roadway surfaces and transport it into other surface environments. Since concentrations of particles on the roadway are dependent on location, time, traffic loads, and a variety of road and driver characteristics, the concentration of TRWP in runoff is highly variable. According to Unice et al. (2019) at least 2 mm/d of precipitation is needed to mobilize

TRWP on the roadway. Baensch-Baltruschat et al. (2020) state that a majority of particles on the roadway will be mobilized by 5 mm/d of precipitation.

Urban roadway runoff is mostly connected to either storm sewers or combined sewers through storm drains. Rural roads and highways are not commonly connected to the sewage system and the road runoff might enter the natural water bodies such as lakes, rivers, and the marine environment without a previous treatment step (Baensch-Baltruschat et al., 2021; Gieré and Dietze, 2022; Parker-Jurd et al., 2021).

Lassen et al. (2015) estimated Denmark's annual tire wear masses and stated that 8 to 40 % of them were released into the aquatic environment. According to Unice et al. (2019), about 50 % of mass fraction (25 to 75 %) is transported via road runoff. Verschoor et al. (2016) estimated that 10 % of emitted TRWP entered surface waters. Unice et al. (2019) estimated that around 18 % of the TRWP that were generated in the Seine watershed were transported into aqueous systems but only 2 % reached the estuary.

1.2.3. Soil as source and sink for TRWP

Either of these values implies that most TRWP produced in a watershed are degraded or are retained in other compartments, consistent with the findings of Baensch-Baltruschat et al. (2020) that 66 to 76 % of TRWP settle on adjacent soil. Unice et al. (2019) estimated that the percentage of TRWP that become bound to the soil matrix is in a range between 25 and 75 % with an average of 50 %. It is also important to note that TRWP associated with soils on unprotected slopes that are subject to erosion may mobilize particles into surface water.

Little is known about the half-life of TRWP in soil and sediment. Unice et al. (2019) assume ranges of half-life between 245 and 980 days in soil and 2450 to 9800 days in sediment based on expected rubber degradation by Cadle and Williams (1980) and a default approach guided by the European Chemical Agency (ECHA, 2016). Wagner et al. (2018) note that the primary components of TWP are rubber and carbon black; therefore, the particles should persist and degradation would be slow.

Concerns over the fate, transport, and toxicity of synthetic polymer materials as well as the recent linking of TWP to toxicity effects in Coho Salmon (Tian et al., 2021) have led to scrutiny and research into the environmental impacts of TWP and TRWP (Barnes et al., 2009; Järlskog et al., 2021; Wagner et al., 2018; Wagner et al., 2022; Baensch-Baltruschat et al., 2020; Koelmans et al., 2019; Mian et al., 2022; Liu et al., 2022; Siegfried et al., 2017) and give rise to a great public interest in strategies for mitigation of potential detrimental impacts from TRWP.

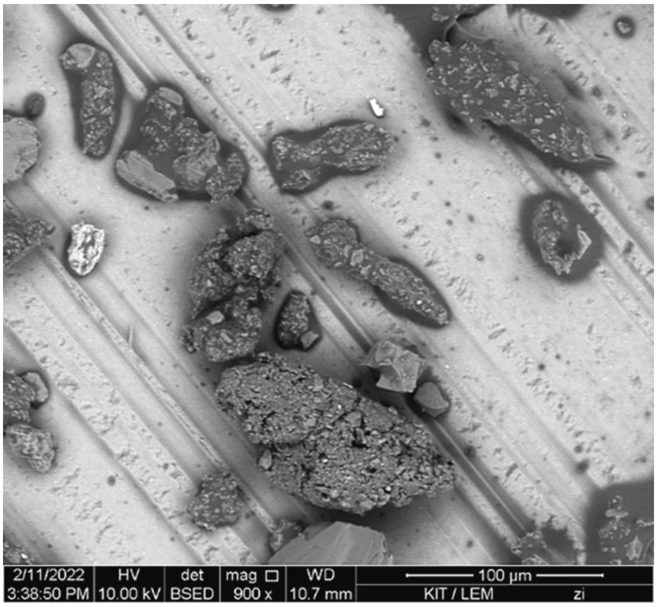

Fig. 1. SEM image of TRWP collected on an aluminum substrate at a tire test bench showing mainly typical TRWP but also pure minerals (@ Karlsruhe Institue of Technology).

2. Methods

The review on mitigation measures for TRWP is based on very comprehensive research on literature from all over the world including scientific literature, proceedings, and policy papers, using SciFinder, ScienceDirect, Google Scholar, and SpringerLink. Furthermore, the authors of this study assessed information from European and US expert panel organizations and networks.

The study assigns the identified measures to the following TRWP mitigation classes:

- Mitigation measures to prevent the generation of TRWP.
- Mitigation measures at the vehicle and the road surface to prevent TRWP from being spread in air, water, and soil.
- Mitigation measures on road runoff and atmosphere to prevent TRWP from accumulation and fate in natural environmental compartments.

To create a comprehensive database for all classes, literature sources that directly address TRWP and those that focus on mitigating microplastics, and TSS were analyzed. The authors assume that these substance groups include TRWP and that any mitigation approach for them is as effective for TRWP, though TRWP have several specific characteristics such as high density and biodegradability which might enforce the removal rate of TRWP compared to microplastics (Vogelsang et al., 2020). Besides, several studies (Vogelsang et al., 2020) have proven that the concentration of TRWP in TSS temporarily and spatially varies, especially for particles smaller than 45 μm. Nevertheless, TSS appears to be an adequate surrogate parameter for TWP in road runoff, since approximately 85 % of TWP are larger than 50 μm (Vogelsang et al., 2020).

For the same reason, the literature review also assessed empirical studies based on the measurement of uncertain marker substances for TRWP. These tracking substances include chemical markers for natural and synthetic rubber such as styrene-butadiene rubber, (extractable organic) zinc, the benzothiazole 24MoBT, and n-alkanes with >35 carbons. However, for example, zinc is not only released by tires but also from brakes, road furniture, and fertilizer (Vogelsang et al., 2020).

3. Mitigation measures

Within the three classes for TRWP mitigation, 50 single abatement actions were found and condensed to 26 major mitigation measures.

3.1. TRWP mitigation measures to prevent the generation of TRWP

The following section comprises 16 technological, regulatory, economic, and educational mitigation measures.

3.1.1. Technical adjustment of the vehicle fleet

The composition of the vehicle fleet is an influencing factor for emission reductions at the source (Andersson-Sköld et al., 2020). Thus, the transition to a greener vehicle fleet needs to be accelerated (Amato, 2018). Through climate change and digitalization, the requirements for environmental behavior and vehicle mobility of the vehicle fleet are changing. Next-generation automobiles will be predominantly battery-powered, highly connected, and fully autonomous. Vehicle emissions will mainly comprise non-exhaust emissions (NEE) including not only tire wear but also brake and road wear.

According to a study by the International Energy Agency (2023), around 26 million electric cars existed worldwide in 2022, five times as many as in 2018. However, due to high battery weights, BEVs (battery-electric vehicles) are usually heavier than comparable ICEVs (internal combustion engine vehicles). Accordingly, they require higher forces for acceleration, which electric motors provide due to their high torques.

The increased forces lead to more tire wear (Andersson-Sköld et al., 2020; Furuseth and Rødland, 2020; Johannesson and Lithner, 2022; Kole et al., 2017; Obereigner et al., 2020; Piscitello et al., 2021; Sommer et al., 2018; Winquist et al., 2021; Worek et al., 2022). The current increase in the share of BEVs is likely to also lead to an increase in NEE (Gieré and Dietze, 2022). In contrast, Timmers and Achten (2016) state that the total PM (particulate matter) emissions of BEVs were comparable to those of ICEVs. Lastly, there are also studies that state that BEVs do not cause higher tire wear emissions at all (Johannesson and Lithner, 2022; Nokian Tyres, 2019; Continental, 2021).

While most authors only mention a relation between increasing mass and higher TRWP generation, some go into detail about the mathematical correlation. Both Aatmeeyata et al. (2009) and Kole et al. (2017) describe a linear relationship between the vertical load and the particle emission, making the vehicle weight a major parameter for the generation of tire particles. Therefore, numerous authors call for lighter vehicles and demand a trend reversal, especially for BEVs (Andersson-Sköld et al., 2020; Barlow, 2014; Boulter et al., 2006; Fussell et al., 2022; Timmers and Achten, 2016). BEVs need to be designed lighter to compensate for the additional weight of the battery compared to an internal combustion engine. Low-density materials can help to achieve this goal (van Basshuysen, 2010). Limiting the battery range or capacity is another option.

Since the development of cars is a prolonged process, the introduction of new materials will only show its effect in the long term. This statement is even more true as the materials required may not exist yet and will have to be developed. The same applies to a trend reversal in battery weight, which is essential to avoid the development of heavier vehicles. Additional advantages of light vehicles are lower energy consumption, increased range, and eventually lower operating costs.

Further research on the impact of electric vehicles on tire wear (Furuseth and Rødland, 2020) and more research and development are needed to optimize electric vehicles in terms of vehicle weight, suitable tires, and battery power density.

3.1.2. *Optimization of driving behavior*

3.1.2.1. The importance of driving behavior for the generation of TRWP. Harsh braking, rapid acceleration, and fast cornering lead to increased emission levels of TRWP due to high forces between the tire and the road. When cornering, lateral acceleration and thus the forces transmitted increase quadratically with the vehicle speed. Even when driving straight ahead at a constant speed, forces are already acting in the tire-road contact patch. To maintain its speed, a vehicle must overcome all driving resistances. At high speeds, air resistance dominates, which also increases quadratically with speed. Air resistance may therefore be one reason why different conclusions have been found about the influence of speed on the emission of TRWP (see Table 1).

Many authors simply summarize the measure under the heading "optimization of driving behavior" or mention the individual sub-aspects such as speed, acceleration, braking, and cornering but do not address their effect on emissions (Amato, 2018; Jekel, 2019; Le Maître et al., 1998; OECD, 2021; Worek et al., 2022). Improving or changing driving behavior is considered to have a significant effect on reducing emissions such as TRWP or PM (Dröge and Hulskotte, 2018; Fussell et al., 2022; Gabbe et al., 2019; Kole et al., 2015; Lenzo, 2022; WDK, 2019). Therefore, a smooth driving style extends the lifetime of a tire, whereas a harsh driving style shortens it.

3.1.2.2. The influence of individual driving conditions. However, some studies could be found that look more closely at the individual influencing factors. For example, Foitzik et al. (2018) give the dependence of ultrafine particle emission (particle number) on braking forces as a quadratic function and that on driving forces even as a fourth-order function for their experimental results on a tire test bench. Kwak et al. (2014) investigated the emission of ultrafine particles for braking processes during their test drives on open roads and obtained a 30 to 40-fold increase compared to driving at a constant speed. Kim and Lee (2018) performed heavy braking maneuvers and recorded the emission of fine and ultrafine PM on a tire test bench. They describe increases of 9 to 10 times the original concentration.

Similar studies exist for the influence of slip angles or lateral forces. Foitzik et al. (2018) identified an exponential relationship between slip angle and particle emission (ultrafine PM). Park et al. (2018) conducted investigations on a tire test bench and conclude that a slip angle of 4° increases PM emission measured by particle mass concentration by 2 to 3 times and measured by particle number concentration by even 160 times compared to the non-slip condition. The strong dependence of the emission on the slip angle is confirmed by the simulation model of Chen et al. (2018), in which they indicate a progressive relationship.

Studies dealing with the influence of vehicle speed on the generation of TRWP come to diverse results (Boulter et al., 2006). Many studies refer to the use of studded tires (Gustafsson et al., 2009; Hussein et al., 2008) and indicate a significant influence of speed. However, these results cannot be applied to conventional friction tires due to different processes in the tire-road contact patch. Other studies look at the influence of the speed of conventional summer and winter tires on TRWP emissions but come to different results (see Table 1).

Therefore, many authors call for speed reduction to reduce emissions (ADAC e. V., 2022; Barr et al., 2021; Denier van der Gon and Cassee, 2012; Fussell et al., 2022; Grigoratos and Martini, 2014; Gustafsson et al., 2019a; Kroher, 2022; Verschoor and De Valk, 2018). This is countered by the findings of Foitzik et al. (2018), who conclude from their research that the speed itself does not affect particulate emissions (ultrafine PM) but only the distance traveled. However, the tests of Foitzik et al. cannot be directly compared with tests on open roads. The difference is that on the test bench, due to the lack of air resistance, no forces have to be transmitted between the tire and the road in order to drive with a constant speed. This indicates that a reduction in speed may well also reduce particulate emissions.

3.1.2.3. Voluntary speed reduction. Voluntary speed reduction is considered a non-regulatory and appropriate measure to reduce tire emissions (Andersson-Sköld et al., 2020). Conditions must be created that induce a voluntary willingness to reduce speed and thus reduce emissions. However, this measure is only a recommendation and therefore not binding for drivers. Incentives to voluntarily reduce speed could help increase this willingness. Modern vehicles can use assistance systems to teach drivers a driving style that reduces TRWP emissions. Some cars already record individual driving behavior by visualizing and storing data on individual trips, with positive feedback leading to better

Table 1
Relations between vehicle speed and generation of TRWP.

Object	Relation	Reference
Tire wear	30 % increase per 10 km/h speed increase	Kupiainen and Pirjola (2011)
Tire wear	13 % reduction for speed reduction from 50 to 30 km/h	Pohrt (2019)
Tire wear	power four in the velocity dependence	Winquist et al. (2021)
Particles emitted by traffic	linear relationship between speed and the number of particles	Elmgren et al. (2017)
Small TWP	higher speed increases generation	Johannesson and Lithner, 2022
Road abrasion	higher speed increases generation	Johannesson and Lithner, 2022; Denby et al., 2013

driving behavior. Instruments such as a simple eco-score as well as training can motivate drivers to improve their driving behavior (Furuseth and Rødland, 2020). In addition to the decrease of TRWP emissions, the voluntary implementation of the measures allows for the reduction of general wear and tear, safety, energy consumption, and operating costs.

3.1.2.4. Introduction of speed limits. A more restrictive way to reduce TRWP is the definition of regulatory framework conditions for example by setting speed limits and threshold values for NEE which all new vehicles, BEVs and ICEVs, must meet (Timmers and Achten, 2016). This approach is in line with studies that looked at the correlation between speed and total tire wear and concluded that the introduction of a speed limit reduces TRWP emissions (Baensch-Baltruschat et al., 2020; Barr et al., 2021; Fussell et al., 2022; Gieré and Dietze, 2022; Piscitello et al., 2021).

3.1.2.5. Introduction of speed and acceleration limiters. For more efficient implementation and a higher effect the reduction of forces transmitted in the tire-road contact patch should be based on technology such as speed and acceleration limiters (Boulter et al., 2006). For safety reasons, only acceleration can be limited but not deceleration or cornering. However, since the acceleration capability of vehicles, especially high-performance and sporty models, often serves as a selling point, vehicle manufacturers probably have no interest in artificially cutting this argument. Particularly in the case of electric vehicles, for which top speed is largely reduced in favor of a longer range, maximum acceleration is often an important performance parameter. While this means that limiting the maximum speed would find higher acceptance among vehicle manufacturers, acceleration performance will become all the more important for their prestige.

