

Review

Measures to Reduce the Discharge of tire Wear into the Environment

Johannes Wolfgang Neupert *, Daniel Venghaus and Matthias Barjenbruch

Department of Urban Water Management, Technical University of Berlin, Gustav-Meyer-Allee 25,
13355 Berlin, Germany

* Correspondence: neupert@tu-berlin.de

Abstract: The environmental impact of tire wear emissions has become increasingly apparent, and efforts to reduce their impact on the environment are on the rise. To minimise the generation of tire wear, it is essential to consider the influencing factors. However, as it cannot be entirely prevented, measures to reduce immissions are also necessary. This paper summarises possible measures derived from the literature, stakeholder workshops, and the authors' own conclusions, taking into account the different perspectives: tire, vehicle, road, sustainable mobility and emissions treatment. The presentation of the entry paths of tire wear into the environment and the hotspots of generation can be used to prioritise reduction measures. Measures should be implemented at a political level, technical solutions applied, and awareness raised among the general public. It is evident that reducing tire wear is a complex task that requires a transdisciplinary approach.

Keywords: tire wear; microplastic; environmental protection; transdisciplinary challenges

1. Introduction

The vehicle tire is an essential component of the chassis and forms a complete wheel with the rim. Its main function is to transmit force from the vehicle to the road. The resulting tire wear is an unavoidable abrasion product of the friction process between tires and the road and occurs wherever there is automobility or other tire applications (bicycles, etc.), and therefore presents a global challenge. According to projections, over 98,000 t of tire abrasion is emitted annually in Germany and 450,000 t in EU member states (EU27) is due to loss on the tire [1,2]. Studies have shown that the tire wear particles are also found as an agglomerate due to the friction process with the road surface: Tire and Road Wear Particles (TRWP) [3,4]. This means for emission balance that there tends to be a higher mass of TRWP emitted into the environment than just the considered loss at the tire. The emitted tire wear particles are approx. 4–350 μm in size (on average 100 μm) [3], with a density of 1.2–1.7 g/cm^3 [5]. Due to the material and size distribution, tire wear is given attention in terms of fine particulate matter (PM10) and also in the microplastics discussion.

1.1. Environmental Relevance

Although sampling and analytics have recently made great progress in detecting tire wear in terms of mass, particle number and degradation products in the environment, there is still a great need for research. Nevertheless, it is possible to detect tire wear in all three environmental compartments: soil, water and air [6–8]. Tire wear particles are generally persistent in the environment and are not readily biodegradable [9].

Tire wear is mainly present as particulate emissions. However, chemical ingredients can also leach into water [10–13]. The antioxidant additive 6PPD is currently receiving significant focus. The ingredient or its degradation products (6PPDq) have been shown to have toxic effects on living organisms in the environment [14–20]. It has also been proven that substances from tire wear can be absorbed by plants [21].



Citation: Neupert, J.W.; Venghaus, D.; Barjenbruch, M. Measures to Reduce the Discharge of tire Wear into the Environment. *Microplastics* **2024**, *3*, 305–321. <https://doi.org/10.3390/microplastics3020019>

Academic Editor: Nicolas Kalogerakis

Received: 26 April 2024

Revised: 17 May 2024

Accepted: 1 June 2024

Published: 4 June 2024



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In addition, part of tire wear is airborne and, thus, as particulate matter (PM), a risk factor for health impairments and premature deaths worldwide [22,23].

Furthermore, tire ingredients can also volatilize as a gas (volatile organic compound—VOC) [24–26]. VOCs still represent a major knowledge gap, as the pathway and effect in the environment are largely unknown [27].

1.2. Trends

The OECD report [22], states that PM10 emissions from road transport fell by around 40% between the year 2000 and 2014. However, this decrease is only due to exhaust emissions; non-exhaust emissions (tires, brakes, roads) remained constant. With further optimization of internal combustion engine vehicles (ICEVs) and an increase in the share of electric vehicles (EVs), exhaust emissions are expected to decrease further, and non-exhaust emissions will be the main source of PM10 emissions from road transport [22].

In Europe, a rising trend in vehicle kilometres can be seen. The mileage is an important factor for total tire emissions. The volume of road traffic is expected to increase over the next few decades [28]. According to JRC estimates [28], road passenger transport will increase by 16% between 2010 and 2030 and by 30% between 2010 and 2050. Freight transport is expected to increase by 33% by 2030 and by 55% by 2050 [28].

Furthermore, there is a trend towards heavier vehicles, which causes a further increase in tire wear emissions. This is discussed in more detail in Section 3.

Accordingly, measures are needed at various levels to reduce tire abrasion in the environment.

