Environmental exposure scenarios for tyre-related pollution from roads

Chief Scientist's Group research report

Environment Agency

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Dr Robert Bradburne
Chief Scientist

Executive Summary

Tyres have been identified as a significant source of microplastics in the aquatic environment, and the potential toxicity of leachates from tyre rubber has been an emerging concern for a number of years. Research published by Tian *et al.* (2021) identified a degradation product of the tyre additive 6PPD as the cause of urban runoff mortality syndrome (URMS) seen in Coho salmon in North America. 6PPD is one example of a range of phenylenediamine (PPD) antidegradants used in tyres, some of which might give rise to common transformation products. A wide range of chemicals are used in tyres, and the relative risk from 6PPD (and related substances) compared to these is not fully understood.

The aim of this project was to develop an environmental exposure scenario for the release and distribution of tyre-derived rubber particles and the substances leached from them to the roadside environment. We reviewed information on the chemical content of tyre rubber and features of road transport, road environments and rainfall events that can be expected to influence releases. The resulting model predicts releases on both an annual and short-term basis. This information can be used in conjunction with existing environmental fate models to screen for acute and chronic aquatic risks arising from the use of vehicle tyres. The exposure scenarios can be adjusted to account for road type, traffic volume, rainfall frequency and interception measures. A case study was conducted to examine the environmental realism of the modelled predictions.

The regional scenario estimates that 54,400 tonnes of tyre-derived rubber particles will be released to the environment in Great Britain (GB) annually, of which 7,000 tonnes is released to surface waters. The regional release is of a similar magnitude to a recently published UK emission estimate, which adds confidence to the prediction. These rubber particles are estimated to release 19 tonnes of 6PPD and 1.2 tonnes of one of its degradant (6PPD-Q) to watercourses (prior to any interception measures) annually. Predicted environmental concentrations (PECs) for 6PPD and 6PPD-Q in a case study conducted for a 1 km stretch of the M6 motorway adjacent to the River Lune are 0.17 – 2.51 µg/L and 0.02 – 0.31 µg/L, respectively within the receiving river, depending on the river flow rate. Concentrations in road runoff predicted by the exposure scenarios are within the range of measured concentrations reported in the global scientific literature, although direct comparison is not currently possible due to a lack of data on weather conditions and traffic density associated with the sampling at these sites.

The report makes a number of suggestions for further work to improve our understanding of the emissions, hazards and risks of tyre additives in GB:

- Improvements to reporting and consistency of tyre particle leaching and particle size characterisation data.
- Further research to determine the potential for long range transport of emissions to air and resuspension of particles on the road surface.
- A targeted monitoring programme to determine the current state of tyre-related chemicals in the GB environment arising from road networks.

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1 Introduction

1.1 Project background

Rubber-based tyres are vital to modern society and are used in huge numbers. The British Tyre Manufacturers Association (BTMA, 2026; accessed 01/05/2026) report that over 50 million tyres are supplied in the UK annually. As a vehicle's only contact point with the road, the surface of a tyre is gradually abraded by friction, giving rise to small particles of rubber. Together with debris and fragments of the road surface, these are collectively called tyre and road wear particles (TRWPs). This is a form of microplastic, and also nanoplastic, and monitoring and modelling have shown that tyres are the source of a significant proportion of microplastics released to the environment (Emission Analytics, 2020; accessed 30/04/2024; HE, 2020; Sundt *et al.*, 2014). Together, emissions from tyre and break wear have now overtaken exhaust emissions as a proportion of emissions of airborne particulate matter below 2.5 and 10 µm in diameter (known as $PM_{2.5}$ and PM_{10} respectively) (DEFRA, 2025a), exemplifying the importance of tyres as a source of microplastic pollution. The continued transition from fossil fuel to electric-powered vehicles over the coming years will also have an impact on the levels of released particulates, since electric vehicles tend to be heavier and have increased torque, which may lead to significantly increased emissions of TRWPs (Beddows and Harrison, 2021; Timmers and Achten, 2016; Woo *et al.*, 2022a). The average mass of new cars in the European Union (EU) has increased by 17% between 2001 and 2021 to 1481 kg, with comparable trends in the UK (ICCT, 2023). This reflects growth in the electric vehicle market, but also increased mass due to the addition of comfort, convenience and safety features on internal combustion engine (ICE) vehicles, and consumer preference for larger vehicles.