3.1.2.6. Optimization of torque allocation. However, approaches were also found in the literature that do not only aim to limit the forces transmitted, but primarily to allocate them more advantageously to the wheels, especially for BEVs. They naturally have higher peak torques than comparable ICEVs which cause higher tire slip energy dissipation indicating tire wear (Gao et al., 2022). To minimize the energy losses and the resulting tire wear, Gao et al. (2022) present a distribution algorithm to optimally allocate driving torques in an all-wheel drive BEV. They consider engine and energy losses due to tire slip. They compare the algorithm with two conventional optimization algorithms for severe acceleration on a high-adhesion road surface and one with low adhesion. For the former, their algorithm achieves an improvement in terms of tire slip energy dissipation of around 30 % compared to the existing ones, while the energy dissipation at the engine increases by around 2 %. On the low-adhesion road, their algorithm was able to reduce the energy loss due to tire slip compared to the two conventional algorithms by around 26 and 3 %, while the energy loss at the engine increased by around 0.5 % and dropped by around 11 %, respectively. Thus, the new algorithm was able to reduce the total energy losses compared to both existing algorithms and on both surfaces (Gao et al., 2022).

Obereigner et al. (2020) chose a different approach to reduce peak torques. They compare simulations of different optimization strategies for an electrically and a conventionally driven vehicle, with the vehicles following a further vehicle in front. One strategy only aimed to minimize tire wear, while the second one additionally pursued increasing traffic capacity. Both resulted in a significant decrease in the transmitted longitudinal forces, with the traffic capacity enhancement variant showing smaller reductions. Transferred to the release of tire abrasion particles, the control strategy that only aimed to minimize tire abrasion, therefore produced the best results. Compared with the vehicle in front, both the conventionally and the electrically driven vehicles were able to reduce particulate emissions, achieving reductions of 58 and 44 %, respectively. The total emission of the ICEV was between 16 % and 36 % lower than the one of the EV which was caused by the higher mass of the latter. However, it should be noted, that Obereigner et al. (2020) assumed a direct relationship between longitudinal forces and the number of particles emitted to calculate their results. The actual correlation has not yet been adequately researched.

The described studies show one more time that such optimization methods cannot only minimize energy consumption but also optimize traffic capacity and tire wear at the same time.

3.1.3. Integration of traction control and ABS

TRWP are the result of frictional forces and sliding processes in the tire-road contact patch. The higher the forces that occur, the greater the stress in the tire and the higher the surface temperature. These two parameters lead to an increase in tire abrasion and thus to increased TRWP generation. However, particularly high stress and temperature occur in the tire if the speed difference between tire and vehicle is large, i.e., for high slip ratios if the tires spin during acceleration or lock up while braking. To avoid both conditions there are technical solutions. For acceleration, traction control systems prevent the wheel from spinning, while during braking events the anti-lock braking system (ABS) ensures the rotation of the wheel, thus allowing for maximum force transmission to reach short stopping distances (Ersoy and Gies, 2017).

A measure to mitigate TRWP is therefore the installation of both systems in all road vehicles (Amato, 2018; Boulter et al., 2006) in order to fully avoid both conditions described above.

3.1.4. Vehicle maintenance

Liu et al. (2021) found that the amount of TWP emitted during service life is closely related to the maintenance condition of a vehicle. The major factors are as follows:

3.1.4.1. The influence of tire inflation pressure. Tire inflation pressure is an important parameter influencing tire wear and mileage by determining the shape of the tire and thus the size and contour of the tire-road contact area (Ersoy and Gies, 2017). Too low inflation pressure results in a longer contact patch, high load on the tire shoulders, and, in turn, the tire wears more at the shoulders (Paige, 2012). On the contrary, too high inflation pressure leads to excessive inner wear, as force transmission can only take place in the tire center (Andersson-Sköld et al., 2020). Aatmeeyata et al. (2009) and Wang et al. (2017) mention a declining linear relationship between inflation pressure and PM emission or total tire wear, respectively. Stojanovic et al. (2021) relate the influence of inflation pressure not to the emission of TRWP but to the lifetime of the tire, concluding that a 20 % reduction of inflation pressure reduces the lifetime by 30 %.

To maintain the optimum tire inflation pressure or the target pressure specified by the vehicle manufacturer, there are assistance systems of varying complexity and accuracy that help the drivers and draw their attention to a pressure that is too high or too low. According to EU Regulation No. 661/2009 of July 13, 2009, tire pressure monitoring systems (TPMS) have been mandatory since November 2012 in order to obtain EC-type approval for new vehicles (European Parliament, 2009). An extrapolation of the emission reduction of microplastics shows that if all vehicles in the Netherlands were retrofitted or equipped with TPMS, approximately 100 tons of microplastics could be saved per year through tire abrasion. According to the same study, a reduction of 70 tons per year could be achieved if only old vehicles were equipped (Verschoor and De Valk, 2018).

Baldwin and Bauer (2008) describe an alternative or complementary possibility with which a longer maintenance interval of the inflation pressure setting could be achieved. This involves a gas mixture with higher nitrogen share to inflate the tire. Nitrogen has a lower permeation rate than oxygen, so it is easier to keep the molecules inside the tire. However, a nitrogen content of around 95 % or more is only achieved with a big technical effort and is therefore not possible for most customers. Some studies mention the potential of airless tires to reduce TRWP (Andersson-Sköld et al., 2020; Worek et al., 2022). However, they do neither provide precise information on their development stage nor the associated savings potential for TRWP.

If vehicles do not have any of these technologies and inflating tires with a high-percentage nitrogen mixture is not an option, e.g., due to a lack of infrastructure, it is still possible to check and adjust the inflation pressure at regular intervals. This particularly applies to drives with unusually high payloads (Winquist et al., 2021). An additional incentive to do so is the fact that optimal inflation pressure leads to lower energy consumption.

3.1.4.2. The influence of wheel alignment. Besides tire inflation pressure, wheel alignment concerning toe angle influences tire wear (Furuseth and Rødland, 2020). If tires are not aligned parallel to the driving direction, they wear unevenly due to the asymmetrical contact patch with the road (Leister, 2015) and faster due to the lateral forces that arise as a result. Asymmetrical wear also applies to incorrect camber angles. If wheels have positive camber, i.e., they are inclined away from the vehicle, the load on the outer tire shoulders increases, so that they wear more intensely there. If, on the other hand, the wheels have negative camber, i.e., they are inclined towards the vehicle, the load on the inner shoulders increases, so that they wear more heavily there. Asymmetrical wear patterns, therefore, indicate incorrectly adjusted or misaligned axle kinematics (Leister, 2015).

Quantitative statements on the influence of the two kinematic parameters on the emission of TRWP could not be found in the literature. Most authors mention that wheel alignment can negatively influence tire wear and should therefore be checked more frequently and readjusted if misalignment is detected (Barlow, 2014; Boulter et al., 2006; Verschoor and De Valk, 2018). The wheel alignment control is part of the mandatory regular vehicle inspections according to EU Directive 2014/45/EU (Furuseth and Rødland, 2020). Checking can be done either in a workshop or informally through the wear pattern of the tires (Johannesson and Lithner, 2022).

An impression of the influence of an incorrectly adjusted toe angle on the emission of TRWP can be derived from the relationship between slip angle and tire wear. From the Chen et al. (2018) data, a progressive relationship can be inferred for this. A qualitative statement on the influence of toe angle is given by (Andersson-Sköld et al., 2020). The authors state that tires wear faster if a toe angle is present, regardless of its sign. However, "correct alignment" is not well defined, as the kinematics of most vehicles show a toe-in that is different from zero in the standard setting (Ersoy and Gies, 2017). In addition, the toe angle changes depending on the vehicle's suspension deflection, so it has to be optimized for the entire wheel lift curve. Summarizing, all studies agree that incorrect toe angle leads to increased tire wear, however quantitative statements on the influence on the emission of TRWP could not be found.

The data on the influence of camber angle is even less clear. The only certainty is that camber unequal to zero wears tires unevenly. However, it is unknown whether that also results in more wear or only a shorter lifetime. According to a study by Däckrazzia (2018), which considered 161 vehicles, the tires of half of these vehicles showed uneven wear patterns, indicating incorrect or misaligned axle kinematics.

3.1.4.3. Minimizing tire wear by optimizing wheel alignment. An approach to minimize tire wear by optimizing wheel alignment was carried out by Schütte and Sextro (2021) using a simulation model in which they varied toe angles and camber angles in the rest position based on standard kinematics and estimated tire wear considering the friction energy. They combined the two optimum settings for toe and camber angle to create a new kinematic system, which mathematically predicts 56.6 % less tire wear for straight-ahead driving at 100 km/h compared to the standard setting. However, the authors themselves note that the model must be extended to include further degrees of freedom and driving conditions for more realistic statements. The only data on the influence of incorrect wheel settings on TRWP emissions were found in Verschoor and De Valk (2018). The authors estimate the savings potential through correctly-aligned wheels for the Netherlands at 50 tons per year and give 10 % as a guideline for unnecessary tire wear due to misaligned wheels.

However, because wheel alignment can change by accidents or even by potholes, bumps, and curbs, checks must be carried out at relatively short intervals. Additionally, completely aligned wheels are opposed by other interests, such as a sportier driving experience (greater toe-in and negative camber) or an allegedly better appearance of the vehicle (negative camber angle).

A technology for inline-detecting incorrect wheel alignment analogous to TPMS has been developed by an Australian company. The technology monitors and corrects wheel alignment while driving and is also designed to minimize tire wear, according to the manufacturer (Doftek, 2022). This technology could eliminate the need for frequent checking and adjusting.

3.1.5. Optimization of tire selection

3.1.5.1. Regulation of winter tires. Choosing the right tires is a challenge for many drivers. There exist a huge variety of designs, usable for different seasons, which differ in abrasion behavior and thus in the release of TRWP. Many drivers use winter tires not only during the winter but also in other seasons. This is often done for convenience and to save the cost of changing tires, though at higher temperatures, winter tires increase fuel consumption compared to summer tires, have poorer braking properties, worsen handling, and wear out more. This is because winter tires are generally made of a softer rubber compound than summer tires and therefore have higher wear rates (Sundt et al., 2016). They produce between 2.2 and 2.7 times more road dust than summer tires (Hussein et al., 2008) but it is not known how much tire wear is generated additionally by the unnecessary use of winter tires in non-winter months.

Limiting the use of winter tires in the off-season is an effective measure to reduce TRWP (Furuseth and Rødland, 2020; Praticò and Briante, 2020; Verschoor and De Valk, 2018). For now, this statement is only a recommendation for drivers to voluntarily contribute to the reduction of TRWP. Most countries have commandments that specify the conditions under which winter tires must be used. However, there are no bans or restrictions on the use of winter tires in summer.

In addition to seasons, dimension, performance, and price are cited as other factors that influence tire wear. Pohrt (2019), Le Maître et al. (1998) and Worek et al. (2022) state that wider tires wear less than narrow tires due to better distributed ground contact and the resulting lower flexing work. Köllner (2022) and Kroher (2022) point out that ultra-high performance tires have particularly high tire wear. Similarly, low-budget tires are said to perform significantly worse than premium tires in terms of tire wear (Emissions analytics, 2020). These facts should be considered by car manufacturers for the tire selection of their cars.

3.1.5.2. Usage of studded tires. Studded tires are used particularly in cold regions during the winter seasons, where roads may be covered with snow and ice. Their use is prohibited in many other European countries due to the extreme damage they cause to roads. In Northern Europe, studded tires are one of the largest sources of PM and the main cause of road abrasion (Furuseth and Rødland, 2020). Thus, the vast majority of studies on their impact on road dust emissions have been conducted in the Northern region. Gustafsson et al. (2008) cite an increase in road dust emissions by a factor of 60 to 100 when switching from winter to studded tires in their experiments with a road simulator. Sjödin et al. (2010) report an increase in road dust emissions of a factor of 10 for studded tires in comparison to winter tires and an increase of a factor of 100 for studded tires in comparison to summer tires. Hussein et al. (2008) report smaller road dust increases of 2 to 6.4 for studded tires in comparison to winter tires and 4.4 to 17.3 for studded tires in comparison to summer tires. It remains to be investigated under which conditions studded tires lead to increased road wear or dust. However, it is indisputable that these tires damage the road surface more severely than friction tires and also generate higher road dust emissions (Dahl et al., 2006; Denier van der Gon and Cassee, 2012; Gustafsson et al., 2009; Kupiainen et al., 2005). Furthermore, using friction tires instead of studded tires leads to additional benefits such as noise reduction and lower energy consumption. Of course, the replacement of studded tires by winter tires is only an option if there are no safety concerns.

In addition to the direct effect on road dust, driving with studded tires roughens the road surface (Vogelsang et al., 2020) leading to increased tire abrasion (Lowne, 1970). Thus, reducing the use of studded tires would have the dual benefit of generating less road dust and polishing the road surface with conventional tires (Vogelsang et al., 2020). How studded tires themselves perform in terms of tire abrasion is still unknown (Vogelsang et al., 2020).

To reduce road wear and dust due to studded tires, there are two options from a technical point of view. The obvious one is to ban studded tires and replace them with friction tires (Andersson-Sköld et al., 2020; Denby et al., 2013; Kupiainen et al., 2017). The second approach is to reduce the number or mass of studs on a tire (Fussell et al., 2022; Kupiainen and Pirjola, 2011). Information about the extent of the decrease in number or mass was not offered in the literature. Another option that may discourage consumers from using studded tires would be taxing their use (Furuseth and Rødland, 2020; Vogelsang et al., 2020).

3.1.6. *Optimization of road surfaces and maintenance*

The road surface influences the emission of TRWP. In addition to the material (composition and grain size), the properties of the road surface and the maintenance condition are influencing factors. Surface characteristics that have an influence on tire wear generation include pavement type, texture, porosity, rutting, wetness, and road temperature (Liu et al., 2021; Ntziachristos and Boulter, 2016; Wik and Dave, 2009; OECD, 2021; Amato, 2018; Buzzi, 2020), with roughness having the largest influence on tire abrasion (Boulter et al., 2006; Buzzi, 2020; Emissions analytics, 2020; Fussell et al., 2022; Lowne, 1970; Pohrt, 2019; Verschoor et al., 2016). This is mainly due to the micro-roughness (Lowne, 1970; Veith, 1995), while the macro roughness only plays a minor role (Lowne, 1970). Lowne (1970) gives a factor of 3 for the difference in tire wear between a polished and a rough road surface. Kupiainen et al. (2017) state that new asphalt pavements produce especially low PM emissions through less road wear, likely due to the bitumen surface cover. Once the cover is removed, emissions increase. The type of applied stone material also seems to make a difference. Accordingly, harder stone such as quartzite is more resistant to road abrasion and therefore generates lower emissions of road dust than granite (Dahl et al., 2006; Gustafsson et al., 2009; Sjödin et al., 2010). Lee et al. (2013) report that generally, concrete has a 2 to 3 times higher wear resistance than asphalt. A statement on the comparison between asphalt and concrete pavements in terms of tire abrasion is given by ADAC e. V (2022). According to this publication, concrete pavements lead to more tire wear than asphalt pavements, which is confirmed by Allen and Kaloush (2006). They found that tire wear rates are 1.4 to 2 times higher for concrete than for asphalt. However, no statements are given about a possible correlation between road and tire abrasion.