2. Materials and Methods

The research was initiated by the EU study in which reduction measures for microplastics were developed. In addition to the literature, there were also stakeholder workshops with participants from politics, industry, NGOs, etc. The number of studies targeting measures of tire wear reduction has become increasingly comprehensive and precise over the years. In the beginning, there was a discussion of rather general measures and knowledge gaps [29–32], and meanwhile, comprehensive studies with proposals for measures at the national and international level have been published [33–38]. The aim of this publication is to present opportunities for the transdisciplinary challenge of reducing tire wear in the environment and to present new proposals. The focus is on tire wear as a particulate emission.

2.1. Background—Entry Path

Emissions are the tire wear particles generated and emitted on the vehicle and are transported into the environmental compartments air, soil and water, where they are described as immissions. Basically, measures can be divided into two groups. They can either focus on emissions and reduce the general generation of tire wear or on immissions and remove the emitted tire wear. For the efficient use of measures, it is therefore of interest to know where tire wear occurs and which input path leads into the environment.

A comprehensive analysis of the input pathway of tire wear from emission to immission was carried out in Baensch-Baltruschat et al. for Germany [2]. Considering different vehicle types (LDV, van, HDV, etc.) and road types (urban, rural and motorway), the inputs into the environmental compartments soil, water and air were recorded (Figure 1). It was deduced that the largest proportion ends up in the soil (approx. 69%), 20% ends up in the water and a general proportion of 5% was determined for the air. In the model, only just less than 8% of the tire wear emitted is removed from the environment through sewage sludge incineration [2].

Mobilised by precipitation [39], the input into water bodies reaches surface waters almost entirely via urban areas. Although wastewater treatment plants have a very good retention capacity, only 43% of the system in Germany is connected to them as a combined sewer system. Of the tire abrasion generated in urban areas, 11% is discharged via combined

sewer overflows and up to 46% is discharged into surface waters, mostly untreated, via the separation system [2]. From this, it can be deduced that urban areas should be prioritised for water protection.

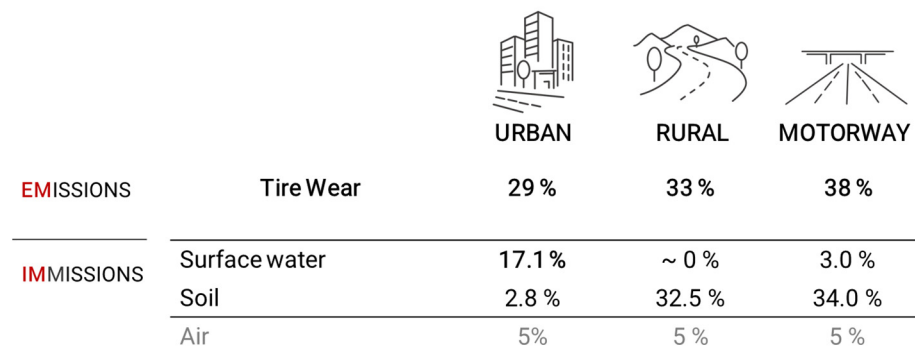


Figure 1. Entry path of tire wear in Germany: emission/immission according to Baensch-Baltruschat et al., 2020 [2].

2.2. Factors Influencing the Generation of Tire Wear

The following section deals with the factors influencing tire wear. Influencing factors show where measures can be taken, especially on the emissions side. In addition, it will also become clear in the following that there is a positive synergy with other environmental issues such as energy saving.

A comprehensive overview of the influences according to Boulter [40] is shown in Figure 2. Here, the possible influencing variables are divided into the four categories of driving behaviour, tire, road surface and vehicle characteristics.