As well as a source of microplastic and nanoplastic emissions, TRWPs are also a vector for chemicals into the environment. Many substances are used in tyre rubber, and studies have shown that tyre particle leachates can be toxic to some species (Baensch-Baltruschat *et al.*, 2020; Wik, 2007). The chemical complexity of tyre rubber, and hence the leachates, make it difficult to identify the actual substances of concern. Some researchers have attempted to tackle this issue using fractionation experiments. For example, Tian *et al.* (2021) suggested that a quinone degradation product (6PPD-Q) of the ubiquitous tyre component 6PPD was directly responsible for acute mortality events involving *Oncorhynchus kisutch* (Coho Salmon) in North America, a phenomenon known as urban runoff mortality syndrome (URMS). Studies have since demonstrated the toxicity of 6PPD-Q to other salmonid species, such as *Oncorhynchus mykiss* (Rainbow Trout) (Brinkmann *et al.*, 2022). As some species of salmonids are native to Great Britain (GB), such concerns have prompted Highways England (HE; subsequently known as National Highways (NH)) to perform targeted monitoring to investigate chemical pollution arising from major trunk roads (NH, 2023c).

Against this backdrop, there is a need to develop exposure scenarios to help assess environmental risks from different tyre additive types in a consistent way. This report provides a brief description of the chemicals present in tyre rubber, and how they can enter the environment (Section 2). It then outlines the approach taken to develop exposure scenario models for normal use of tyres (Section 3 and Section 4) using data found in the scientific literature, and provides guidance on how they can be used. The models are largely based on existing models developed in the UK and the Netherlands and cover both regional and local releases. The outputs are release quantities of rubber and chemicals from the road environment that can be used as inputs into environmental fate models. Case studies are reported in Section 3 and Section 4 to test the robustness of the model by comparing the output to measured values obtained from the academic literature.

We have published an accompanying report (EA, 2025) that compared the available chemical hazard data with modelled environmental concentrations using output data from the first (unpublished) draft iteration of the exposure scenarios described in this report. This identified a number of chemicals that may pose a risk to the environment, for the purposes of further regulatory investigation. The exposure scenarios have now been refined based on stakeholder input, and so the final iteration of the exposure scenarios presented in this report may affect the predicted environmental concentrations (PEC) and resultant priority ranking in the EA (2025) report.

Note: The first draft iteration of this report also included a scenario to examine release of chemicals from rubber crumb (which is commonly used in artificial sports pitches, etc.). Work on this part of the report stopped following the publication of a Defra review into potential risk management options for intentionally added microplastics (DEFRA, 2025a).

2 Tyre wear particles and chemical additives

2.1 Tyre wear particles

There are several definitions reported in the literature for tyre wear particles. The following definitions are used in this report:

- Tyre particle (TP) – TPs for research purposes are generated by the frictionless removal of particles from a tyre, for instance by cutting with a knife or grating. These may then by further reduced in size using cryogenic milling. The physical characteristics of the resulting particles depend on the method used for generation and researchers do not use a standard protocol for measuring these characteristics. These particles consist only of rubber from the tyre. Cryomilled tyre tread (CMTT) is a type of TP that is widely used as a reference material in laboratory studies because it provides a consistent and readily available surrogate for TRWPs. However, CMTT contains no mineral fraction (as opposed to TRWPs) and represents fresh, unaged particles. By contrast, TRWPs collected from road surfaces are effectively pre-aged through environmental exposure (Weyrauch *et al.*, 2023).

- Tyre wear particle (TWP) – TWPs are typically generated by running a tyre on a rolling road in a controlled laboratory situation and collecting the particles generated with a vacuum system held close to the tyre. The particle size and shape differ from TPs and they may contain components sourced from the rolling road as well as the tyre. TWPs can be regarded as more representative of particles in the environment than TPs as they are generated in more realistic conditions. Importantly, morphology, particle size and emission rate vary with the forces acting on the tyre: longitudinal forces (e.g. braking and acceleration) and lateral forces (e.g. cornering) both influence the size distribution, with greater forces generally producing larger particles (Tonegawa and Sasaki, 2021; Zhong *et al.*, 2024).