Many authors suggest the use of abrasion-resistant pavement materials (Boulter et al., 2006; Gustafsson et al., 2019b; Vogelsang et al., 2020) to minimize road wear. Quartzite could be used instead of granite (Gustafsson et al., 2008). However, Gustafsson et al. (2008) note that low road wear does not automatically mean low particulate emissions, as reduced road wear from more abrasion-resistant materials could be overcompensated by higher tire wear due to higher abrasiveness. Johannesson and Lithner (2022) also draw this conclusion. According to them, the development of a pavement that reduces tire abrasion could be difficult, because the technical requirements for such a pavement conflict with safety-related demands (Johannesson and Lithner, 2022). For example, the optimization of micro-roughness in favor of low tire wear results in a conflict of objectives with high grip, especially for wet conditions, which require high micro-roughness.

Potential measures to reduce emissions through road management include regular road maintenance, successive pavement optimization, and sewers to capture and collect traffic dust (Andersson-Sköld et al., 2020; Baensch-Baltruschat et al., 2020; Boulter et al., 2007; Buzzi, 2020; European Commission, 2021; Furuseth and Rødland, 2020; Gabbe et al., 2019; Gulia et al., 2019; Hero, 2018; Hussein et al., 2008; Johannesson and Lithner, 2022; Kupiainen et al., 2020; Sartor and Gaboury, 1984; Sundt et al., 2016).

Some authors call for more-resistant pavement markings without going into more detail about them (Boulter et al., 2006; Vogelsang et al., 2020).

3.1.7. *Reduction of gritting material*

Gritting materials are used to protect pavements and roads from snow, black ice, and to reduce the risk of accidents. Gritting materials remove material from the road through friction between gritting particles and the road surface (Boulter, 2005). They also produce PM (Mathissen et al., 2012) and lead to an increase in particle emissions in general (Norman and Johansson, 2006). Studies in Helsinki have shown that grit can contribute to an average PM_{10} suspension and concentration of up to 25 % (Kupiainen et al., 2017). To avoid road wear and tire abrasion, reducing the amount of gritting material is an appropriate measure (Amato et al., 2010). In a 4-year scenario modeled with NORTRIP, in which no traction sanding occurs, the result would be a PM_{10} reduction of between 4 and 20 %, compared to the initial concentration. Without salting during the winter months, PM_{10} levels would decrease by 0.1 to 4 % (Stojiljkovic et al., 2019). Compared to salt, sand appears to be more abrasive. The reduction of gritting materials is a measure that can be implemented very quickly but its effect is limited to countries with harsh winters. A ban on gritting materials does not seem reasonable, as their use is essential to increase road safety.

3.1.8. *Optimization of tire material*

3.1.8.1. Filler materials. The tire material is a key factor influencing tire wear. Tire manufacturers are constantly striving to further develop their materials in a wide variety of ways. The problem is that some of the parameters to be optimized conflict with each other, what is known as the "magic triangle" in tire development and describes the fact that the three most important target figures rolling resistance, wet grip, and abrasion resistance cannot be changed independently or even optimized simultaneously. If one of the three parameters is improved, this automatically worsens at least one of the other two (Kole et al., 2017). The only way to escape this situation is to develop innovative materials such as silica that allow for better compromises between two or even three parameters.

The most-frequently mentioned measure in literature is the use of silica as filler instead of carbon black which has been the main reinforcing agent for tires (OECD, 2014). Silica as an additive increases the abrasion resistance to a greater extent than carbon black (Praticò and Briante, 2020; Verschoor et al., 2016). Ten Brinke (2002) reports that silica increases tire resistance while minimizing energy losses and at the same time does not deteriorate wet grip ability. Currently, “highly-dispersible” (HD) silica is added as filler rather than standard silica used in the early stages of the technology's development. Compared to standard silica, tire compositions containing HD silica exhibit superior wear resistance as well as improvements in wet grip and rolling resistance (OECD, 2014). Using silica instead of carbon black to minimize abrasion is also confirmed by Kocher (2010). However, the author points out that generally there is a correlation between the abrasion rate and the size of the emitted particles. Accordingly, larger particles are emitted at high abrasion rates while small abrasion rates predominantly cause smaller particles (fine fraction). If this relationship can be applied to silica-containing tires, which are used among others because of their lower abrasion, the PM emission would increase with an increasing proportion of silica tires (Kocher, 2010). In addition to that, silica has already been used in tire production for years, making it difficult to estimate the remaining potential to reduce tire wear.

Shoul et al. (2022) further propose to replace common silica with green silica, which can be obtained, for example, from the ashes of rice husks and other plant waste products, thus offering a very cost-effective way of production. Green silica provides high abrasion resistance and is a good alternative to carbon black (Shoul et al., 2022). According to Stojanovic et al. (2021), further improvement in terms of abrasion resistance can be achieved by adding nanoprene and nanosilica. However, there are economic as well as environmental barriers such as the high cost of nanotechnology, unreliable production techniques, the uncertainty over environment, and health and safety risks (OECD, 2014).

3.1.8.2. Self-healing tire materials. Another approach pursues the development of self-healing or self-repairing tire materials. This involves modifying conventional tire rubber by adding further substances to enable it to independently compensate for damage and aging processes (Gieré and Dietze, 2022). Das et al. (2015) presented an approach in which they transform conventional brombutyl rubber (BIIR) into a highly-elastic material additionally exhibiting self-healing properties. A completely cut sample could regain its original properties through the self-healing process (Das et al., 2015). Also based on bromobutyl rubber modified with butyl imidazole is the self-healing rubber material described by Le et al. (2017). A blend of BIIR with natural rubber is reinforced with carbon nanotubes (CNTs). The addition and blending with natural rubber increase the tensile strength of the compound. The self-healing ability is achieved by using butyl imidazole (Le et al., 2017). Araujo-Morera et al. (2019) describe the development of a self-healing material based on styrene-butadiene rubber (SBR) by adding ground tire rubber. This allowed them to reduce rolling resistance while keeping both the wet grip and the healing ability (representing abrasion resistance) of the material constant. It was further shown that tire blends of SBR and ground tire rubber allowed for full recovery of stiffness and relaxation dynamics after cyclic deformation (Araujo-Morera et al., 2019). All approaches to achieve self-healing ability are of great interest for tire development, which is in some instances mentioned explicitly within the publications, but more detailed information on the impact on tire wear is not offered.

3.1.8.3. Improvement of tire aging resistance. In the long term, the improvement of the tire aging resistance can also be attributed to the increase in abrasion resistance, for which additives are usually added to the rubber compound (Baldwin and Bauer, 2008). These are intended to prevent or at least slow down the various aging processes occurring on the tire, e.g., due to UV light, moisture, oxidation by ambient oxygen (Praticò and Briante, 2020) and ozone (Osswald et al., 2019), or biological degradation (Wagner et al., 2022). Three approaches exist to protect tire rubber from ozone: the addition of waxes that form a protective layer on the tire rubber, the addition of highly-saturated rubber, and the use of chemical antiozonants (Osswald et al., 2019). Cataldo (2019) describes how the antiozonants PPDs protect the rubber from reacting with ozone. Additionally, thermo-oxidation due to elevated temperature results in either chain scission or additional crosslinking in rubber material (Baldwin and Bauer, 2008). Chain scission may lead to exposure of the underlying filler material, which increases surface wettability and causes surface cracking (Tomer et al., 2007). To prevent thermo-oxidation, other additives called antioxidants can be added to the tire.

Photooxidation is also regarded as a possible degradation path of TRWP (Baensch-Baltruschat et al., 2021). UV radiation leads to rubber degradation, which increases the material's brittleness due to further crosslinking (Ossola and Wojcik, 2014). To avoid photooxidation, further protective agents can be added to the material, analogous to the avoidance of ozonation and thermo-oxidation (Wagner et al., 2022).

Aboelkheir et al. (2019) claim that certain types of bacteria can cause the biodegradation of rubber material, which results in bio-devulcanization or bio-desulphurization of the vulcanized rubber polymer chains. This leads to depolymerization, and low-molecular weight compounds are formed on the surface. As a result, the hydrophilicity of the material increases (Aboelkheir et al., 2019), which can affect aging resistance. The biological aging due to microbial activities can be mitigated by increasing filler content such as carbon black (Tsuchii et al., 1990). However, conflicts may arise as the increasing environmental concern focuses on the sustainability of the life cycle of tires. Thus, it is rather claimed that tire composition should be altered to improve the biodegradability of rubber materials (Stevenson et al., 2008).

3.1.8.4. Reduction of rolling resistance. In addition to increasing abrasion resistance, a goal of the tire industry is to reduce rolling resistance. The use of silica instead of carbon black provides advantages in this respect (Krömer et al., 1999) and can also improve wet grip (Martin et al., 2015). According to the study by Shoul et al. (2022), using silica can reduce rolling resistance by 20 to 30 %, which has a corresponding impact on the emission of greenhouse gases. Conventional silica could additionally be replaced by green silica.

Further on, rolling resistance is strongly affected by the loss of tire inflation pressure. By dispersing nanoclay in rubber, permeability through the tire's inner liner can be reduced, which is not possible with conventional systems using halobutylrubber (OECD, 2014). Plate-like structure of nanoclays increases path tortuosity and reduces air loss, thus inhibiting the increase in rolling resistance (Thuruthil Raju et al., 2020).

3.1.9. Elimination of vent spews

Some tires have production residues when brand new, leading to increased material loss during the first kilometers driven and thus to an unnecessary hazard to the environment. The thin rubber threads or pins, also called “vent spews” have no technical significance and therefore do not contribute to driving performance or safety (ADAC e. V., 2022; Silvestro and Gielen, 2018).

A simple measure to reduce the introduction of rubber particles into the environment is therefore directed at tire manufacturers, who should either plan their production process in a manner that residues on tires do not occur in the first place or remove them in an additional step of production before the delivery to customers (ADAC e. V., 2022). This removal could be implemented quickly and provides a cost-effective measure to prevent the emission of tire rubber. Another possibility to avoid these residues would be the ban on the delivery or sale of tires containing vent spews so that tire manufacturers would be forced to comply with these rules. Information on the mass of these production residues, as well as on the proportion of tires currently affected, could not be found in the literature.

3.1.10. Limiting tire mass loss

Policy makers have already deliberated on regulations such as the introduction of a legal limit on how much abrasion a tire is allowed to generate per distance traveled (Buzzi, 2020) or adopting a legal threshold value for tire wear (Furuseth and Rødland, 2020; Praticò and Briante, 2020; Verschoor and De Valk, 2018). However, due to safety reasons, experts doubt the technical feasibility of this measure. Furthermore, no standardized measurement method is available so far

(Furuseth and Rødland, 2020) to set a limit value for tire wear to which all stakeholders agree. Therefore, proactively developing low-abrasion tires and promoting their use through economic incentives appears more effective than legal limits.

3.1.11. Labeling of tires

Since 2021, the EU has required new car tires to be labeled, with tire manufacturers providing information on fuel efficiency, wet grip, and noise emissions. Many authors (Boni, 2018; European TRWP Platform, 2020; Praticò and Briante, 2020; Verschoor and De Valk, 2018) recommend that the abrasion performance of tires should also be stated on the label. Already in 2018, the European Parliament proposed to add minimum mileage and abrasion performance specifications (Boni, 2018). Verschoor and De Valk (2018) recommend a label with a tire abrasion indicator, Furuseth and Rødland (2020) the inclusion of wear rates for tires, Praticò and Briante (2020) the specification of factors for tire abrasion, Johannesson and Lithner (2022) demand eco-labeling (e.g., colored icons) regarding the wear propensity of tires. To motivate consumers to prefer the use of less-wearing, ecological tires the appeal "reduce microplastics" should be added to the labeling system for tires. In this way, the driver would put more attention to the TRWP issue, and at the same time, the tire industry would be motivated to introduce more wear-resistant tires to the market.

In addition to the abrasion performance of a tire, the label might also indicate its environmental impact. Wik and Dave (2009) recommend using toxicity testing according to ISO 6341 as a key performance indicator. The consequence if tires do not meet the limitations towards environmental impact and wear resistance might be a ban of those. Internationally valid and binding labeling is essential. The content and design of the label should be uniform. To reach this aim, a global standard could be the goal for the tire label. This would increase transparency and comparability of quality and environmental compatibility of tires.

3.1.12. Economic measures

In addition to educational and regulatory measures, governments and their authorities can also take economic measures to reduce TRWP. Higher costs for driving (Johannessen et al., 2022) have a regulating effect. Economic instruments like pricing, taxation, fees, or subsidies (Baensch-Baltruschat et al., 2020; Verschoor et al., 2016; Winquist et al., 2021) set economic incentives.

Verschoor et al. (2016) name taxation as a suitable monetary measure to reduce TRWP. There are several types of taxations to decrease emissions: carbon dioxide tax, congestion tax, kilometer tax, pollution tax, traveled distance tax, tax on vehicle weight, a higher fuel tax, or general taxation on vehicles (Kupiainen et al., 2017; Fussell et al., 2022; Johannessen et al., 2022; Piscitello et al., 2021; Denier van der Gon and Cassee, 2012; Elmgren et al., 2017). Winquist et al. (2021) recommend contrary to taxes subsidies for the use of eco tires. Sundt et al. (2016) propose a differentiated tax system for cars to encourage eco-driving, besides economic incentives to decrease private car use in cities, and incentives for lightweight and low-power engines. In addition, incentives should also be introduced for the use of combined intermodal traffic (Baensch-Baltruschat et al., 2020), for fuel-efficient tires (Boni, 2018) and for sustainable driving behavior (ETRMA, 2020). Fussell et al. (2022) propose financial incentives for low-wear brake materials - this idea could be adopted for tire materials.

Legal instruments such as taxation are intended to motivate people to reduce their emissions. The implementation of some measures means higher costs for vehicle owners. Therefore, the social balance must be considered when implementing economic measures. To increase the acceptance of economic measures, the revenues could be used to improve street cleaning or public transport, accompanied by persuasion and education.

3.1.13. Increasing general awareness of TRWP

The impact of tire wear on the environment and especially the possibilities to reduce tire wear are not widely discussed among the public. It is, therefore, an urgent task to raise public awareness of TRWP involving all stakeholders (ADAC e. V., 2022; Baensch-Baltruschat et al., 2020; European TRWP Platform, 2019; Hainschink, 2022; Patil et al., 2021; Sundt et al., 2016; Verschoor et al., 2016; Faino, 2018). Especially manufacturers and politicians should be aware of their responsibility and give the issue of tire wear a higher priority (ADAC e. V., 2022; Kole et al., 2015) e.g., by launching awareness and information campaigns for the public (Verschoor et al., 2016; ADAC e. V., 2022; European TRWP Platform, 2019; Hainschink, 2022; Sundt et al., 2016). Aspects that could be included in such campaigns are for example using modes of transport that emit less TRWP, promoting public transport, vehicle maintenance, the positive effect of a proper driving style, the negative environmental impact of heavy cars in terms of TRWP (European TRWP Platform, 2020; Hainschink, 2022; Kupiainen et al., 2017; Winquist et al., 2021). Smart vehicle models which inform, teach, or help motorists while driving to develop a driving style that reduces TRWP emissions are also an opportunity to support awareness. Training courses on low-emission driving or eco-driving with education and guidance on the driving style are also possible (European TRWP Platform, 2019; Johannesson and Lithner, 2022).Raising awareness on the topic of TRWP can have a strong impact because it helps other mitigation measures to gain more attention and can lead to more sustainable driving behavior.