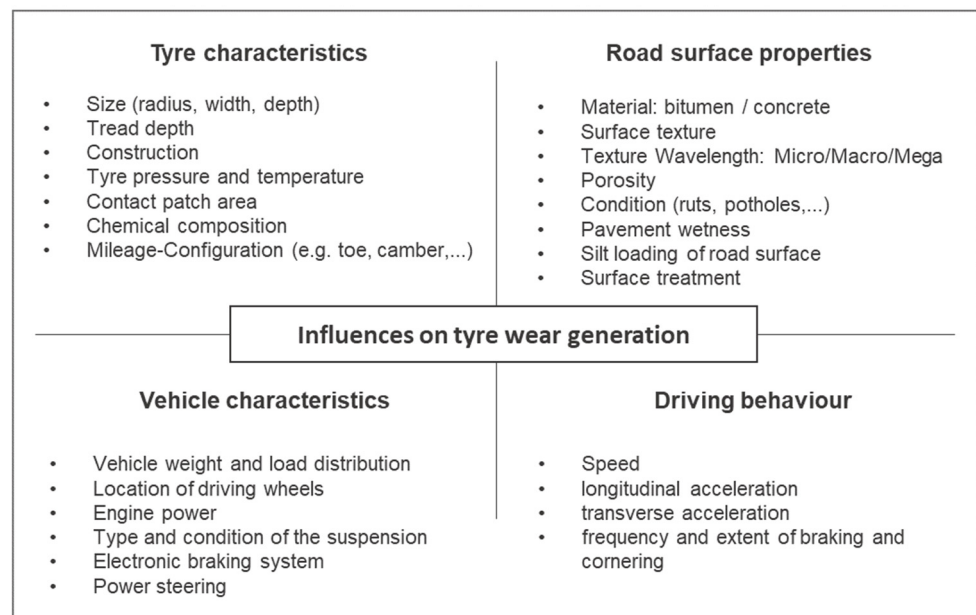


Figure 2. Influencing factors of tire wear generation according to Boulter 2006 [40].

The influences shown affect the emission rate [mg/vehicle km] and are therefore also parameters for reducing emissions. It is assumed that driving behaviour and road topology have the greatest influence on the generation of abrasion. Driving behaviour or vehicle operation and topology are interrelated, so that only limited separate assessments of the individual influencing factors are feasible under real environmental conditions [41]. However, stress caused by longitudinal and lateral acceleration on the tire increases tire abrasion emissions [42]. Test stand investigations can confirm this statement regarding PM emissions [43]. TireWearMapping [44] has modelled the physical parameters with the result

that increased emissions at curves and intersections can be assumed. This statement can be confirmed by environmental samples [45]. Accordingly, it is recommended to prioritise measures to reduce emissions at so-called hot spots of tire wear.

The list of influencing factors in Figure 2 makes it particularly clear which stakeholders need to be considered for mitigation measures: tire manufacturers, car manufacturers, users or customers, road constructors and policy makers.

It becomes clear that not only an interdisciplinary but even a transdisciplinary approach is necessary to efficiently reduce tire wear. In order to develop a holistic solution, perspectives from science, industry and municipalities are required.

3. Tire Wear Measures

The following chapter describes possible measures to reduce tire abrasion into the environment. Both emission-side and immission-side measures are considered and are presented in the following subgroups:

- Tires;
- Vehicles;
- Roads;
- Sustainable mobility;
- Emission treatment

The actions are primarily aimed at policy makers and relevant industry stakeholders. However, user behaviour will also be taken into account.

3.1. Tires

A vehicle tire is a composite material consisting of several rubber components, supplemented by reinforcing materials (e.g., textile or steel). It is used to transfer power from the vehicle to the road surface and must also withstand lateral and longitudinal forces in addition to the wheel load (vertical force). The tire is designed and evaluated for a wide range of driving characteristics, such as road grip in different weather conditions or damping properties. In addition, parameters such as rolling resistance, mileage and noise development must also be considered. However, certain parameters are trade-offs among what is desired, so a tire cannot be optimized at will. Accordingly, the challenge for tires and vehicle manufacturers is to make compromises in development and implementation [46].

3.1.1. Test Method and Emission Limits

In the EU, the general approval regulations for the marketing of passenger vehicle tires are formulated in Regulation No 117 of the Economic Commission for Europe of the United Nations (UNECE) [47]. It is focused mainly on rolling sound emissions, adhesion to wet surfaces and rolling resistance.

There is currently no approved standardised emission test for vehicle tires to determine the particulate emission rate. However, the EU-funded LEON-T project is currently gaining findings in order to propose a test method [48].

In general, a standardized test method and limit should consider the physical properties and chemical composition of the emitted tire wear. The physical characteristics include the emitted particle mass, number and size distribution. It is essential to prevent an increase in the potentially toxic particulate matter fraction (especially below PM_{2.5}) [49]. A limit value based only on mass may lead to less tire wear being emitted in general, but it does not reflect a shift from large/few particles to small/many particles. Furthermore, it is assumed that larger particles are better retained during emission treatment.

The challenge in tire development is to move the composition (and construction) towards higher abrasion resistance while ensuring the same driving safety. Nevertheless, as shown in the ADAC study [50], there is a large potential for tire manufacturers to produce tire wear emission-optimized tires that also provide driving safety.

3.1.2. Disclosure of Ingredients and Reduction of Environmental Risk

This measure aims to reduce tire wear not quantitatively but qualitatively in terms of environmental impact.