- Tyre and road wear particle (TRWP) – TRWPs are particles collected from the roadside that contain rubber from tyres and minerals from the road, particulates arising from the abrasion of road markings, brake dust and other debris**.** The higher mineral content increases the density of TRWPs compared with TPs or TWPs, making them more likely to sink when released into slow-moving watercourses. TRWPs are usually pseudospherical (rugby-ball-shaped) with the longest dimension being approximately 200 µm (see Table 3). TRWPs are considered the most representative particle type when considering emissions from tyre use, but it remains uncertain whether all rubber released from tyres occurs in this form. For example, smaller fractions such as PM_{10} may be emitted directly into the air with minimal interaction with the road surface, in which case their

composition could resemble TWPs or even TPs. Because of this uncertainty, and the lack of studies examining the full range of particle types, there is limited consensus on the overall size and shape distribution of particles released during tyre use.

The reported mass lost from a tyre by road abrasion during its lifetime is variable. Martínez *et al.* (2013) reported that an average new car tyre weighs 11 kg and a used tyre weighs roughly 9 kg, suggesting that approximately 2 kg of material is lost through abrasion during the service-life of the tyre. Mayer *et al.* (2024) indicate that 1.2 – 6.7 kg of particles are released across the lifetime of various vehicle tyre types, which equates to 10 – 16% of the total mass depending on the source tyre type. Previous regulatory reports (EA, 1998, 2005a) estimate losses of 10 – 20% by weight over the lifetime of a tyre, equating to a total loss in the UK of up to 53,000 tonnes of rubber each year from the 380,000 tonnes of car and truck tyres in use in 1996.

Once TRWPs are generated, they may be deposited on the surface of the road or roadside, where they accumulate during dry weather. Particles on the road surface may subsequently be washed into rivers, streams and terrestrial environments when it rains (Kole *et al.*, 2017; Kovochich *et al.*, 2021; Thames21, 2023; accessed 30/04/2024).

The global average for annual TRWP release per capita is 0.81 kg (Sieber *et al.*, 2020), of which 6 – 45% are transferred into the aquatic environment, depending on the availability of surface water treatment systems (Wagner *et al.*, 2018). TRWP fate models for the USA and Switzerland predict that a large part of the TRWP mass remains on the roads or is deposited on roadside soils and that only 18 – 22% enters surface waters (Sieber *et al.*, 2020; Unice *et al.*, 2015). These findings point to a high potential for roadside soils to act as a sink for TRWPs and a long-term source of contaminants.

Goehler *et al.* (2022) indicated that up to 53% of microplastics collected through road runoff mitigation measures are TRWPs, while HE (2020) noted that sources of TRWPs may account for up to 40% of microplastics found in rivers and streams associated with the GB Strategic Road Network (SRN). The SRN comprises of 4,500 miles of motorways and major ‘A’ roads managed by NH. Further investigation involving sampling and analysis of microplastics in the environment associated with road use reported TRWP concentrations between 0.01 and 28.9 mg/L in surface water runoff (NH, 2023c).

Particles may also become suspended in air upon generation. Although the size fraction does not necessarily dictate environmental behaviour, larger TRWPs (i.e. >10 µm diameter) entering the air are typically deposited to the road surface or to the land adjacent to the road (Parker-Jurd *et al.*, 2021). Particulate matter with a diameter under 10 µm (i.e. PM_{10} and $PM_{2.5}$) may travel further when suspended in the air (Zhang *et al.*, 2023), leading to deposition further from the road (Reynolds *et al.*, 2024). The chemical risk posed by the transport of these small particles is further compounded by indication that the increased surface area of ≤PM_{10} results in an increased leaching rate (Hu *et al.*, 2023), exposing populations and ecosystems not typically found near roads. Particles deposited to the road surface may also be resuspended when a vehicle passes.