3.1.14. Improvement of communication between stakeholders

In order to reduce TRWP, measures need to be taken in different areas which are interrelated. These areas are represented by different stakeholders including the automotive industry, tire and road manufacturers, policymakers, authorities, and society. Communication among these stakeholders helps to coordinate the different and interrelated actions to mitigate TRWP. For example, tire manufacturers need to adapt tire design, traffic infrastructure needs to be improved, vehicles need to become smarter, drivers need to change their driving behavior, and legislators need to set limits.

WDK (2019) recommends a dialogue between tire manufacturers, the automotive industry, EU institutions, national authorities, NGOs, the water sector, mobility associations, and research institutions. Suitable communication formats include conferences, discussion and information forums, and workshops. To achieve broad acceptance, the public, science, and environmental organizations should be involved. For specific topics such as electromobility, it is advisable to launch bilateral discussion formats (European TRWP Platform, 2019). Not only communication but also networking between stakeholders needs to be stimulated (Denier van der Gon and Cassee, 2012). Communication, networking, and cooperation between stakeholders are essential to implement international strategies against TRWP.

3.1.15. Optimization of traffic management

There is a variety of measures to reduce traffic volume and improve traffic flow, which can be grouped under the term traffic management. The steadily growing number of vehicles leads to more associated transportation infrastructure and traffic volume. Consequently the slowly-moving traffic and congestions as well as vehicle emissions increase (Amato et al., 2013). The latter not only applies to greenhouse gas emissions but also to non-exhaust emissions such as tire, brake, and road wear. Amato et al. (2009), Hicks et al. (2021) and Panko et al. (2018) cite road traffic as a major source of PM_{10}. Traffic, and therefore emissions, are expected to increase by about 30 % by 2030 if no traffic-reducing measures are taken (Sundt et al., 2016). Reducing traffic volume means reducing emissions from traffic (Fussell et al., 2022; World Business Council for Sustainable Development, 2020). Halving the number of vehicles on the road results in halving the emissions. The goal is to reduce traffic volumes, especially private transport (Gable et al., 2022; Gabbe et al., 2019), while simultaneously improving traffic flow (Stojanovic et al., 2021; Sundt et al., 2016; Denier van der Gon and Cassee, 2012).

Autonomous vehicles can help improve the traffic flow through driver assistance systems (Furuseth and Rødland, 2020). Verschoor et al. (2016) suggest to optimize vehicle use by reducing vehicle kilometers. Fussell et al. (2022) and Johannesson and Lithner (2022) recommend taxing kilometers driven. Piscitello et al. (2021) demand stronger taxation of fuel and vehicles themselves. Sundt et al. (2016) see urban and traffic planning as possible solutions. Johannessen et al. (2022) suggest improving infrastructure for pedestrians and cyclists. Improved traffic flow plays an important role, especially in cities, where traffic lights or stop-and-go traffic cause a lot of TRWP (Köllner, 2021). Traffic flow can be optimized through traffic control measures and improved traffic regulation (Düring et al., 2010; European TRWP Platform, 2019; Sonwani and Shukla, 2022).

Traffic management also includes the promotion of public transport. The use of public transport reduces the volume of traffic and thus TRWP (Gieré and Dietze, 2022). This includes investing in and improving public transport infrastructure (Sonwani and Shukla, 2022; Barr et al., 2021; Denier van der Gon and Cassee, 2012; Piscitello et al., 2021). Extensive, well-functioning, and modern public transportation systems are needed. Complementing this, more bike lanes and sidewalks, car-sharing systems, and community carpooling make public transportation more attractive (Hainschink, 2022; Johannessen et al., 2022; Sonwani and Shukla, 2022; Vogelsang et al., 2020). Increased use of public transport additionally saves CO_2 emissions.

3.1.16. Emission factors for TRWP

Traffic emissions can be estimated using emission factors (EFs). There are different EFs for urban, rural, and highway driving, and different road types (Geilenkirchen et al., 2021). EFs are emission values and indicate the amount of particulate matter, as the number of particles or mass, per vehicle kilometer driven. There are EFs for road surfaces, vehicle types, road markings, or vehicle brakes. They are usually expressed in milligrams per vehicle kilometer (mg/vkm). The particle sources are tire abrasion, brake abrasion, or road abrasion. The latter includes abrasion from road markings. Added to this is atmospheric dust deposited on the road.

Fig. 2 shows a range of EFs measured for several broad categories of road vehicles. Comparing the data taken from several references reveals remarkably similar EFs for passenger vehicles, whereas heavier vehicles have a much broader range of reported EFs. Between passenger vehicles and heavy trucks, there is approximately a factor of 10 regarding the expected emission rates. Overall, the general trend shows clearly that with increasing vehicle mass more TRWP are emitted per distance traveled.

To estimate the amount of TRWP, it is useful to introduce EFs. They help to estimate, quantify, and reduce TRWP emissions (AIRUSE, 2013). Different countries work with different EFs (Dröge and Hulskotte, 2018). Mathissen et al. (2012) determined EFs for different road surfaces, with values sometimes differing by a factor of 1000. Baensch-Baltruschat et al. (2021) therefore recommend harmonizing EFs by determining EFs for different road types, road surfaces, and vehicles.

EFs for vehicles, tires, and road types must be determined experimentally. Experiments to determine EFs must also take into account external influences such as atmospheric conditions, precipitation, or road moisture, as they have a major impact on particle generation (Amato et al., 2010). One result of experiments was that EFs depended more on vehicle speed than on the type of tires and road surface (Dahl et al., 2006). Season, location, and traffic volume also have an influence: EFs are higher in winter than in summer, lower in rural (highways) than in urban areas (Amato et al., 2013), and higher on slow roads than on fast roads (Etyemezian et al., 2003). EFs can be stored in databases and provided to the general public (Gable et al., 2022). More research is needed on the EFs of EVs (Prenner et al., 2021) and the influence of vehicle weight on EFs (Timmers and Achten, 2016). EFs can be used to derive limits that all vehicles must comply with (Timmers and Achten, 2016). The determination of EFs is a complex measure to reduce TRWP. Four things need to be considered: (1) EFs need to become more accurate, (2) EFs need to fully capture the transportation system, (3) knowledge gaps need to be filled, and (4) EFs need to be made available for sharing.

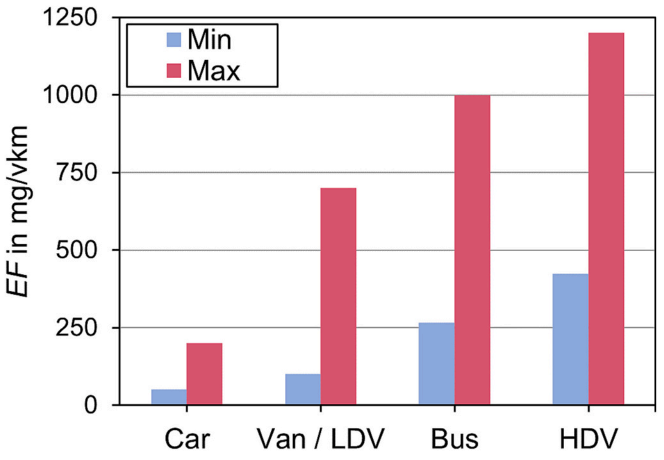

Fig. 2. Range of emission factors for vehicles in milligrams per vehicle kilometer (mg/vkm) LDV and HDV refer to light-duty vehicles and heavy-duty vehicles, respectively.

(Figure is based on data from Gustafsson (2002); Verschoor et al. (2016); Lee et al. (2020); UNECE (2013); Hillenbrand et al. (2005); Gebbe and Hartung (1997); Grigoratos et al. (2018); Prenner et al. (2021).)

3.2. TRWP mitigation measures at the vehicle and the road surface

The following section comprises four mitigation measures including technological devices to capture TRWP at the vehicle, road pavement as a trap for TRWP, as well as street cleaning and dust binding to remove TRWP.

3.2.1. Collection devices at the vehicle

Assuming that tire abrasion cannot be avoided, the best option is to collect generated particles directly at the vehicle and prevent them from entering the environment. Three approaches have been found in the literature. The first one aims to capture particles using a directed airflow through the wheel arch. By installing aerodynamic baffles, it can be guided through a filter behind the wheel arch, where particles are separated (Dong et al., 2021). Enclosing the wheel arch is likely to enhance the efficiency of particle collection by minimizing their potential pathways (Boulter et al., 2006). The ZEDU-1 project (DLR, 2021) of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt – DLR) aims to develop a prototypical vehicle following this approach. According to the project objective, this should reduce tire abrasion entering the environment by up to 90 %. An additional advantage of a directed airflow through the wheel arch derives from the cooling effect on the tire (Piscitello et al., 2021). Numerous authors report increased tire abrasion for higher surface temperatures (OECD, 2021; Pohrt, 2019; Vogelsang et al., 2020), however, the information on the effect of tire temperature on TRWP generation is contradictory. While Piscitello et al. (2021) give a 4.6 % reduction in TRWP at a 2 to 3 °C lower tire temperature, Sjödin et al. (2010) indicate an opposite trend for the winter tires in their study. According to their experiments, the particulate matter emission of winter tires decreases with increasing tire temperature, while it increases for summer tires.

The second approach consists of a filter that is mounted on the rooftop or underbody of a vehicle, where particle concentrations are high due to resuspension. The filter captures particles, both freshly formed and resuspended, ensuring that resuspension cannot occur again. Since the filter works solely with the flow created by the airstream, it does not require any additional drive (Schulz, 2019; Streuff et al., 2022). Alternatively, an active system using a fan in combination with the particle filter can filtrate high volume flows and operate even if the vehicle is not moving. This method is particularly efficient if the particle filter is combined with the vehicle's induced draft fan, which is installed in the front area. The mitigation performance depends on the ambient PM concentration. The larger the particle concentration the higher the reduction performance. Whereas at a PM_{10} concentration of 25 μg/m^3 (annual mean value in Stuttgart, Germany) half as much PM can be filtered as emitted by the vehicle itself, the ratio is around 2 for a PM_{10} concentration of 104 μg/m^3 (annual mean value in Peking, China) (Streuff et al., 2022).

The third approach uses electrostatic attraction for particle collection. Due to friction processes between tire and road, emitted particles are electrostatically charged and can be separated from the volume flow using an electrostatic separator. This technology can be applied by collecting behind the wheel. According to Hatton (2021), a reduction of up to 60 % of emitted particles can be achieved for the airborne fraction.

The approaches described are promising, but most of them have not yet reached the production stage and therefore need to be further developed requiring high investments. The main difficulty is adapting the systems to a wide variety of vehicles and traffic situations. For these reasons, the mitigation measure should rather be regarded as long-term. In the short term, only the use of fine dust filters in conjunction with the existing blowers could be implemented in vehicles, so further studies should be carried out to get a better understanding of the efficiency of such systems. However, with all new developments and extensions side effects must be considered. For example, an increased cooling of the tire using a modified wheel housing may reduce abrasion but could increase rolling resistance (Greiner, 2019) and thus energy consumption.

3.2.2. *Road surface as a trap for TRWP*

TRWP are created and accumulated on the road surface before the particles spread to the environment via different pathways (Verschoor et al., 2016). In general, coarser, more porous pavements increase the generation of PM_{10} (Grigoratos and Martini, 2014). However, these pavements can also act as a sink for road dust including TRWP since coarse particles on the road surface are partly trapped in the pores of the pavement (Kole et al., 2017; TRL Limited, 2002). Kole et al. (2017) figured out that in very-open asphalted concrete, which usually has a hollow space volume of 15 to 25 %, 95 % of tire wear is captured. In the Netherlands, a layer of open-graded asphalt on motorways is already widely implemented and seems to be very promising (Geilenkirchen et al., 2021; Gieré and Dietze, 2022). Verschoor et al. (2016) state that approximately 40 % of all the TWP in the Netherlands are retained in open asphalted concrete. Vieira et al. (2019) measured a reduction of 52 % of PM_{10} close to a double-layered porous asphalt road compared to measurements with non-porous stone mastic asphalt. However, this pavement is more susceptible to frost damage and abrasion. The latter mainly occurs in urban areas due to frequent braking and acceleration and through the use of studded tires (Verschoor et al., 2016; Barr et al., 2021; Lundberg et al., 2020). Thus, porous pavement is mainly applied in countries with moderate-Mediterranean climates like the Netherlands, hardly in Nordic or alpine countries, and usually not in urban regions (Kole et al., 2015; Verschoor et al., 2016).

To control the TRWP emission porous pavement needs strict maintenance concepts. Kole et al. (2017) state that the very-open asphalt needs to be cleaned twice a year to maintain its draining, noise-reducing, and trapping capacities (Geilenkirchen et al., 2021; Amato, 2018).

Porous asphalt has a multi-use effect: the water on the road surface is quickly transported into the pores improving the water drainage from the surface (Amato, 2018). Driving noise and road dust are reduced (Lundberg et al., 2020; Gehrig et al., 2010). Metals adsorbed to or forming part of the trapped particles are retained in the matrix of the road structure as well (Geilenkirchen et al., 2021).

An option that reduces both tire wear and noise emissions is the use of shredded scrap tires or grinded tires as filling material in road construction which is proposed by Piscitello et al. (2021), Buzzi (2020), Bressi et al. (2019), and Frolova et al. (2016). They indicate a 30 to 50 % reduction in tire wear, increased pavement abrasion resistance, and higher road durability. Allen and Kaloush (2006) studied the addition of ground tire rubber to polymer binders. The rubber-modified asphalt showed a 50 % reduction in TRWP generation compared to concrete (Allen and Kaloush, 2006).

Replacing current pavements is a long and cost-intensive process, which makes this mitigation measure a long-term process (Verschoor et al., 2016). As an example, installing porous pavements on 95 % of the motorways in the Netherlands took about 35 years (Verschoor et al., 2016).

3.2.3. *Street cleaning*

Street cleaning can contribute to removing particles deposited on the roads and prevent them from dispersing further into the environment (OECD, 2021). Small particles are usually resuspended to a lesser degree than larger particles, as they are trapped more easily in the microstructure of the road surface (Vogelsang et al., 2020).

The criteria for the selection of street cleaning are the efficiency of sediment dust removal, air quality improvement in the vicinity of the road by reducing ambient PM_{10} and $PM_{2.5}$ levels, and stormwater quality. Many factors influence the efficiency of road cleaning, such as frequency, equipment choice, speed of the machine, the rotational speed and angle of the brushes, as well as its inclination and design, the condition and structure of the road surface, the number of passes, road condition, sanding or salting of the road, car parking, presence of construction/demolition works, unpaved areas, accumulation curve, and sediment size distribution which significantly affect the cleaning efficiencies (AIRUSE, 2013; Järlskog et al., 2017; Snilsberg et al., 2018; Abdel-Wahab et al., 2011; Vanegas-Useche et al., 2015; Vogelsang et al., 2020).