A discrepancy exists between the objectives of the composition of the contents, which stabilises the tread of the tire against environmental influences and the emitted particles, which retain these properties in the environment and are therefore difficult to degrade.

However, tire wear represents a special position in the microplastics debate, as the tread composition consists of a large number of complex substances. The tread can consist of 400 different organic compounds [51] and essentially contains the following components [52,53]:

- Rubber/Elastomere: natural rubber (NR) (polyisoprene [C₅H₈]_n) and synthetic rubber, e.g., styrene butadiene rubber (SBR) or butadiene rubber (BR);
- Reinforcing agents (Filler): soot/carbon black (C), silica (SiO₂) and chalk (CaCO₃);
- Softener: consists of oil and resin;
- Textile and metal net;
- Vulcanization agents: sulfur (S) and zinc oxide (ZnO);
- Additives: preservatives (halogenated cyanoalkanes), antioxidants (amines, phenols), desiccants (calcium oxides), plasticizers (aromatic and aliphatic esters), and processing aids (mineral oils, peptizers).

The chemical compounds derived from tires include 6PPD, PAHs and benzothiazoles [54,55]. The first measures regarding PAH have already been taken in the EU. Due to the implementation of the EU REACH Regulation, PAH concentrations in tires are limited: benzo[a]pyrene (BaP) to 1 mg/kg (0.0001% by weight) and the sum of the eight listed PAHs to 10 mg/kg (0.001% by weight) [56]. A comprehensive overview of the European Union's regulations pertaining to the entire lifecycle of tires is provided in Giechaskiel et al. [57].

However, the REACH regulation currently does not provide sufficient transparency. It is necessary to disclose the ingredients used and to understand their mixture effects and impact on the environment [58]. With knowledge of the substances used, the next step could be to use REACH to effectively regulate problematic substances with limits or even bans on their use. The Department for Toxic Substances Control (DTSC) in California has already taken this step.

The DTSC shows that other environmentally relevant substances need to be regulated and is acting against the use of 6PPD in motor vehicle tires. Tire manufacturers had to submit a Priority Product Notification (PPN) by Nov 2023, where the use of 6PPD had to be declared. Subsequently, information must be provided on whether the chemical will be removed, the product withdrawn, the product-chemical replaced, or a preliminary alternatives analysis report submitted [59].

However, the consideration of chemical composition is highly relevant from the point of view of environmental protection. In the Emission Analytics report [51], 300 different tires available on the European market were analysed for tire wear rate and their chemical composition. A method is presented whereby the measured wear rate and chemical composition can be combined to give an estimation of the emission rates of specific organic chemicals into the environment. The least toxic tire had a rate 85% times less than that of the most toxic tire and shows the potential to reduce the impact of tire wear in terms of quality as well [51].

In order to regulate or prevent the use of environmentally harmful substances, it is recommended that tire manufacturers should be required to disclose the substances they use, as is already the case in other sectors such as cosmetics [60].

3.1.3. Labelling

The tire label is designed to provide the user with the most important parameters for comparing different tires at a glance when making a purchase. A tire label for motor vehicle tires was introduced in the EU tire market in 2012 [61]. The label must now contain the following information attributes: fuel consumption, wet grip and noise classification [62].

The label is to be expanded to include further information, and a study was conducted to investigate the influence of the label on purchasing behaviour [63]. The study found that an explicit presentation of particulate tire wear emissions would have a negligible impact on purchasing behaviour. However, tire wear could be considered in a mileage parameter, which emerged as the third most important factor in the study when respondents were asked to identify the aspects they considered when comparing tires [63]. One possibility would be to define the mileage parameter as the product of tire abrasion emission factor and tread depth, as is currently being examined by the “UNECE Task Force—Tire Abrasion” [64].

3.1.4. Permit Winter Tires in Summer

The benefit of winter and summer tires is the optimum performance of the tire adapted to the seasonal weather conditions. The ambient temperature has a high impact on the tire wear generation and leads to increased emissions rates of winter tires used in the summer session [65]. Therefore, a ban the use of winter tires in summer can reduce unnecessarily generated tire wear [50].

3.2. Vehicles

In the EU, air pollutant emissions from passenger vehicles are limited by the “Euro Emissions Standards” [66]. Exhaust emissions are analysed for carbon monoxide (CO), oxides of nitrogen (NO and NO₂), unburnt hydrocarbons (HC) and particulate matter (PM). In addition, CO₂ (consumption) targets are set for a vehicle fleet of a manufacturer. Tire abrasion has not yet been considered but is addressed in the forthcoming EU7 [66]. How and to what extent tire wear is to be limited is not known.