2.2 Chemical additives in tyres

Tyres are made from a variety of natural and synthetic rubbers, often containing multiple types within a single tyre. Monomers include isobutene, butadiene, styrene, acrylonitrile and 2-chlorobutadiene. The rubber is moulded around physical stabilising materials (e.g. steel, textile or plastic cables and belts) to provide a rigid structure. The tyres also contain smaller amounts of organic and inorganic additives which are present to impart various functions (see Table 23) (Martínez *et al.*, 2013; OECD, 2004). The exact composition is proprietary information and varies between manufacturers and tyre types (e.g. summer versus winter tyres (Rodland *et al.*, 2024), tyres for different types of vehicle (Pehlken and Essadiqi, 2005)). There is uncertainty regarding the composition of the tyres in use in GB, which may be either domestically manufactured or imported. The BTMA (2020; accessed 11/02/2025) state that 48% of tyres imported into GB come from Europe, 40% from China and the remainder are from Asia (excluding China). As of 2026, there were three tyre manufacturing sites in GB, with 19 retread sites (BTMA, 2020; accessed 25/02/2026). Retreading is a process where the old tread is removed and new tread is remoulded onto an old tyre body (BTMA, 2019; accessed 14/04/2025).

There are many different chemical additives in a single tyre, which may be mixtures of multiple substances themselves. A list of relevant substances is provided in Annex 5, the functions of which are described in the OECD (2004) emission scenario document on additives in the rubber industry. Key functions of additives are for vulcanising, protection (e.g. from oxidative damage), and as processing aids. Vulcanising agents cross-link polymer chains, with thiazoles, thiurams, sulfenamides and guanidines being the most commonly used. The protective additives extend the storage and service lives of rubber products and include N,N′-substituted p-phenylenediamine (PPD) antioxidants / antiozonants. Processing aids include dispersants, homogenisers, plasticisers and coupling agents, which can improve product quality and production efficiency, for example, hexamethoxymethylmelamine (HMMM). The European Tyre and Rubber Manufacturers' Association (ETRMA, 2019) report that the key components of tyre tread fall into two general categories based on their relative reactivity: those that provide structure, protection and physical properties (polymers, fillers, oils, waxes, processing aids and antioxidants); and those that are more reactive and perform functions during manufacture (sulfur compounds, accelerators and retarders, adhesives and activators). The reactive chemicals are typically consumed in the tyre manufacturing process, specifically in the vulcanisation and curing steps. However, the reaction efficiency may not be 100%, and reactive chemicals are still found in low concentrations within tyre leachate (Weyrauch *et al.*, 2023).

Certain classes of chemicals may be present as impurities within intentionally added components. For example, the ETRMA (2025) have indicated that phthalates are not intentionally added as plasticisers within tyre manufacture. However, phthalates have been detected in tyre-derived rubber crumb and are the focus of ongoing regulatory scrutiny, and so are included in Annex 6 (ECHA, 2018).

Novolac resins are an essential ingredient in rubber compounding for tyre manufacture. They increase the tackiness of the rubber and improve adhesion of the different layers during vulcanisation. They are generally added in amounts up to 1.5% by weight of the rubber formulation, though can be present at up to 10% (OECD, 2004). These tackifier resins are produced using alkylphenols such as 4-tert-octylphenol and para-C_{12}-alkylphenols (EA, 2005b, 2007). Both are Substances of Very High Concern (SVHCs) under UK REACH. The maximum concentration of free alkylphenol in the resins used to make tyres is assumed to be 3% based on information provided by industry (EA, 1998, 2005a).

Additives that are not chemically bound to the polymer structure can migrate through the matrix and leach out of the rubber under some conditions. It is expected that some chemical classes, such as antiozonants, undergo “blooming” where they migrate to the surface of the tyre to prevent oxidation of the tyre rubber. Cross-linking within the rubber matrix may hinder the rate at which this migration to the surface occurs. TRWPs can disintegrate into smaller particles by photooxidation, mechanical abrasion, thermal degradation and microbial degradation (Foscari *et al.*, 2024; Wagner *et al.*, 2022; Zhang *et al.*, 2024b), thereby increasing the surface area for leaching and transformation of additives due to physical effects. Leaching of substances occurs at the surface of the particle and the attachment or detachment of mineral particles affects the surface area of TRWPs, the chemical profile and consequently the rate of leaching. The particle size distribution of TWRPs, particularly at the smaller end of the microplastic range (1 – 100 µm) and into the nanoplastic range (<1 µm) is expected to have a significant impact on leaching rates.

The ‘tyre triangle’ is conceptual balance between rolling resistance, wear resistance and wet traction; adjustment of one factor will impact all factors, but not necessarily improve them. As each chemical within the tyre rubber is added to perform a specific function, replacement of chemicals for the purpose of tyre property change or chemical replacement due to regulatory action can have pronounced effects on tyre properties and emission rates. Extensive testing of tyre performance is required, so it is expected that formulations that result in failure of safety standards (e.g. UN/ECE (2011)) would not reach the market.