Different authors report that street cleaning devices, especially mechanical sweepers are more effective in removing coarser particles (> 100 to 125 μm) and have limited effects on smaller or airborne particles, whereas vacuum- and regenerative air sweepers perform better at removing finer sediments (AIRUSE, 2013; Amato et al., 2013; Vogelsang et al., 2020; OECD, 2021). Some studies report increased or no significant decrease in PM_{10} and $PM_{2.5}$ levels short-term after sweeping and vacuum street cleaning (Gertler et al., 2006; Norman and Johansson, 2006; Bogacki et al., 2018; Baumbach et al., 2007). For example, $PM_{2.5}$ levels increased from 133 to 211 mg/km after sweeping (Gertler et al., 2006).

By characterizing the size distribution in the wash water of the sweeper using dynamic light scattering, Polukarova et al. (2020) recently showed that sweepers (vacuum type produced by Johnston Beam) can sweep up smaller particles including micro and nanoparticles. Selbig (2016) showed a reduction in the mean total concentration of suspended solids in the gutters of a street swept by a mechanical sweeper by 74 % and a vacuum sweeper by 85 %.

Schilling (2005) reports that street sweeping is most effective when implemented monthly, bi-weekly, or weekly. Järlskog et al. (2020) conclude that weekly sweeping can prevent further transport of tire and bitumen microplastic particles into the receiving waters. It may also be cost-effective to prioritize street sweeping for highly-frequented roads, that are not connected to the sewer. Sweeping only at the hot spots, like main roads as well as intersections are presented in the case study “Research Project RAU-TWP in the environment” using in-situ trails and a precipitation-runoff model. Compared to the baseline scenario of cleaning all roads in the test area once per week, the 3-fold cleaning of either only the main roads or only the intersections reduce the tire abrasion input into the sewer by 42 and 36 %, respectively (Venghaus et al., 2021).

Precipitation and moisture also influence cleaning efficiency (Vaze and Chiew, 2002; Abdel-Wahab et al., 2011; Snilsberg et al., 2018). The use of water during sweeping to reduce dust resuspension is suggested by many authors (Busse et al., 2020; Magnusson, 2019; Amato et al., 2010; Fussell et al., 2022; Järlskog et al., 2017; Kryłów and Generowicz, 2019). Zhang et al. (2021) conclude that water sprinkling is a temporary measure to reduce the PM concentration in the road environment. Ang et al. (2008) combined a modified mechanical broom and water flushing in Stuttgart and achieved efficiencies of 60 to 80 % for reducing the dust load lasting over one rush hour depending on the particle size. Gieré and Dietze (2022) suggest a combination of sweeping and rinsing at hotspots to avoid further fragmentation of TRWP deposited on the road caused by vehicle-driving movements.

TRWP concentrations of up to 204 mg/g in tunnel dust are reported by Bank (2022) and therefore tunnel wash water should be cleaned before the release into surface waters. Considering that the street washing alone does not mitigate TRWP but moves it into the road runoff, it may be combined with road runoff treatment.

Street cleaning management needs to be flexible for specific local conditions such as weather, and season variability (Andersson-Sköld et al., 2020; ETRMA, 2018). Neupert et al. (2021) suggest a digitally adapted municipal street cleaning with intelligent networking of different city districts. Sweeping timing should also be adjusted in accordance with the parking activities of vehicles on the roadside to minimize interference (Pitt, 1979).

Additionally, the efficiency of street cleaning depends on the road surface macro texture and maintenance state. A smooth surface is simpler to clean than a rough surface with ruts and damages and porous asphalt (Kupiainen et al., 2017; OECD, 2021).

Pollutants can accumulate in snow and enter the environment when the snow melts, but there is currently no data available on the concentration of TRWP in the snow (Andersson-Sköld et al., 2020). Snow is removed via trucks, and then dumped into water bodies or stored in snow deposits. In Oslo, snow is treated in a snow-melting plant before it is discharged (NIVA, 2018). “An urban snow-melting and filtering technology by Clewat Ltd. is in the piloting stage in Finland” (CleWat LTD, 2022). A ban on direct disposal of snow into waterbodies could be implemented, as is the case in parts of Sweden (Andersson-Sköld et al., 2020; Kole et al., 2017).

It is recommended that local authorities comply with the following steps before planning street cleaning: firstly, evaluate the magnitude of the problem for a single street; secondly, select the streets which are critical for the dust load situation; thirdly, know the accumulation rate of sediments; and lastly, determine the most effective cleaning criteria such as frequency and timing (Amato et al., 2010).

Street cleaning is a non-structural measure and can reduce the need for later treatment of road runoff (Järlskog et al., 2020). Continuous and effective cleaning mitigates the build-up of road dust load on the street and its subsequent resuspension as well (Kupiainen et al., 2017). Street sweeping does not require additional infrastructure, however, the collected dust and debris require safe disposal after collection (OECD, 2021).

3.2.4. *Dust binding*

Dust binders do not remove particles from the environment but stop further dispersion or resuspension by increasing the mass, moisture, and aggregation of deposited particles (Andersson-Sköld et al., 2020; Amato et al., 2014). They are classified in five categories according to their chemical composition and the suppressant mechanism: salts, polymers, surfactants, resins, and bituminous products (Amato et al., 2010; Watson et al., 1996). There is a variety of different dust suppressants available most commonly calcium-magnesium acetate (CMA) and chloride salts (Boulter et al., 2007). Denier van der Gon and Cassee (2012) observed that traditional street cleaning machines in combination with dust binding are more beneficial in reducing PM_{10} than street cleaning alone.

Regional differences are relevant as dust binders are less effective in warmer climates. A case study by Amato et al. (2014) showed no statistically significant reduction in ambient PM concentrations with CMA and $MgCl_2$ in a Mediterranean city (Barcelona). Road washing with large amounts of water reduces the curbside PM_{10} concentration more effectively (∼18 %) than a dust binder(∼8 %) (Amato et al., 2016). Gustafsson et al. (2019a) trace this to the rapid drying of the chemicals. However, at a site in Germany Leiber et al. (2012) did also not find a reduction of PM_{10} and $PM_{2.5}$ within the process-related uncertainties by the use of CMA.

In colder climates, authors found binders to be especially effective with reduction potentials ranging from 35 to 43 % for CMA, $MgCl_2$, $CaCl_{2,}$ and sugar solutions on PM_{10} levels (Hafner, 2007; Gustafsson et al., 2010; Norman and Johansson, 2006; Berthelsen, 2003). Kupiainen et al. (2017) report that under Nordic conditions, dust binding with hygroscopic solutions has been demonstrated to be the most-efficient short-term method for reducing PM_{10} suspension emissions. PM_{10} reductions with CMA and $MgCl_2$ in tunnels have also been reported (Værnes, 2003; Tønnesen, 2006; Aldrin et al., 2008).

The dust binder effect lasts very short-term and depends on meteorology, traffic intensity, temperature, and humidity (Denier van der Gon and Cassee, 2012; Fussell et al., 2022). They need to be applied regularly for a continuous effect. Johannesson and Lithner (2022) state that dust binders are expensive and give an example of the city of Stockholm, which spent around 4 million euros on dust binders annually on approximately 30 streets between 2013 and 2015. Johannesson and Lithner (2022) also note, that instead of a fixed schedule dust binders should be applied when needed. The risk of creating an impervious surface must be considered when choosing a sufficient amount to spray on the street, to ensure driver safety (Barlow, 2014).

Some dust suppressants are harmful to the environment (Barlow, 2014). However, magnesium chloride and calcium chloride are corrosive and harm vegetation, groundwater, and surface water (Gustafsson et al., 2010). CMA is less corrosive, however, the degradation of higher CMA concentrations may cause oxygen deficiency in aquatic environments (Gustafsson et al., 2010).

3.3. *TRWP mitigation measures on atmosphere and road runoff*

The following section comprises six mitigation measures to prevent TRWP from entering the natural environment including mitigation measures to capture airborne TRWP by vegetation and abatement actions to remove TRWP from road runoff by decentralized and semi-centralized treatment as well as centralized wastewater treatment plants.

3.3.1. *Treatment of airborne TRWP*

Particularly in cities, fine dust is a health problem and the concentrations of $PM_{2.5}$ and PM_{10} occasionally exceed the legal limits. Nevertheless, only a few studies deal with mitigation measures to remove suspended TRWP from the air. These studies investigate the planting of vegetation and peeling of the verge.

3.3.1.1. Planting of vegetation. It is well known, that vegetation plays an important role in trapping gaseous and particulate pollution from the atmosphere (Sonwani and Shukla, 2022). The accumulation of PM differs for different plant parts and tree species (Xu et al., 2019; Sonwani and Shukla, 2022; Fuller et al., 2009). Many influencing factors are described by Fuller et al. (2009) such as plant foliar and canopy characteristics, particle size, concentration, deposition velocity, wind speed, etc.

Janhäll (2015) found that key factors for the ability of vegetation to improve air quality are their density and porosity. Low vegetation placed close to air pollution sources should be dense to provide a large surface area to enable deposition. Besides that, it should be porous to allow a sufficient airstream to penetrate the hedge. The vegetation is most efficient when it captures the full height of the plume and should be placed close to the source because the concentration of the pollutants increases with proximity to the source (Janhäll, 2015).

One option is adding trees to the sidewalk on trafficked streets. Maher et al. (2013) found that silver birch trees planted at a city block in Lancaster City in the UK have adsorbed as much as 50 % of PM generated by vehicles. “Studies conducted in the UK reported that planting trees on one-fourth of the available urban area can reduce PM_{10} concentrations by 2 to 10 %” (McDonald et al., 2007). Tiwary et al. (2006) studied the particle collection efficiency of three-hedgerow species for the particle size range of 0.5 to 20 μm. The hawthorn hedge turned out most efficient, but on a low level. The efficiency for particles from 2.75 to 6.25 μm is only 0.75 to 5.8 %. Ozdemir (2019) found, that the most-effective arrangement of Mediterranean Cypress trees in a thick line with no gaps decreased the $PM_{2.5}$ concentration to 28.81 $\mu g/m^3$ compared to 35.54 $\mu g/m^3$ with no trees. Gourdji (2018) figured out that larger vegetation on roofs such as shrubs, trees, and intensive green roofs remove air pollutants to a large extent. Gourdji (2018) mentions that the resistance of vegetation to environmental conditions such as drought is a major parameter for the appropriate selection of plants. The deciduous character of some vegetation also significantly reduces the efficiency of particle collection. Furthermore, sufficient roadside space must be available in urban areas (Boulter et al., 2007). Summarizing, vegetation has multiple positive impacts on our ecosystem: retention and storage of rain water, providing scenic public landscape, and cooling in addition to the filtration of airborne PM (Janhäll, 2015).

3.3.1.2. Verge peeling. The verge next to the street accumulates road dirt and vegetation grows there. The vegetation is milled of every 3 to 6 years and mostly deposited next to the verge or disposed in individual cases. Since a major portion of TRWP remain close to the source, it is assumed that tire wear can be found on the green verge next to the street. Therefore, tire wear is located in the so-called verge peeling and should not enter the water or soil body via percolation with the verges at the side of the road (Busse et al., 2020). Busse et al. (2020) suggest a standardized handling across Germany by the legislator for the disposal of verge peeling. This can be transferred to any country.

3.3.2. Treatment of road runoff

The majority of TRWP remain on the roadway or in the near surroundings until the particles are washed off by rainwater or removed by street cleaning. According to Arias et al. (2022) highway runoff sediments show up to 480 mg_{TRWP}/g sediment. Thus, road runoff is the major entry path of TRWP into the aquatic and terrestrial environment.

Usually, in urban areas, the road runoff flows through a combined sewer system into WWTPs or – in the case of a separated sewer system – is directly discharged into the adjacent water bodies, mostly without any further treatment. To relieve the sewer systems and minimize combined sewer overflow[1] events, decentralized and semi-centralized on-site treatment systems are often implemented on or nearby roads (Vogelsang et al., 2020). Regular maintenance of these systems is a key parameter to ensure their efficiency (Buzzi, 2020). The garbage collection service can help to develop a proper maintenance plan, as they regularly drive the streets and could provide information on the condition of the drainage systems, stormwater sedimentation ponds, and wetlands, which can become a water quality issue without proper maintenance (Buzzi, 2020).

In densely-populated urban areas, the installation of separate rainwater drainage infrastructure is challenging. If climate change will cause more extreme weather events, drainage systems have to be rethought (Neupert et al., 2021). Kabisch et al. (2020) suggest a more holistic approach where the less contaminated road runoff is decoupled from the central sewage system and directed into urban green areas and retention basins which – if space can be provided – contribute to a green/blue city infrastructure.

Outside of cities, stormwater from roads is usually drained openly, e. g., over the verge, and infiltrated into swales or the natural ground. Vogelsang et al. (2020) report removal rates of up to 70 % of TSS based on a study from Amundsen and Roseth (2004) depending on the kind of soil and vegetation.

The present study differentiates decentralized road runoff treatment/point of use solutions, semi-centralized road runoff treatment, and centralized road runoff treatment (WWTP).

3.3.2.1. Decentralized road runoff treatment. Common technical approaches to retain road runoff and treat it near the source of emission include on-site management e.g., using different local solutions and natural processes, such as green roofs, rain barrels, infiltration in ditches, gullies, and bio-retention filters (also known as rain gardens) (Tedoldi et al., 2017; Eckart et al., 2017; Funai and Kupec, 2017; Andersson-Sköld et al., 2020). These point-of- use solutions take up fewer land area than stormwater ponds, are often the most cost-effective, and are easy to monitor, especially in rural areas (Buzzi, 2020). Common decentralized technologies to reduce TRWP are described in this section.

3.3.2.1.1. Roadside gully pots. Roadside gully pots are small retention basins embedded in the ground with diameters around one meter and a volume of retention of about 0.8 m^3, with a certain distance in between to retain solids in storm runoff from urban roads. They are directly connected to the urban sewage system to reduce the overall hydraulic load during heavy rainfall events (Gieré and Dietze, 2022). Some gullies are equipped with particle traps (Bank, 2022). To maintain adequate retention they have to be emptied regularly (Buzzi, 2020) not exceeding a filling level of >50 % (Lindholm, 2015; Mosevoll and Lindholm, 1986).

A schematic illustration of a roadside gully is shown in Fig. 3.

The retention efficiency of gully pots for solid particles ranges from 20 to 50 % according to field tests. It highly depends on the flow velocity of the rainwater (Pitt and Field, 2004; Deletic, 2000). The faster the rainwater flows, the shorter is the time for the particles to settle. Especially particles with smaller diameter cannot be retained in gully pots to a significant degree as they already settle more slowly than the larger ones. At lower rainfall (5 L/s), particles <80 μm are hardly trapped (Vogelsang et al., 2020; Furuseth and Rødland, 2020). The particle fraction with a diameter of 80 to 250 μm can be rejected in common gully pots by about 20 % during normal rainfall events (15 L/s), and approximately by 8 % at a higher rainfall velocity of 25 L/s (Vogelsang et al., 2020). Since TRWP sizes in road runoff range between 6 and 649 μm with an average of 158 μm by number (Kovochich et al., 2021a), it can be concluded that during normal rainfall a remarkable fraction of TRWP can be captured at gully pots. However, the completely smaller and more mobile fraction with a high surface-to-volume relation (more area for the adsorption of contaminants) gets unobstructed into the aquatic environment.