3.2.1. Reduction of Vehicle Weight

A clear trend in vehicle technical parameters is evident in the EU. In the last 20 years, there has been a significant reduction in CO₂ emissions of around 50% of new car and van fleets, even though the weight and engine power of passenger cars are increasing [67]. Until now, fuel consumption was one of the motivating factors for reducing weight. With the increased market share of Battery Electric Vehicles (BEVs), the influence of vehicle weight on fuel consumption is decreasing as a result of the possibility of recuperation. Since the vehicle tire is subjected to the same (similar) stress during deceleration through recuperation as it is through a braking system, the correlation between CO₂ and tire wear is disconnected. This means that CO₂ decreases, and tire wear emissions remain the same or even increase. The largest market share of new vehicle registrations in 2022 is in the SUV/off-road segment [68].

3.2.2. Wheel Alignment Maintenance

In order to ensure stable straight-line driving through the chassis, the vehicle manufacturer specifies defined toe-in settings. Depending on the type of drive (front or rear axle), the wheels can be set either toe-in or toe-out in relation to each other, i.e., the wheels are not aligned exactly parallel. However, extreme toe values should not be selected, as these have a negative effect on tire wear [46].

Signs of wear and tear can lead to deviations in the wheel alignment. As such incorrect settings can occur unnoticed, there is a risk that a vehicle will be driven on the road for long distances with increased tire wear. Das et al. [69] carried out experiments with extreme tire misalignments. It was shown that not only did the tire wear increase, but the CO₂, CO, and NO_x also increased in the ICE vehicle due to the increased frictional resistance.

In the EU, Directive 2014/45/EU [70] mentions a check of tire alignment, but this is not considered essential for testing as part of the roadworthiness test.

In order to optimize tire wear and driving safety, it is recommended to include a measurement of the track in the periodic roadworthiness tests and to adapt it to vehicle manufacturer specifications.

3.2.3. Acceleration Control/Driving Style

Acceleration is one of the main parameters for describing driving style [71], which is considered one of the main factors influencing tire wear [72]. At the same time, it is also relevant for driving pleasure and therefore also a sales argument, which has certainly provided advantages for the growth of e-mobility. Despite the passion for driving and competition in vehicle sales, one should consider acceleration, which has not yet been directly limited. However, a certain type of acceleration limitation is already in operation: the traction control system (TCS) [73]. This prevents tires from spinning during acceleration and is therefore more relevant for rare extreme cases.

On a voluntary basis, there are already approaches from vehicle insurance companies that evaluate the driving behaviour of insured persons by means of a driving profile. According to this, insured persons receive a discount for sustainable driving with low acceleration and deceleration values, known as usage-based insurance [74]. The background to this is the connection between aggressive driving and increased accident risk. The symbiosis with tire abrasion emissions creates advantages on several levels.

In order to achieve a significant impact, the general acceleration of the vehicle can be limited. The focus here can be placed locally on urban areas, as the increased acceleration and braking at crossings leads to increased tire wear emissions. Tracking via GPS provides the vehicle with the information to limit maximum acceleration in urban areas. This measure would also relieve the aquatic environment in particular (see entry path) [75].

In addition, modern vehicles usually have different driving modes that can be set by the driver, such as Comfort, Sport, Eco, etc. This allows the driver to decide whether they want to drive as dynamically or energy-efficiently as possible. Consequently, this also has an effect on tire wear. In a pilot test, it was shown that driving in eco mode results in 30% less tire wear compared to comfort mode [75].

Setting eco mode as the default setting when starting to drive could be a promising measure, as the driver has to actively decide against sustainable driving.

Driving behaviour will reach a new level as soon as autonomous driving takes over a relevant share of traffic. The number of acceleration and braking manoeuvres could be minimised by taking account of traffic far ahead and environmental influences.

3.2.4. Tire Pressure Monitoring

Operating the tire in its non-optimal pressure range leads to increased tire wear. A tire under-inflation by only 0.2 bar leads to increased tire wear of 5% [76]. Tire pressure monitoring is already required by the tire pressure monitoring system (TPMS) in the EU [77]. However, the focus is only on safety-relevant pressure differences. Adjusting the sensitivity of the sensors so that information about tire wear-relevant pressures is also transmitted could represent a benefit for an already-established system.

3.2.5. Collecting Tire Wear Particles on the Vehicle

A plausible approach is to collect tire abrasion directly on the vehicle. The fact that tire wear only makes up a very small share of the total road dust resuspended make this approach challenging. A collection system would therefore also have to collect all the other predominantly mineral particles that are resuspended [78].

An innovative proposal is made by the Tyre Collective, whereby a collection device is to be used to collect the tire wear directly behind the tire [79]. Scientific reports on pilot tests have not yet been published.