The EA (2005a) reported information on the chemical composition of tyres, and this is summarised in Table 23.

2.3 Summary

TRWPs are generated as tyres make contact with road surfaces generating friction. Tens of thousands of tonnes of TRWPs are expected to enter the GB environment each year, accounting for a significant amount of microplastic and nanoplastic pollution. These particles collect in road dust until wet precipitation events transport them into the aquatic environment or to soils adjacent to the road. Any TRWPs that are suspended in air will,

depending on particle size, either deposit to the soil or surface waters adjacent to the road or travel further on wind currents. This is illustrated in Figure 1.

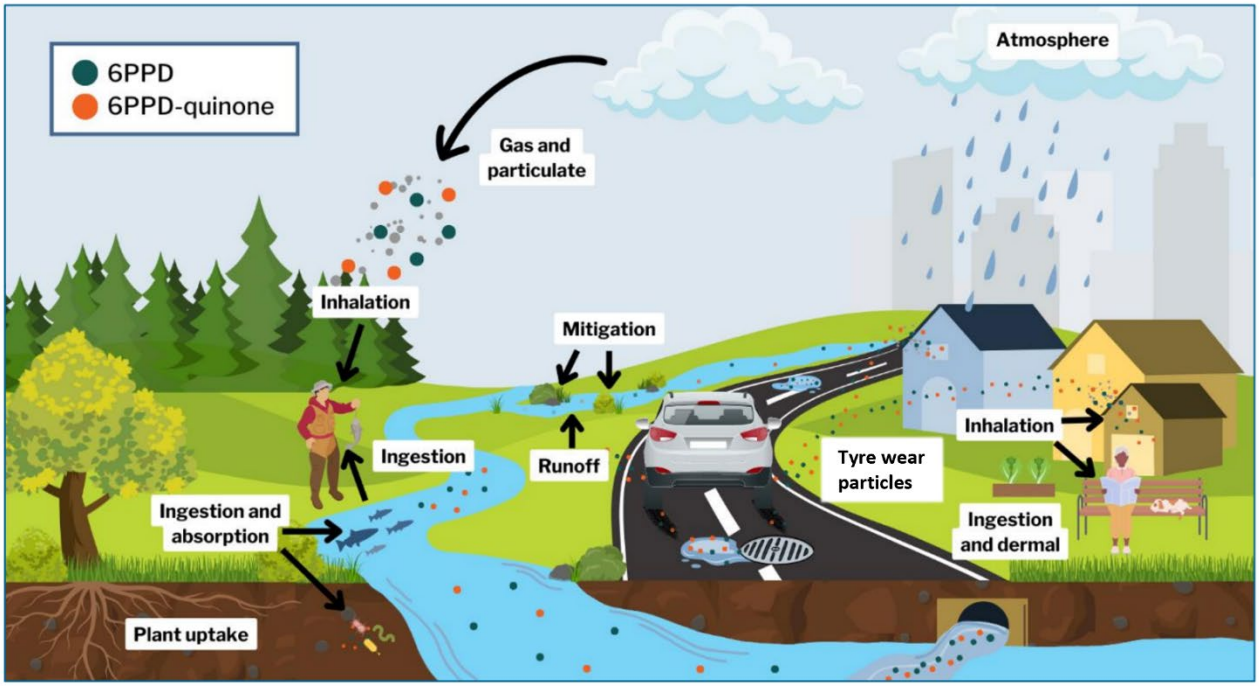


Figure 1 Conceptual Transport and Exposure Model of TWPs and 6PPD. Reproduced with permission from ITRC (2023)

As the chemical additives in the particles can be leached, TRWPs are a vector of chemicals (such as 6PPD) to these environmental compartments.