Within field tests at the Panke River in Berlin, Venghaus et al. (2021) figured out that decentralized filtration units have a removal rate of 50 %. Based on these empirical data and assuming that urban hotspots such as junctions and main streets are equipped with roadside gullies and/or swales (see next section), they calculate a possible decrease of the TRWP concentration in the Panke River by 32 %. In combination with intense street cleaning, they even calculate a removal rate of 58 to 71 % (Brook-Jones, 2022).

3.3.2.1.2. Subsurface treatment units. There exists a large variety of subsurface treatment units which are designed to remove TSS from stormwater and deliver pre-treatment quality water or final water quality for direct discharge to the local aquatic recipient. They can be

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[1] Combined Sewer Overflow (CSO) can happen during heavy rainfall when the inlet volume flow exceeds the maximum hydraulic load of a WWTP and a part of the wastewater volume is discharged into the receiving water without any further treatment.

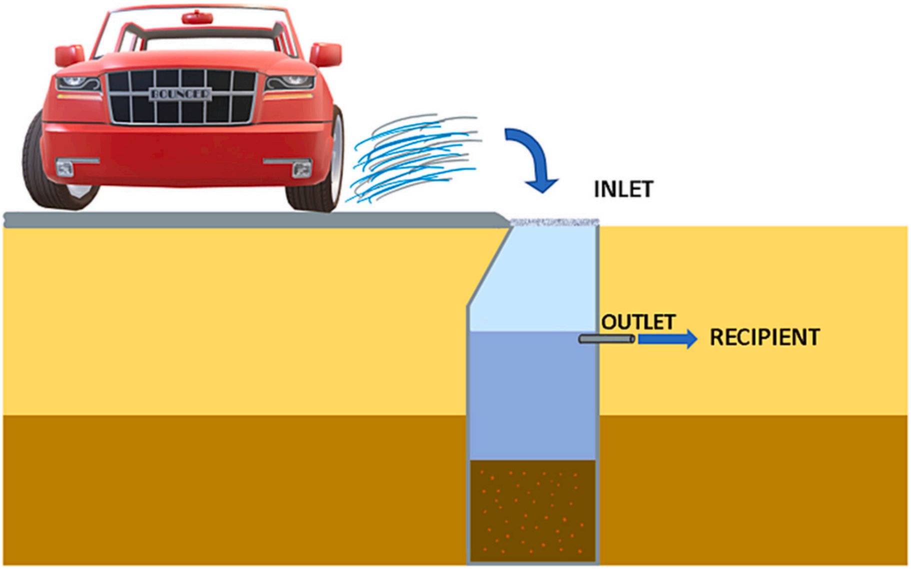


Fig. 3. Schematic illustration of a roadside gully.

adapted to complex traffic situations and road conditions e.g., where sites are constrained or surface systems are precluded for other reasons (Vogelsang et al., 2020). Some examples of commonly used subsurface treatment units are given as follows:

Vortex separators allow particles to settle by applying centripetal force and achieve removal rates of 50 % TSS under optimum conditions (Vogelsang et al., 2020). Wet basins and lamella basins use gravitational forces for particle settlement and reach a removal rate of 80 % TSS. Infiltration chambers are modular structures installed typically under parking or landscaped areas that provide large void spaces for the temporary storage of stormwater runoff before infiltrating it into the underlying native soil. They need low maintenance and achieve a removal efficiency of 75 % TSS (Vogelsang et al., 2020). Ballasted flocculation uses a chemically enhanced settling process and achieves removal efficiencies of 70 to 90 % TSS (Vogelsang et al., 2020). Cartridge filters and media filters (such as sand, olivine, aluminum silicate, calcite, zeolite, and filtralite) reach removal efficiencies of 80 % TSS, sometimes even 100 % (Vogelsang et al., 2020). Soakaways are installed in urban areas and allow the replacement of direct discharges on busy roads by underground settling ponds to capture tire abrasion. Decentralized shaft systems also offer a countermeasure (Steiner, 2020).

Within the project “Urbanfilter” sponsored by the Audi Foundation and conducted by the Technical University Berlin, tailor-made filtration systems with different types of filters are applied to street drainage (street, gully, and drain) with a planned operation time of one year (Audi, 2022). The project team aims to develop novel digitization approaches: linking the filtration system with important parameters such as street cleaning, average daily traffic volume (ADTV), rush hours, and climate prediction to determine the optimum time to empty the filter (Brook-Jones, 2022).

3.3.2.2. *Semi-centralized measures.*

Semi-centralized systems are mostly applied for the treatment of highly-polluted road runoff, which is drained and collected along frequently-used rural roads, urban streets, and/or motorways to disburden the sewage systems and the receiving waters, respectively (Åstebøl and Hvitved-Jacobsen, 2014).

Venghaus et al. (2021) calculated the overall reduction rate of semi-centralized treatment plants for the German river Panke according to German guidelines. Assuming a retention of 80 % for particles smaller than 63 μm, they state that these systems can reduce the TRWP concentration in the Panke River by 51 %. If these treatment plants will be installed in the entire catchment area at main streets and junctions and in combination with regular street sweeping (three times per week at junctions) the removal rate can be even higher (64 %).

However, significant management improvements and technological enhancements are required since these systems often suffer from irregular, poor maintenance and are initially not designed to trap TRWP (Baensch-Baltruschat et al., 2020).

Fig. 4 shows the working principles of commonly used semi-centralized systems helping the reader to differentiate between similar systems.

3.3.2.2.1. *Retention basin.*

Retention basins (also named: wet ponds, sedimentation ponds, wet detention basins, and stormwater management ponds) are constructed ponds with vegetation around the perimeter and a pool of water in their design that is most of the time filled with water (see Fig. 4a). They capture stormwater runoff from impervious surfaces (e.g., streets, sidewalks, roofs). Retention basins help to mitigate flooding and improve water quality by retaining suspended particles and dissolved contaminants from road runoff. The runoff is drained into the pond and held from days to weeks before discharge, allowing pollution removal processes to occur. Retained TRWP can accumulate in the sediments over the years until the sediments are removed, dewatered, and sent to a soil treatment facility for further processing (Liu et al., 2019b).

Well-designed retention basins can trap suspended particles and achieve maximum removal rates of 90 to 100 % TSS (Jönsson, 2016). Based on influent and effluent data from 74 studies (primarily in the U.S.) the anticipated average TSS removal of retention basins is 76 % (Clary et al., 2020). However, none of these studies specifically addresses the removal efficiency for TRWP. Furthermore, sedimentation ponds for runoff from roads are only designed to trap particles of sizes from 10 μm to 5 mm so far (Blecken, 2016; Andersson-Sköld et al., 2020). According to Steiner (2020) retention basins with sand as filter medium perform better in terms of hydraulic load and prevent the retained particle more efficiently from migrating into the deeper soil layers than retention ponds with soil as filter material. Assuming zinc as a marker substance, they achieved a removal efficiency of 90 % in field tests performed in Switzerland. Based on the assumption that 80 % of TSS are retained in the wet pond and the subsequent infiltration/filtration as well, a process train of retention, and infiltration can achieve overall removal efficiencies for TSS of 96 % (Vogelsang et al., 2020). According to Nikiema and Asiedu (2022), the costs for retention basins are 20 % lower than those for wetlands.

Schernewski et al. (2021) conducted a study about urban

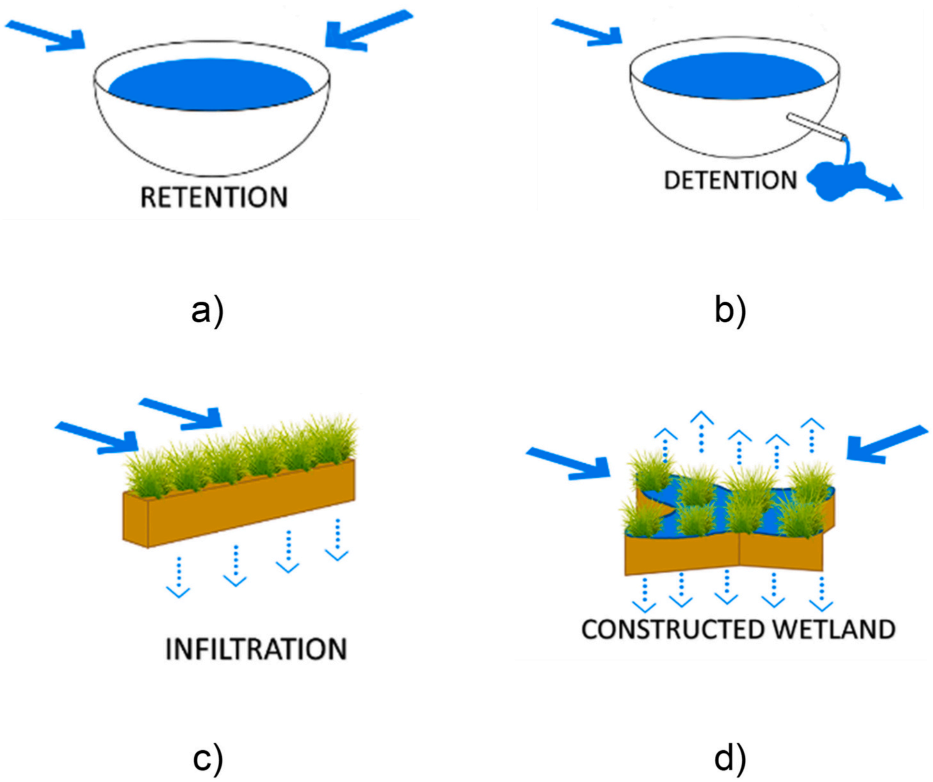


Fig. 4. Working principle of a) retention basin, b) detention basin and c) infiltration basins, d) constructed wetland.

microplastic in the Baltic Sea region. The authors state that the implementation of retention measures could reduce the total amount of microplastics reaching the Baltic Sea by >30 % and as a positive side effect also the release of nutrients and other pollutants. According to their calculations, an increase in sewer overflow volume from 1.5 to 3.0 % resulting from climate change (more heavy rainfall events) would increase the annual microplastic loads by >60 % and could not be compensated by other measures such as the improvement of WWTPs.

3.3.2.2.2. Detention basin and infiltration ponds. A detention basin (also called dry pond, holding pond, retarding basin, or dry detention basin) is a structure into which stormwater runoff is directed, held for a period (detained), and slowly drained to a surface water body (see Fig. 4b). The temporary storage of runoff water aims to decrease downstream peak flow rates (Pekarek et al., 2011). Detention basins are installed on densely-trafficked roads larger than 30,000 ADTV to relieve the subsequent sewer system by retarding the rainwater runoff (Vogelsang et al., 2020). Whereas detention basins mainly discharge the road runoff to a downstream water body, infiltration ponds release water only through infiltration, evaporation, or emergency overflow during flood conditions (see Fig. 4c). They need to be maintained more frequently (at least yearly (OECD, 2021)) than detention basins.

According to Åstebøl and Hvitved-Jacobsen (2014), the expected TSS removal efficiencies of infiltration basins are approximately 80 to 95 % for TSS (Vogelsang et al., 2020). Common detention basins have significantly lower retention capacity for TSS and particle-associated pollutants, particularly at high hydraulic loads since the excess flow is discharged downstream without enough retention time for the settlement. Unice et al. (2019) estimate that detention basins remove 40 to 60 % of TRWP. A supplementary filtration unit might increase the removal capacity.

3.3.2.2.3. (Constructed) wetlands. A constructed wetland is a man-made basin that contains slowly-moving surface or subsurface water, a substrate of e.g., soil, gravel, rock, organic materials as well as water-tolerant plants, and organisms similar to those found in natural wetlands (see Fig. 4d). These engineered systems are designed to provide water quality improvements similar to their naturally occurring counterparts, the wetlands (Pekarek et al., 2011). Once operated sustainably, wetlands as well as retention basins can become permanent in the landscape.

Based on influent and effluent data from 74 studies (primarily in the U.S.) the anticipated average TSS removal of constructed wetlands is 55 % (Clary et al., 2020). However, none of these studies specifically addresses the removal efficiency for TRWP. In contrast to these studies, Gill et al. (2017) report that in highway runoff TSS concentration is efficiently reduced by >80 % in wetlands. Jönsson (2016) conclude that wetlands can be an effective way to separate microplastics since they demonstrated high separation efficiencies of 90 to 100 % for microplastic particles larger than 20 μm, but the specific separation efficiencies for TRWP have not been studied so far (Andersson-Sköld et al., 2020). Further investigations of the performance of constructed wetlands on removing microplastics demonstrate removal efficiencies of >99.7 % for microplastics with a size exceeding 20 μm (Liu et al., 2019a; HELCOM, 2015). Ziajahromi et al. (2020) found that 15 to 38 % of microplastics in the sediments accumulated in a floated wetland (small artificial platforms allowing plants to grow on floating mats in open water) were synthetic rubber-carbon-filled particles, most likely derived from vehicle tires.

3.3.2.2.4. Bioretention (biofilters). Bioretention is the process of collecting stormwater in a treatment area consisting of soil and plant materials to facilitate infiltration and remove sediment and other contaminants through physical, chemical, and biological processes (Pekarek et al., 2011). It comprises bioretention ponds, dry swales, and filter strips.

Bioretention ponds are shallow depressions in the landscape that are designed to capture and infiltrate stormwater runoff in a short period (typically 12 to 48 h). They are constructed with engineered soils and an underdrain, as well as deep-rooted, aesthetic, and native/adapted plants. Water collected in the pond either infiltrates into the surrounding soil or is eventually discharged into a storm drain system through the underdrain. (Pekarek et al., 2011). Dry swales (also named grass swales) are established bioretention systems, which are configured in contrast to classical bioretention basins as shallow, linear channels (refer to next section) (Minnesota, 2022). Filter strips are vegetated areas used to reduce stormwater runoff velocity, filter out pollutants, and enhance infiltration. A filter strip is often used around the perimeter of a rain garden or along a stream channel (Pekarek et al., 2011).

According to Lange et al. (2022), bioretention for microplastic particles larger than 100 μm shows removal rates of 90 % whereas for smaller particles <30 % of the particles are retained. They figured out that a vegetated basin performs better than a pure sand filter (70 %) for the removal of microplastics. Bioretention systems once installed and vegetated have a relatively low maintenance effort, mainly for the monitoring of plant growth.

3.3.2.2.5. Roadside swales. For many roads, no drainage systems exist and most of the road runoff ends up in swales along the roads especially in rural areas (see Fig. 5a, b). A swale is a broad, shallow, gently sloping channel to transport the road runoff away from the road by infiltration in the ground or as an open water system to a nearby recipient. Swales may be lined with vegetation, compost, riprap, or other material and are designed to slow runoff velocity and trap particulates. Vegetated swales are often referred to as bioswales, enhanced swales, or water quality swales. Water treatment is aided by a soil bed (natural or amended) with an underdrain system typically composed of a perforated pipe surrounded by gravel. Check dams may be used to temporarily retain stormwater runoff in the swale (Pekarek et al., 2011).