Another innovation is presented by Mann + Hummel, where filtering solutions with fans are installed under the vehicle [80] or as the Audi Urban Purifier in front of electric vehicles [81].

3.3. Roads

Tire–pavement behaviour is essential for the friction process between the tire and the road and is therefore also relevant for tire wear [82]. The road surface influences

abrasion behaviour primarily through the texture. The main influencing factor is the micro texture, where the wear rate increases with the roughness, while the macro texture is less relevant [83,84].

3.3.1. Porous Asphalt

Porous asphalt with 15–20% hollow space is initially used for stormwater drainage and noise reduction, but the asphalt can also act as a particle trap [85]. The ability to retain tire abrasion for retention reinforces the use of porous asphalt. Regular cleaning of the pavement is crucial. It is recommended to maintain the pavement twice a year [85].

3.3.2. Optimized Road Design to the Edge of the Road

Road dust is not homogeneously distributed along the pavement cross-section and accumulates mainly at the edge of the road [45,86,87]. At the same time, during a rain event, the stormwater also has a potentially higher mobilisation rate of deposited particles, as the stormwater collects here and runs towards the nearest road drain. It is therefore proposed that the pavement is not constructed uniformly (Figure 3). The side area can be equipped with porous asphalt or also with technical retention solutions.



Figure 3. Pavement design along the edge.

3.4. Sustainable Mobility

The measures within the sustainable mobility section are exclusively aimed at reducing the generation of tire wear emissions.

3.4.1. Speed Limit

Speed itself has a rather subordinate influence on tire wear. However, it is important to consider speed in context. The maximum permitted speed has an influence on traffic dynamics, which, with the associated acceleration and deceleration processes, has a major influence on tire wear. The study by Luhana [88] even showed that there is a negative correlation between tire wear and average speed. The higher abrasion rate at low average speeds is explained by the increased braking and acceleration processes that primarily occur in urban driving situations [88].

Speed limits can be discussed for the various road types: urban, rural and motorway. In a number of member states, there is a growing tendency to limit speed in urban areas for both safety and environmental reasons (in particular, for air quality and climate change

reasons). For example, Spain has introduced a 30 km/h speed limit in urban areas for roads with one lane in each direction. Similarly, Paris implemented a general speed limit of 30 km/h in 2021 [89].

The significance of an urban speed limit of 30 km/h in Germany and its federal states in terms of tire wear emissions has been investigated by the TireWearMapping project [44]. With the physical model, a tire wear emission reduction of about 50% was calculated for both passenger cars and heavy-duty vehicles.

3.4.2. Public Awareness

Public awareness and knowledge of the issue of tire wear has an impact at various levels. The background to driving style has already been discussed from the vehicle perspective in Section 3.2.3. In addition, drivers can be given increased awareness. Starting with driving school or public awareness campaigns (e.g., “deadly dust” initiated by the tire wear collective and how&how), drivers can be made aware of the link between driving style and tire wear [90].

The same applies to tire pressure checks. In the absence of a technical solution, the responsibility lies with the driver. It is useful to provide free tire inflators at petrol stations with additional information on incorrectly set tire pressures.

However, public awareness can also be raised on the immissions side. As already shown in Section 2.1, the main input of tire wear into the aquatic environment is mainly from urban areas through road runoff. In the separation sewer system, the road runoff water is usually untreated, infiltrated or discharged into the nearest surface water body. In order to raise awareness among the general public about separation systems and the discharge of road runoff into surface waters, information could be displayed directly on the gully. Figure 4 shows an example from New Zealand where a fish is used to indicate “Drains Only for Rain”. In addition, further details could be communicated, e.g., by using a QR code, which indicates which water body this specific gully discharges into.

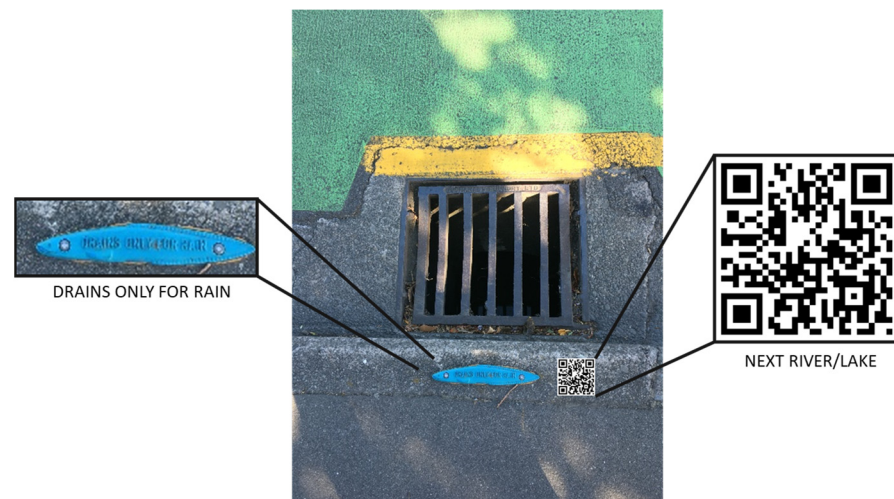


Figure 4. Which water body does this gully discharge into?