3 Environmental exposure scenarios: use of tyres

3.1 Development of exposure scenarios and model to predict TRWP release from vehicle tyres

The primary focus of this project was to estimate the mass of TRWPs released from tyres at a geographically specific location based on the attributes of that site, as this approach is most applicable to predicting the possibility of URMS. However, microplastics and the substances contained in them have also been linked to adverse chronic effects in the environment. To estimate releases that can be used for a more generic risk assessment, a regional approach is also needed that can also be used to calculate generic local releases. If the concentration of a given additive in tyre tread or TRWPs is known and a leaching rate can be identified, then the mass of this additive leached into the environment can be estimated from the released TRWP mass. Understanding the fate of TRWPs once they have been generated means that predictions can be made for both the mass of TRWPs and chemical additives entering each environmental compartment at both the local and regional scale.

Therefore, the initial part of the project consisted of a literature search (Annex 1) to find a model or identify sources of information, such as the release rate of tyre particulates and associated leached chemicals, which could be used to parameterise a model. This search first identified over 150 scientific articles and was later expanded to include a further 300. There are several key reports examining the generation and environmental distribution of non-exhaust vehicle emissions (i.e. TRWPs) and road-derived microplastics in GB published by DEFRA (2019), the Department for Transport (DfT) (2025b) and NH (2023c).The European Environment Agency (EEA) has also published emission inventories for vehicle tyre wear (Ntziachristos and Boulter, 2019). Several academic groups in GB and elsewhere have active research programmes focussed on pollution arising from road runoff, such as the work conducted by Johannessen and Metcalfe (2022) and Thompson (2025).

There are a number of models available that estimate the release of TRWPs or microplastics to the environment. These models are generally unsuitable for the purpose of quantifying the mass of TRWPs released to the GB environment on a local and regional scale as they are location (i.e. not GB) or scale specific. The modelling of leachates is typically not included within these models. Examples include models developed by Domercq *et al.* (2022); Huang *et al.* (2024); McCarty *et al.* (2023); Mian *et al.* (2022); Obermaier and Pistocchi (2022). There are also process-based ecohydrological modelling approaches, such as the VELMA framework recently applied by Halama *et al.* (2024) to assess watershed-scale contaminant dynamics, which may provide a more realistic representation of TRWP degradation and transport processes.

A geographical information system (GIS)-based model, the Road Pollution Solutions Tool, has been developed by Thames21 and Middlesex University. This is an online, interactive and evidence-based decision tool that predicts the pollution risk posed by London's SRN, identifies pollution pathways into rivers and guides and prioritises where and how nature-based solutions can be used (Thames21, 2023; accessed 30/04/2024). The current version addresses only a limited number of tyre constituents and is not suited to the type of generic risk assessments that are performed under the UK REACH Regulation. However, this type of model could potentially provide a higher tier approach in the future.

ETRMA (2010) have produced specific environmental release categories (SpERCs) to provide emission factors for formulation and industrial use in the tyre and general rubber goods (GRG) industry. These SpERCs can be considered for use as generic inputs to EUSES or similar environmental exposure and fate models.

The OECD (2004) developed a basic exposure scenario for the release of tyre ingredients and their degradation products, but this uses a basic emission factor of 0.12, representing the fraction of the total substance present in tyres emitted in a region. This does not account for tyre wear rates, leaching rates of different types of substances, or immobilisation within the road environment. The rate of leaching from tyre particulates and the chemical's subsequent environmental fate depend on its physicochemical characteristics, such as: acid dissociation constant (pKa); water solubility; octanol-water partition coefficient (K_{OW}); sorption to organic carbon (as indicated by the organic carbon-soil partition coefficient, K_{OC}); as well as its stability in environmental media.

Recently, Zheng *et al.* (2025) published a UK-scale spatial analysis of TRWPs, using the UK Integrated Assessment Model (UKIAM) (ApSimon *et al.*, 2021; Oxley *et al.*, 2004; Oxley *et al.*, 2009) coupled with emission pathway estimates for different road types derived from literature values. The model accounts for vehicle type and uses annual average daily traffic flows. The model estimates release of TWPs (i.e. rubber) and not the road wear component. The authors estimate 79,500 tonnes of TWPs are released from UK (including Northern Ireland) roads annually.