Åstebøl and Hvitved-Jacobsen (2014) state that roadside swales have a removal efficiency of up to 70 % for TSS. Bäckström (2002) reports 15 to 20 % removal of particles by grassed swales where the verge constituted 50 % of the road area (Vogelsang et al., 2020). Similarly, according to Unice et al. (2019), swales for water management for rural roads may remove 60 to 90 % of TRWP. However, swales that are designed to infiltrate water might become clogged by sediment from runoff particles, so a periodical replacement of the sediment is required to ensure optimal function. The results from Dröge and Tromp (2019) show that tire particles can settle in smaller road wells and that the tire particle concentration in grass-filled side areas (swales) decreases with distance to the road. However, since roadside swales are solely designed for drainage and are not connected to the sewage system, not only TRWP but also any other contaminant such as heavy metals potentially migrate into the soil and aquatic environment.

3.3.2.3. Centralized measures (wastewater treatment plant)

3.3.2.3.1. Wastewater treatment plant. In combined sewer systems, road runoff is treated at the wastewater treatment plant. Only few knowledge about the fate of TRWP in WWTP exists. This is mainly due to the lack of reliable standardized analyzing methods for TRWP in wastewater. Studies about TRWP behavior in WWTP, so far regard TRWP as part of TSS or microplastics and/or measure marker substances.

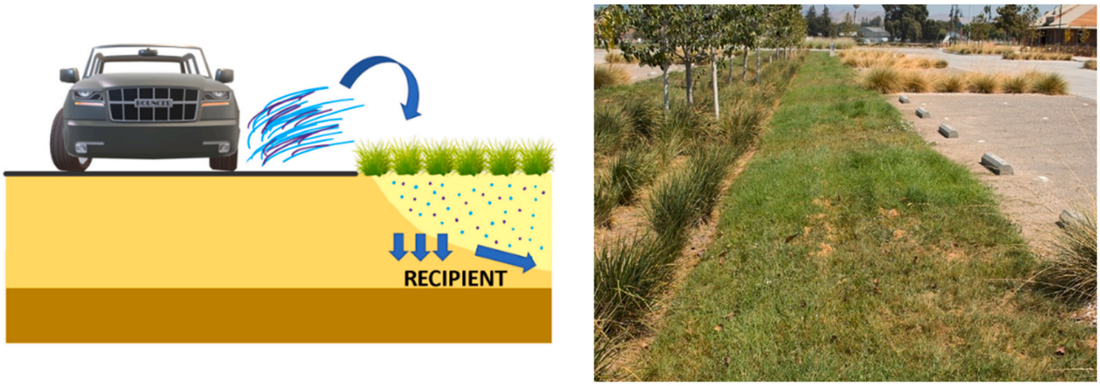
In general, it is well known that WWTPs can reject >80 to 95 % of microplastics along the mechanical, biological, and chemical treatment process chain, mainly at the primary treatment, assuming that control systems inhibit combined sewage overflow events (Carr et al., 2016; Siegfried et al., 2017; Kabisch et al., 2020; Magnusson and Norén, 2014; Brandsma et al., 2013; Talvitie et al., 2017).

A study of three Swedish treatment plants showed that the removal efficiency for microparticles larger than 300 μm was over 99 % (Magnusson and Wahlberg, 2014). For smaller particles between 20 and 300 μm they report slightly lower removal rates between 70 and 90 %.

A wastewater treatment plant consists of a combination of processes including sedimentation and filtration processes which are the major removal mechanism for microplastics (Tchobanoglous et al., 2014).

Primary treatment mostly comprises a rake with rough and fine screens, followed by a sand filter and a sedimentation basin as a primary clarifier. According to Dris et al. (2015), the fraction of massive particles (1000 to 5000 μm) can be reduced to 7 to 45 % after the preliminary treatment including only a rake and primary clarifiers (Simon et al., 2019). However, the major fraction of TRWP is smaller than 1000 μm. Vogelsang et al. (2020) state that 40 % of suspended solids can be removed if fine screens (mesh size 0.1 mm) are applied in addition to rakes. Relatively dense particles with an apparent density in the range of 1.7 to 2.1 g/cm^3, can be separated from the water by sedimentation. For synthetic particles such as TRWP, the formation of biofilms on the surface can further promote particle deposition, which makes sedimentation occur even for low-density polymers (Liu et al., 2019b). Vogelsang et al. (2020) calculated that particles larger than 30 to 40 μm will be settling out at normal operational conditions. However, at the maximum dimensioning load of 2.5 m/h at heavy rainfall events, only particles larger than 40 to 50 μm can be expected to settle out which accounts for 85 % of TWP since, approximately 85 % of the TWP volume is estimated to consist of particles with a size larger than 50 μm. Talvitie et al. (2017) figured out in field tests at a Finnish WWTP that a membrane bioreactor instead of primary and secondary treatment achieves a removal rate for microplastics of 99.9 %. Wang et al. (2020) investigated the impact of biochar as an additive to rapid sand filters and observed that the removal rate of a common sand filter can be increased from 60 to 80 % up to 95 %. Studies showed that up to 99 % of microplastics in the influent of wastewater treatment plants are removed during the primary and secondary treatment process (Simon et al., 2018; Sun et al., 2019).

Secondary Treatment comprises a biological treatment to reduce nitrogen components followed by chemical treatment, usually a phosphorous precipitation. According to Sun et al. (2019) and Besseling et al. (2017), common secondary treatment (biological treatment with activated sludge/clarification) reduces microplastics in wastewater by 0.2



a) b)

Fig. 5. a) Schematic illustration of a roadside swale; b) photo of a bioswale at a parking area.

to 14 % relative to the influent. Chemicals (ferric sulfate) and flocculating agents employed during secondary treatment probably help to agglomerate microplastics (Murphy et al., 2016). These agglomerates can be removed by sedimentation and flotation and at the same time reduce dissolved substances in the wastewater (Barkmann et al., 2022). Due to protozoa or metazoan feeding, microplastics might be trapped in sludge flocs. Bio-coatings may operate as wetting agents, altering micro/nano plastics' surface characteristics and relative densities (Fazey and Ryan, 2016; Rummel et al., 2017).

However, it is still unclear whether the surface modification provokes also opposite effects leading to further breakdown into smaller particles that are more difficult to remove (Lv et al., 2019; Ruan et al., 2019; Nikiema et al., 2020). Though TWP are very slowly biodegradable in soil (half-life of 245 to 890 days (Cadle and Williams, 1980)), their degradation in water might be enforced through nitrifying bacteria which can biodegrade heavily degradable organic hazardous compounds (Vogelsang et al., 2020). However, to the author's knowledge, no experimental results about the (bio)degradation of TRWP in biological treatment facilities exist so far.

Tertiary treatment comprises a second sedimentation basin, sometimes followed by a further treatment step, e.g., activated carbon filtration and/or flocculation. Sun et al. (2019) figured out that tertiary clarifiers remove microplastics by 0.2 to 2 % relative to the influent. Advanced final stage treatment processes specifically customized for microplastic retention significantly increase the following removal rates: disc filter: 40 to 98.5 %; rapid sand filtration: 97 %; and dissolved air flotation: 96 % (Mintenig et al., 2017; Talvitie et al., 2017). A combination of flocculation and successive sedimentation is effective in the removal of TSS with densities larger than 1 g/cm^3, whereas flotation as an alternative separation mechanism to sedimentation has almost no impact on the elimination of TRWP (Vogelsang et al., 2020).

Advanced treatment/fourth treatment comprises further treatment processes to remove micropollutants, such as pharmaceuticals using oxidizing and filtration processes. To remove microplastics Barkmann et al. (2022) suggest applying membrane filtration processes such as microfiltration and ultrafiltration solely or in combination with biological treatment as a membrane bioreactor. These filtration technologies allow to reject particles larger than approximately 2 to 100 nm (ultrafiltration) and 0.1 to 10 μm (microfiltration) (Baker, 2004). However, fouling and abrasion of the membranes might occur resulting in a drastic loss of removal rate (Pizzichetti et al., 2021).

Most possible technical mitigation measures have already been very well established (high maturity) and widespread. Their enhancement such as the implementation of finer screens at the primary treatment or the application of a disc filter at the tertiary treatment is relatively simple to realize. Regular maintenance and improving the operational effectiveness of WWTPs can be impactful (Buzzi, 2020).

3.3.2.3.2. Treatment of sewage sludge. All particles removed by different wastewater treatment processes end up in the sewage sludge. Sludge treatment comprises in most cases the dewatering and stabilization of the sludge followed by a fermentation process in a digestion tank. According to Kabisch et al. (2020), up to 99 % of the particles from wastewater are accumulated in the sewage sludge. A study carried out for Swedish WWTPs figured out that 40 to 60 % of microplastics are transferred to the anaerobically digested sludge, although it remains unclear to what extent treatment may lead to microplastic degradation to a size not detectable by commonly employed analytical methods (Tumlin and Bertholds, 2020). The thermal hydrolysis of the sewage sludge, which occurs in the digestion tank, is of special interest since this process possibly makes the TRWP more susceptible to biodegradation (Mahon et al., 2017; Cole et al., 2013; Zubris and Richards, 2005). Regmi (2018) investigated the pathways of microplastics along a large-sized WWTP. She figured out that the microplastic particles are enriched in the digested sludge with a ten times higher concentration compared to the influent.

The sewage sludge is commonly used in agriculture as fertilizer, soil conditioner, incinerated, or disposed on landfills (Buzzi, 2020; Duis and Coors, 2016). Applying the sludge in agriculture leads to the contamination of the terrestrial environment with microplastics, if not biodegraded beforehand (Baensch-Baltruschat et al., 2020; Buzzi, 2020). In 2021 44 % of biosolids were applied on land in the U.S. (United States Environmental Protection Agency, 2023). In 2015, Norway still used 52 % of treated sewage sludge as fertilizer for agriculture (Vogelsang et al., 2020). Lofty et al. (2022) state that between 31,000 and 42,000 tons of microplastics are applied to European soils annually by this entry route. To mitigate the release of TRWP into the soil, the sewage sludge from combined sewer systems can be incinerated which is already common practice in some countries. For example, Switzerland has implemented a ban on the use of sewage sludge in agriculture (Gieré and Dietze, 2022). Once the cost-extensive incineration facilities are installed sewage sludge incineration is a short-term solution to mitigate reentering of microplastics as well as other pollutants (Duis and Coors, 2016).

3.3.3. Washing of vehicles

Washing vehicle wheels, wheel arches, chassis, bodywork, and brakes regularly can impact the number of particles deposited on the road and therefore their resuspension (Piscitello et al., 2021; Watson et al., 2000). Thorpe and Harrison (2008) show that TWP become electrically charged when resuspended, increasing their tendency to adhere to surfaces. This primarily appears to affect the smaller airborne particles, so the mass of particles removed may be limited. Regarding this, Daimler AG patented a cleaning device for a car wash with the specific aim of minimizing particulate emissions from passenger vehicles (Lallement et al., 2021).

4. Data and knowledge gaps

To understand and limit the emission of TRWP it is crucial to identify data and knowledge gaps where further research activities are necessary. This section describes the most important research and data gaps in general as well as on the mitigation actions.

4.1. Generation, measurement and testing of TRWP and TWP

4.1.1. Method to generate and quantify TRWP and TWP

There is a lack of suitable methods for the generation and quantification of TRWP under defined conditions. ISO/TS 22638, 2018 is the first standardization approach that specifies a method for the generation of TRWP in a road simulator laboratory that is representative of actual driving conditions. However, the reproduction of roadway conditions in a stationary test bench is considered difficult and needs further inquiry (Andersson-Sköld et al., 2020; Grigoratos and Martini, 2014). The absence of fully-developed and implemented methods for tire abrasion testing makes it impossible to compare the tire abrasion behavior of different tire types and brands under standardized conditions. Thus, thresholds for the generation of tire wear as a basis for regulatory measures cannot be determined and controlled. For example, the European Commission discusses the setting of thresholds for tire mass loss in the framework of the Euro 7 (European Commission, 2022). However, within the first proposal, no limit values for tire wear were given. This is due to the confusion on how methods to produce tire wear under defined conditions can be applied since not only bench tests are required but also RDE (real driving emissions) tests must be carried out.

4.1.2. Methods to measure and quantify TRWP and TWP after release

There is an urgent need for fully-standardized, harmonized, and consistent methods to measure the quantity of TRWP in the environmental compartments, road runoff and the sewage system to assess the prevalence and environmental fate of TRWP (European TRWP Platform, 2019; Andersson-Sköld et al., 2020; Fussell et al., 2022; Busse et al., 2020; Faino, 2018; Furuseth and Rødland, 2020; Verschoor and De Valk, 2018). Commonly-used methods for sampling, sample processing, and characterizing of particles cannot be readily applied to TRWP. Furthermore, analytical results of different studies are not comparable since various marker substances are measured, such as zinc, natural, and synthetic rubber, but no "gold standard" exists. Besides, usual pyrolysis-gas chromatography–mass spectrometry (Py-GC–MS) methodologies face difficulties with the complex organic constituents in sediments and other environmental samples where TRWP are present. This makes the comparison of measurement campaigns on TRWP throughout different studies challenging (Andersson-Sköld et al., 2020). Harmonizing this process is crucial for better consistency(OECD, 2021).

An initial guideline for quantifying SBR/BR and natural rubber in TWP and TRWP towards future inter-laboratory standardization of Py-GC–MS has been presented in two ISO Technical Specifications. ISO/TS 20593, 2017 specifies a method for the determination of the airborne concentration (μg/m^3), mass concentration (μg/g), and mass fraction (%) of TRWP in ambient PM samples. ISO/TS 21396, 2017 specifies a method for the determination of the soil or sediment mass concentration (μg/g) of TRWP in environmental samples. However, they are hardly applied for the quantification of TRWP so far. Recent studies deal with the refinement and enhancement of the proposed ISO Technical Specification (More et al., 2023).

4.1.3. Laboratory testing of TRWP

There is a lack of standardized procedures (e.g., analytical protocols for processing, sampling, analysis) for the implementation of laboratory tests to investigate the behavior of TRWP under specific conditions. Current research results are often not comparable or even misleading due to different test setups. (Kim and Lee, 2018; Grigoratos and Martini, 2014; Denier van der Gon and Cassee, 2012).

4.2. Course, surface, and cleaning of roads, roadside

4.2.1. Impact of road course and road surface on the generation of TRWP

Boulter et al. (2006), Denby et al. (2013), and Gustafsson et al. (2008) describe a general lack of information about road roughness, macrotexture, and temperature of roads and their impact on TRWP. Further data about the effect of road surface materials, stone hardness, and alternative pavement would be useful (Faino, 2018; Johannesson and Lithner, 2022; Lowne, 1970; Sjödin et al., 2010; Denier van der Gon and Cassee, 2012). Da Cunha Rodovalho and De Tomi (2017) consider road design, including curve radius, road grade, and road surface materials as important factors that need more attention. Also, the abrasion rates of road markings should be further quantified (Johannesson and Lithner, 2022; Klüppel, 2014; Vogelsang et al., 2020). Kole et al. (2017) and Köllner (2021) criticized that the data is usually fragmented and localized. For example, often no registry exists, where the local road specifications are documented.

4.2.2. Impact of roadsides maintenance and vegetation on the removal of TRWP

Considering roadsides, only little information is available on the effect and frequency of verge peeling. The same applies to planting vegetation, where the PM_{10} or $PM_{2.5}$ accumulation on different plant parts is given, but no specific measurement on TRWP was conducted.