3.4.3. Reduce Vehicle Kilometres Driven

Probably the most efficient way to bring emissions down is to reduce the number of kilometres driven by vehicles [22]. Wilkinson et al. [91] states that the strongest driver of car mobility is the convenience of driving. Promoting sustainable initiatives is the way forward. There is a wide range of options here, from pavement quality to promote alternative transport, to taxines or driving bans.

Copenhagen sets the best example. By investing in cycling-friendly infrastructure, the number of kilometres cycled is increasing while cycling risk, casualties and fatalities are falling [92]. The initiatives promoted include replacing bumpy cobblestones on defined

strips with flattened smooth stones but also a “green wave” for cyclists signalled with LED signals along the route to pass several green traffic lights for optimum speed [93,94]. With these and other initiatives, Copenhagen achieved in 2016 that more cyclists have entered the city by bike than cars have since records began in 1970 [92].

Other options include (bicycle) sharing services and very well-functioning and well-developed local public transport [33]. Freight transport should also be transferred from road to rail and waterways.

More stringent measures include increased taxation and Urban Vehicle Access Restrictions (UVARs), which are being enforced in an increasing number of cities (e.g., Stockholm, London, Milan, Paris and Madrid) [22].

3.5. Emission Treatment

In addition to Section 3.4. which focusses on reducing tire abrasion emissions, this section deals with the topic of emission reduction through emission treatment.

3.5.1. Define Hot Spots and Discharge Points and Implement Monitoring

In order to specifically tackle emitted tire wear, it is necessary to understand where and how much tire wear is generated in the road traffic network. As already described in Section 1.2, hot spots of tire wear can be identified, and the pathway into the aquatic environment can be described [44,45]. With a downstream monitoring concept, where initially only traffic volumes would have to be considered, meaningful statements could already be made on the inputs of tire wear into the water bodies at the respective discharge points.

An initial holistic approach is provided by the EU-funded project “Noise and Emissions Monitoring and Radical Mitigation” (NEMO), which has developed a monitoring concept in the transport sector focussing on CO₂ and noise [95].

3.5.2. Road Runoff Treatment

Tire wear is usually discharged into surface waters via road runoff in a separate sewer system without treatment, as described in Section 1.2. Decentralised sustainable drainage systems (SuDS) can provide an effective solution to retain tire wear particles in the road runoff where filter systems are installed in gullies [96]. The aim is not to install these at every road runoff but to use the hot spot approach of tire wear generation.

In order to obtain acceptance for the use of such decentralised filter systems from the local authorities, not only is the retention capacity relevant but also the maintenance costs and effort. In Berlin, gullies are usually cleaned once a year. An increase in this period and significantly higher maintenance costs for the individual gullies is not considered acceptable.

An innovative retrofit approach was developed in the URBANFILTER project, funded by the AUDI Environmental Foundation. Successful test stands and in situ investigations have been completed here [97]. Furthermore, in a number of countries, investigations of SuDS are required [98]. These investigations must include an examination of the total suspended solids retention rate. In order to facilitate this examination, an alternative test substance has been developed, which is made from real road sweepings and better represents the boundary conditions that would be present in real use [99].

In the event that structural measures are required and/or sufficient construction volume is available, semi-centralised systems may also be a viable solution. These do not necessarily have to be exclusively technical structures but can also be combined with vegetation as wetlands or soil filters. Rodgers et al. were even able to demonstrate that planted soil filters are an efficient solution for the retention of the critic substance 6PPD-Q [100].

3.5.3. Extended Producer Responsibility (EPR) Compensation and Modulated Fees

The previous section raises the question of who must or can pay for the costs of installing road runoff filter systems. Experience has shown that there are local authorities

that are already interested in equipping road runoff systems out of their own sustainable motivation, but this is the exception rather than the rule.