Comparison between outputs of different models was beyond the scope to this report. However, given the similarities to the approach used by Zheng et al., to the regional exposure scenario developed here, further assessment is warranted, and a comparison is made in Section 3.3.4.1. In any case, the models listed above discussed aspects of the exposure scenarios developed in this report, but none provided a comprehensive model that could be applied directly to GB that quantifies the release of both TRWPs and leachate to multiple compartments. These models either focus on only the aquatic environment, the quantification of release of either exclusively TRWPs or leachate, and are in some cases location specific and not relevant to the GB environment. Therefore, the local and regional scale exposure scenarios developed here apply approaches and data from a range of research and models. These exposure scenarios form the basis from which a detailed model can be parameterised. The release values from both of these scenarios can be input into environmental exposure models as a method to predict

the environmental fate of a substance and estimate exposure concentrations in different environmental compartments. For example, the regional exposure scenario developed in this report can be inputted into the European Union System for the Evaluation of Substances (EUSES) model (ECB, 2004) (see Annex 7). EUSES is a model that estimates the environmental fate of chemicals based on release quantities and physicochemical parameters. It is commonly used to satisfy regulatory obligations under EU and UK REACH.

3.1.1 Conceptualisation of the exposure scenario

To identify all the parameters relevant to the release and transport of TRWPs and the substances leached from the particles, the individual mass-flow stages in the exposure scenario must be conceptualised (Figure 2).

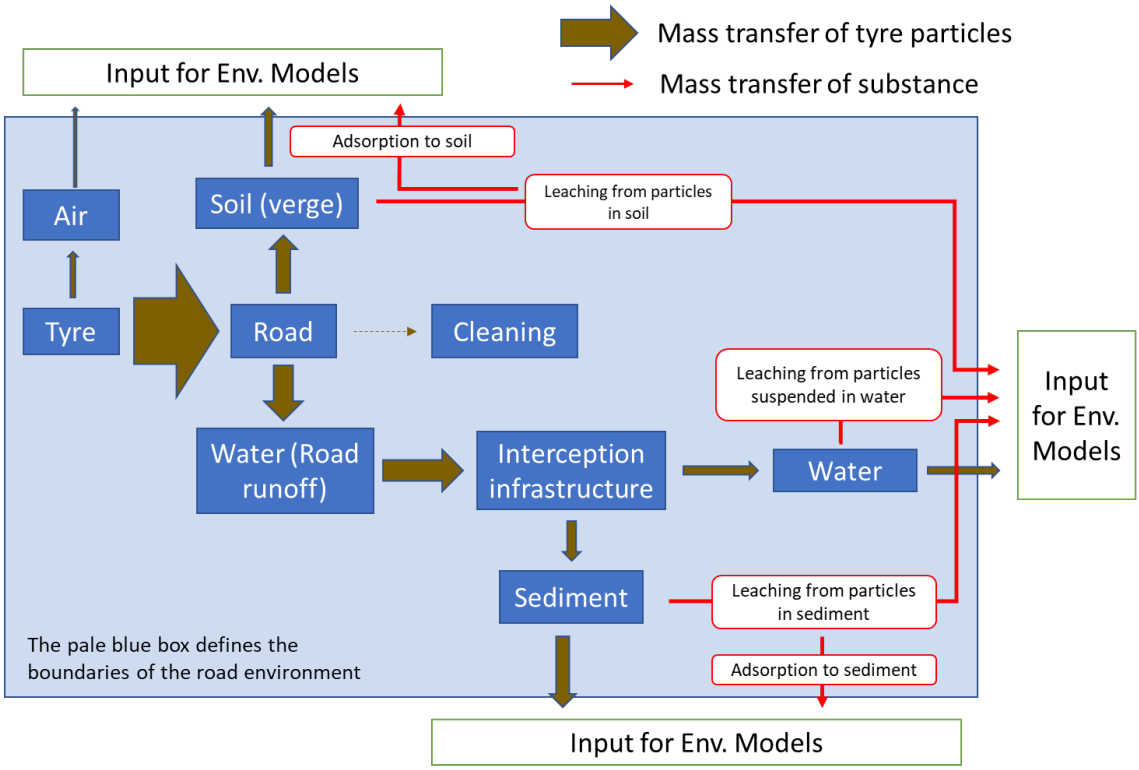


Figure 2 Conceptual mass flow of tyre rubber and its component chemicals within the road environment

The exposure scenarios are designed to address the processes that occur in what will be referred to as the "road environment". This covers the road itself, the verge of the road and any associated drainage infrastructure, including risk management measures (RMMs) that can trap released particles (often referred to as interception or mitigation measures). The exposure scenarios are designed to predict release masses of both rubber particles and substances from the road environment into the general environment away from the road. These masses are intended to be used as inputs into appropriate environmental fate models.