4.2.3. Impact of street cleaning and dust binding on the removal of TRWP

The results of studies concerning street cleaning are often contradictory, because of the different setups, methodologies, sampling procedures, and analysis methods used. They often refer to the PM_{10}, or $PM_{2.5}$ concentration, or the overall collected debris and not to TRWP. Further research is needed for a reliable assessment of the efficiency of road sweeping at retaining TRWP, costs, and environmental impact. (Andersson-Sköld et al., 2020). There is only a limited number of studies on dust binders on paved roads available, especially concerning the possible environmental hazard and health impact, which may be worse than the road dust itself (Barlow, 2014).

4.3. Emission factors

Emissions factors for different types of roads, road surfaces, environmental and traffic conditions, and vehicles strongly influence the calculation of tire wear releases into the environment (Baensch-Baltruschat et al., 2020). With these specific EFs, it would be possible to refine models on TRWP emission (Baensch-Baltruschat et al., 2020). Boulter et al. (2006) declared that the lack of agreement on EFs significantly hinders the development of new emission models and simulations. The present methodology is not satisfactory (Jekel, 2019). Should these models become precise and accountable they could be used to identify abatement strategies and would increase the environmental friendliness and cost-effectiveness of driving (Denby et al., 2013; Winquist et al., 2021). A comprehensive database is needed to determine specific EFs for different influencing aspects (OECD, 2021).

4.4. Tires and further vehicle components

4.4.1. Impact of the tire specification on the generation of TRWP

According to Andersson-Sköld et al. (2020), Nguyen et al. (2018), and Sjödin et al. (2010), the effect of tire type, pressure, and temperature on the generation of TRWP needs further research. Another important topic that attracts attention, especially in the Nordic countries in Europe and some States in the U.S., is the use of winter and studded tires. Though the application of studded tires in winter is common there, Boulter et al. (2006) report a lack of empirical data on the impact of studded tires on TRWP generation. Verschoor and De Valk (2018) note that no quantitative data were available on the effects of winter tire use in summer on tire abrasion. Furthermore, a knowledge gap exists in the comparison of studdles winter tires with less-wearing studded tires in terms of TRWP. Thus, further research is needed in this area (Kupiainen et al., 2017).

4.4.2. Impact of vehicle components other than tires on the generation of TRWP

Besides tires, other vehicle components could further minimize the TRWP emission. The suspension, wheel alignment, and tire balance affect the generation of TRWP but are still not fully researched (Andersson-Sköld et al., 2020; Johannesson and Lithner, 2022). In general, many vehicle-related studies consider mutually dependent factors making it impossible to isolate the impact of one single parameter. For example, EVs have a large weight which impacts the generation of TRWP, particularly in conjunction with the high torques of EVs compared to ICEVs. Nevertheless, there is little research on NEE linked to vehicle weight alone (Timmers and Achten, 2016; Hicks et al., 2021; Gao et al., 2022; Barlow, 2014).

4.5. E-mobility and autonomous driving

Generally, few studies are available on the impact of the electrification and autonomous driving of the vehicle fleet on TRWP. Thus, Furuseth and Rødland (2020) recommend further research on EVs within the context of TRWP e.g., on EV emission factors (Prenner et al., 2021), since the market share of EVs continuously grows and they are supposed to have a significant impact on the generation of TRWP. Kole et al. (2017) regard autonomous vehicles and their assistance systems, which can reduce TRWP generation through intelligent driving programs and anticipation of traffic situations, as a field that has not yet been fully explored.

4.6. Pathway and treatment of road runoff

Very little is known about environmental concentrations, degradation, sedimentation, and retention of TRWP (Baensch-Baltruschat et al., 2020; European TRWP Platform, 2020; Johannesson and Lithner, 2022). Thus, laboratory and field studies as well as monitoring methods to investigate the environmental behavior of TRWP in different environmental and technical compartments such as surface waters, soils, sediments, WWTPs, and sewage sludge are necessary to develop tailor-made, efficient mitigation solutions for TRWP (Faino, 2018; Baensch-Baltruschat et al., 2020).

Wastewater treatment processes are an option to significantly reduce microplastics. However, due to a lack of microplastics monitoring and of data on ecotoxicological effects, risks to human health and ecosystems above certain concentration thresholds cannot be demonstrated which makes it impossible to implement wastewater treatment standards for TRWP (OECD, 2021). Furthermore, most available studies build on a single one-time measurement of microplastics ignoring the wide temporal and spatial variation in influent and effluent wastewater quality. The lack of consistency in analytical protocols for sampling, processing, and analyzing microplastics (including TRWP) limits the comparability and evaluation of available studies (Weis, 2020). Thus, further research on methods to identify and quantify TRWP in inhomogeneous, complex matrices such as road runoff, wastewater, and sewage sludge is necessary as mentioned above (Andersson-Sköld et al., 2020; Baensch-Baltruschat et al., 2020; Wik and Dave, 2009). However, even if more knowledge had been gained, associating certain microplastic removal rates to specific parameters, such as the employed treatment process, could be challenging. This is because during wastewater treatment, numerous interactions occur between various biological, chemical, and physical processes.

4.7. *The impact of climate*

Currently, there is no data on the quantities of TRWP in snow available which would be necessary to know whether snow removed from streets poses an environmental risk and should be treated before deposition (Andersson-Sköld et al., 2020). Many studies focus on the impact of heavy rainfall events on road drainage and WWTPs, but the effect of temporary and/or long-term droughts on the sewage system is hardly investigated. For example, retention basins that dry up for longer periods can become a habitat for small animals such as rats or mice which might contaminate the basin once it is filled again with road runoff. Furthermore, the vegetation on constructed wetlands can dry out resulting in a drastic decrease of TSS removal and retention capacity.

5. Conclusions

Generally, technological and management mitigation measures to reduce the generation of TRWP are beneficial since they contribute to preventing TRWP from being released into the environment where the mobility and dispersion of the particles increase. Once TRWP is released into the environment, industrialized countries already provide potential technological mitigation measures which are mainly well established. For example, street cleaning and wastewater technologies show good removal efficiencies for TRWP. But in most cases these measures are not adapted to TRWP capturing and removal so that their full capability in removing TRWP is still not exploited.

Mitigation measures for TRWP not only consider TWP but also the generation of road wear particles. Thus, the improvement and maintenance of roads are impactful mitigation measures as well since the road surface highly contributes to the generation of road abrasion particles.

Important next steps to implement mitigation measures for TRWP are the determination of limit values for the TRWP generation and the establishment of thresholds for the concentration of TRWP in technical and environmental compartments as well as their monitoring and controlling. However, fully-developed methods for tire abrasion testing are still not available. This makes it impossible to compare the tire abrasion behavior of different tire types and brands under standardized conditions. This problem also exists for the verification of mitigation actions after the release of TRWP since fully-harmonized and -standardized methods for measuring and quantifying TRWP in the environment are not available so far. If the impact of mitigation actions cannot be reliably and reproducibly proven and monitored, results across studies cannot be compared, and regulative measures to protect the environment against TRWP cannot be controlled.

Thus, knowledge gaps (e.g., measurement methods, emission factors, pathways) need more research activities in a short to medium time. Also, field tests and pilot studies are highly needed to demonstrate the effectiveness of the abatement measures under real conditions.

Concerning management actions to cope with the TRWP mitigation, all relevant stakeholders (tire, vehicle, and road manufacturers) on national and international levels must cooperate because of the complexity of the TRWP issue and the necessity of international regulations. They should determine a common mitigation strategy for TRWP, enhance mitigation technologies, improve maintenance, and use the already existing knowledge base, as well as digitization approaches to build up an international database that provides the most suitable mitigation technologies and case studies. To push the mitigation measures for TRWP, a regulatory framework could be a main driving force. On a European level, initiatives on unintentionally released microplastics (including TRWP) are foreseen by (or likely to be published) in 2023. Strategic action plans to reduce TRWP, which might derive from the EU initiative, should integrate all policy areas such as local air quality, climate, environment, and public health, as these can generate co-benefits and save costs.

In any case, there is no individual measure that can solely solve the TRWP issue, but potentially a set of combined measures could be more effective.

5.1. *TRWP mitigation measures to prevent the generation of TRWP*

5.1.1. *Vehicle and tires*

- To reduce emissions, driving maneuvers such as strong acceleration, heavy braking, and fast cornering should be avoided, as should extremely high speeds.
- Vehicles should be driven with tires adapted to the current environmental conditions, correct tire pressure, and correct wheel alignment (toe and camber angle).
- Tire pressure is already automatically monitored in many vehicles, alerting the driver to possible necessary actions. Implementing such systems in older vehicles accounts for most of the reduction potential.
- Automatic systems for monitoring and even correcting chassis settings are under development. As soon as these are ready for series production, they should be installed in vehicles across the board.
- Battery-electric vehicles will most likely increase the emission of TRWP due to higher weights and torques. A trend reversal towards the development of lighter vehicles is required; the use of lightweight materials or the deliberate reduction of the battery capacity can help to reach this goal.
- Traction control and anti-lock braking system can have the positive side effect of reducing the emission of TRWP in extreme situations. Old vehicles and vehicles in emerging or developing countries should therefore be retrofitted/equipped with these assistance systems.
- Technical precautions in vehicles such as speed and acceleration limiters could help to implement eco-friendly driving behavior. Braking and cornering can neither be restricted nor limited due to safety reasons.
- Research on promising technological approaches and devices (e.g., collection systems at the wheel) to capture TRWP directly at the wheel should be reinforced.
- New and innovative materials are needed for tire production to overcome the conflict of objectives summarized in the “magic triangle” such as self-healing materials, the addition of nanomaterials, and the substitution of carbon black by silica.

5.1.2. Regulation and education

- Geographical and climatic aspects are relevant selection criteria for regulations (e.g., regulation on studded tires and gritting materials in Nordic countries).
- A time limit on use or a ban on winter tires outside of the winter months is helpful since winter tires wear off more in summer and at higher temperatures.
- The legislator is recommended to reduce tire wear by imposing regulations on the regular checking and adjustment of the wheel alignment.
- Legal limits for tire mass loss are only possible if there is a standardized measurement method available and if tire and automobile manufacturers, research, and legislators agree on technically feasible limits.
- Providing information about mileage or a tire abrasion indicator on the already existing tire label would create transparency. Besides labeling tires, labeling roads would be an interesting option.
- Residual rubber on the tire that comes from tire production should be banned immediately, as it represents an unnecessary emission of microplastics.
- Taxation, fees, subsidies, or incentives are supposed to motivate people to change their driving behavior and reduce emissions voluntarily. When implementing economic measures, the social balance must be taken into account.
- Increased use of public transport reduces the overall traffic volume and thus generation of TRWP. Municipal authorities should make public transport more attractive.
- Educational measures should raise awareness for the TRWP issue and can be achieved e.g., through workshops, campaigns, and teaching the drivers at driving schools. These activities should be initiated by both industry and politics.
- Educational and regulatory measures can be implemented nationwide and international and need few technological efforts, however, complex, time-consuming political and administrative decision processes are necessary to implement them.

5.2. TRWP mitigation measures at the vehicle and the road surface

- Promising approaches to collect particles directly at the vehicle already exist but they require further development and must be designed for use in all vehicles.
- Climatic effects are highly relevant for the choice of the best-performing technology. As example, porous pavement is not usable in countries with harsh winter conditions but highly efficient for countries with moderate climates as shown in the Netherlands in combination with processes to remove the particles from the road.
- Smooth road surfaces lead to less emission than rough ones creating a conflict of objectives with safety-related demands.
- Street cleaning could be effective in the removal of road dust; a combined process with washing is preferable if the wash water is treated before discharge; frequent street cleaning at hotspots is expected to be almost as effective as street cleaning of the entire city.
- Vegetation has a multiple use-effect, is relatively cost-efficient, and is low-maintenance but requires space that is hardly available in urban areas.

5.3. TRWP mitigation measures on atmosphere and road runoff

- Road runoff treatment systems are very well established, have a broad scope, and can significantly remove TSS. Processes that combine sedimentation and filtration achieve the best removal results.
- Retrofitting, maintenance, and control systems will improve the removal efficiency.
- Identification of hotspots (high load and/or high volume of the road runoff) where the treatment facilities operate most effectively (optimum cost-use relation) helps save costs.
- Multiple use: road runoff treatment removes further diffuse pollutants (e.g., brake wear, nutrients, and heavy metals adsorbed to TSS).
- Decentralized and semi-centralized stormwater treatment is substantial for flood management being a useful entry point to enhance TRWP removal strategies; decentralized treatment systems such as gullies are cost-efficient and space-saving.
- WWTPs are highly-efficient traps for TRWP; however, combined sewage overflows (CSO) must be strictly avoided; separated sewer systems including road runoff purification are preferable in terms of TRWP removal (comparable efficiency, no risk of CSO).
- The practice of spreading sludge on agricultural land leads to high microplastic pollution including TRWP and should be avoided.
- Increasing numbers of heavy rainfall events and/or droughts due to climate change influence the dimensioning and management of road runoff treatment systems and road cleaning in the short to long term and thus, affect the efficiency of TRWP mitigation measures.

5.4. Main research gaps

The major knowledge and data gaps where further R&D is highly required are as follows:

- Research on the interfaces where TRWP is generated (road surface and tire: quantity and quality).
- Research on specific emission factors, e.g., for strong acceleration, harsh braking, fast cornering, as well as for EVs.
- Research on smart devices for capturing TRWP directly at the vehicle.
- Research on TRWP pathways (road surfaces, roadsides, catch basins, sewer systems, and other adjacent environments) and their multiple influencing factors (weather, degradation, time of day, location, topography, traffic patterns, traffic control, land use).
- Assessment and optimization of best management practices and mitigation strategies for road runoff treatment and street cleaning by laboratory and field tests.
- Research on standardized tire abrasion measurement and environmental monitoring methods.

6. Key findings and recommendations

Based on their expert knowledge, the authors provide key findings and propose recommendations to make the comprehensive study which includes a variety of mitigation measures and considers lots of scientific disciplines more accessible to the readers.

- All relevant stakeholders (tire, vehicle, and road manufacturers) on national and international levels need to determine a common mitigation strategy for TRWP because of the complexity of the TRWP issue and the necessity of international regulations.
- Strategic action plans to reduce TRWP should integrate all policy areas such as local air quality, climate, environment, and public health, as these can generate co-benefits and safe costs.
- No individual measure can solely solve the TRWP issue, but a set of combined measures could be more effective, especially when implementing at hotspots.
- Standardized measurement methods for TRWP emissions and quantification are crucial to implement TRWP as a factor in tire labels and regulations and as a key parameter for regulations such as limited discharge concentrations and their controlling and monitoring, respectively.
- The feasibility of the already existing ISO Standards for TRWP generation and quantification has to be proven by experts from research and authorities.

- To be able to compare results across studies and to clarify contradictory results, methods need to be standardized, validated and subsequently applied throughout the field.
- Field tests and pilot studies following standardized experimental protocols are highly needed to demonstrate the effectiveness of the abatement measures under real conditions.
- Future mobility trends (e-mobility and autonomous driving) are upcoming important issues within the context of TRWP mitigation and should be further investigated.

CRediT authorship contribution statement

Ilka Gehrke: Supervision, Project administration, Methodology, Writing – review & editing. **Stefan Schläfle:** Methodology, Writing – review & editing. **Ralf Bertling:** Methodology, Writing – review & editing. **Melisa Öz:** Methodology, Writing – review & editing. **Kelvin Gregory:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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