Another option is the introduction of so-called Extended Producer Responsibility (EPR). In Germany, for example, the recycling of packaging is linked to licence fees (Grüner Punkt—Green Dot) in order to finance a recycling system [101]. Tire and vehicle manufacturers could have to adopt a similar approach here. Similar to the Green Dot or the CO₂ certification trade, this could be used to finance the installation of road runoff filter systems at hot spots. This system could be tightened up in combination with modulated fees. With the emissions test introduced (Section 3.1.1), placing high-emission tires on the market could become more expensive for manufacturers than placing emission-optimised tires.

In a similar way, there are efforts in the EU to reduce the CO₂ emissions of cars and vans, the so-called incentive mechanism for zero- and low-emission vehicles (ZLEV) [102].

3.5.4. Optimized Street Cleaning

Before the tire wear is washed into the road runoff, road cleaning can play an important role here and absorb tire wear. Cho et al. [103] has shown that the mass of microplastics increases with the number of days of the dry period and is washed away especially at the beginning of a rain event (first flush effect). Contrary to a routine plan, street cleaning at hot spots should be connected to the weather forecast as part of an intelligent network system [45].

3.5.5. Sustainability Hub

The measures presented have shown how complex the challenge of reducing tire wear is. It is the tire and vehicle manufacturers, policy makers, municipalities and local authorities and vehicle users who are opening up a transdisciplinary level. To this end, a sustainability hub is to be established to bring together all relevant stakeholders. As a nexus and centre of competence, pilot projects for reduction are to be initiated and the experience gained from them passed on to society. The ideas presented on awareness campaigns and the intelligent network system should also be mentioned here (Section 3.5.5). As a non-profit organisation, it even has the opportunity to implement EPR measures. Polluters could promote non-profit projects via the sustainability hub in order to generate a sustainable environmental impact.

4. Discussion and Conclusions

The current outlook shows an increase in tire wear emissions in the coming years. The main drivers here are, above all, the increase in vehicle weight and performance as well as rising the annual kilometres driven.

The media presence in relation to tire wear has been unbroken for many years and reflects the public interest in the topic. At the same time, the implementation of single measures faces a low level of acceptance, which must be seen as a chance for interdisciplinary approaches. The issue has attracted particular attention due to the consideration of tire wear in the upcoming European emission standards EURO 7. Other measures are largely CO₂-oriented but also optimized for tire wear and must be pursued.

On the other hand, it must be questioned whether measures such as an adjustment of the weights and dimensions of road vehicles by the planned EU directive is also the right step with regard to tire wear. It must be examined to what extent this will penalise rail transport, which is an effective alternative for freight transport considering tire wear [104,105].

The use of sewage sludge as a fertilizer because of pollutants, including heavy metals and organic pollutants, is a controversial discussion in the EU [106–109]. Also controversial is the potential reintroduction of tire wear retained in sewage treatment plants and should be considered.

In general, there is still a lot to learn about tire wear in order to close research gaps [22]. Extensive cooperation is needed between tire and vehicle manufacturers and the scientific community.

From a scientific point of view, there is a great need for environmental measurements in order to be able to make reliable statements [110]. For example, markers embedded in tires to detect abrasion in the environment are an interesting prospect for the future.

A concrete physical description of tire wear in the environment would also benefit measures such as road runoff filter systems. This requires standardized sampling and analysis procedures [111]. There is often a lack of important descriptions of the sampling strategy (volume vs. time sampling) to ensure the comparability of different studies [112].

Unresolved research areas also include understanding the fate of the emitted tire wear particles. How does the ageing of the particles work, and what environmental impact do they have [113]? Finally, this publication focuses on the use phase of the tire. However, the raw material extraction and production phase before the use phase and the end-of-life and repurposing scenarios after the use phase are also relevant for environmental protection [114].

There are already initiatives for the sustainable extraction of natural rubber, e.g., the Global Platform for Sustainable Natural Rubber [115].

Repurposing scenarios should be viewed rather critically, as tire material is introduced directly into the environment as a playground surface or granulate for sports fields and comes into contact with people [116].

Finally, as vehicle users, we should consider whether it is worth sacrificing some driving pleasure for the benefit of the environment.

Author Contributions: Conceptualization, J.W.N.; methodology, J.W.N. and D.V.; validation, J.W.N.; formal analysis, J.W.N. and D.V.; investigation, J.W.N. and D.V.; resources, M.B.; data curation, J.W.N.; writing—original draft preparation, J.W.N.; writing—review and editing, J.W.N., D.V. and M.B.; visualization, J.W.N.; supervision, M.B.; project administration, M.B.; funding acquisition, J.W.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by EUROPEAN COMMISSION, Specific Contract number 09029901/2021/847848/SFRA/ENV.B.1 implementing Framework Contract ENV.B.3/FRA/2019/0017.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The contracting authority had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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