The exposure scenarios address release of rubber particles from tyres and the subsequent leaching of its component substances. Some substances, such as

vulcanising agents, are intentionally transformed during tyre manufacture. This can result in the formation of compounds other than those intentionally added. Therefore, the exposure scenario does not predict the transformation or degradation of component substances in the tyre manufacturing process or within the tyre itself, although understanding this process is important for selecting the correct input parameters.

Additives other than vulcanising agents are typically not consumed during the tyre manufacturing process but are intended to chemically react during the lifespan of the tyre (e.g. antioxidants and antiozonants). Most of the chemicals in tyres can be expected to degrade to some extent during the lifespan of the tyre. In combination, these complex processes mean that many more substances can be leached from tyres than are added.

The exposure scenarios assume that substances contained within the TRWPs do not degrade within the road environment. While this assumption may not be entirely accurate, insufficient data on the full range of tyre components and their degradation rates and products prevents this factor from being incorporated into the model. Further environmental fate modelling could be carried out to address this limitation.

3.1.2 Release, transport and exposure of tyre particles

3.1.2.1 Release of particles from tyres

The exposure scenarios and model developed in this project first assess and quantify the mass transfer of tyre rubber between different receiving sites in the road environment (see Figure 3). To calculate the mass of TRWPs that enters the environment, the inputs must be parameterised. A literature search (see Annex 1) was carried out to support this and provide input data.

A bottom-up approach to calculating the mass of TRWPs was chosen, based on the emission rates of TRWPs from different vehicles, on different road types and the distances driven, similar to the model developed by Mian *et al.* (2022). Vehicle travel distance data is readily available from the DfT while tyre wear rates for different vehicles are available in the literature. This approach was considered most applicable to both a local and regional scale, as opposed to the per capita (Sieber *et al.*, 2020) or mass balance approaches (Obermaier and Pistocchi, 2022) employed in some other models. Values in tonnes are rounded to the nearest whole value and values in kg are to one significant figure.

3.1.2.1.1 Road types

The exposure scenarios and model account for different road types, which feature different driving styles and TRWP emission rates. National-scale analyses show that in GB most land lies within just a few hundred metres of a road, and that the majority of road length is made up of minor or local access roads (Phillips *et al.*, 2021). In order to ensure data entry and parameter selection remains simple, roads are not categorised as described in the Design Manual for Roads and Bridges (NH, 2020; accessed 03/06/2024) and are instead categorised as being either urban, rural or motorways. Further

subdivision of road types is unlikely to change overall exposure outcomes and would complicate inputs. The definitions are not rigid and user discretion should be used when selecting the appropriate road type.

1. Urban roads are those within urban centres such as towns and cities where there would be regular braking and acceleration. These typically feature maximum speeds of 40 miles per hour (mph).

2. Rural roads are those that are not within urban areas and typically feature more bends or corners. For example, these are typically country “A” or “B” roads. These roads typically have speed limits of up to 60 mph.

3. Motorways are those with higher average speeds of up to 70 mph but relatively little braking, acceleration or requirement to change direction. Dual carriageways and motorways are included within this category of road, even if they are present within rural or urban settings.

The literature acknowledges that the rate of release depends on both the type of road and the type of vehicle but often examines only one of these variables. This means that there are a lot of values for the rate of release of rubber from cars in an urban environment but less data and therefore increased uncertainty for other road types and vehicles.

3.1.2.1.2 Emission rates

Collated TRWP and TWP emission rates from the literature search were used as the basis of the exposure scenarios and can be found in Annex 2. Results were collated for the following vehicle types: ICE cars, electric cars (battery electric vehicles, BEVs), motorbikes, vans, small lorries, large lorries and buses/coaches.

The road fraction of TRWPs does not contribute significantly to leachate mass. To determine a representative estimation of leachate from the rubber, the road fraction must therefore be accounted for in the collected literature emission rates. Data for the fraction of road wear in TRWPs is limited and often reported in numerous dimensions, such as by density (Klockner *et al.*, 2021b) or volume (Sommer *et al.*, 2018). Alves *et al.* (2020) and Kreider *et al.* (2010) reported TRWP road wear fractions by mass of 18% and 49% respectively, which equates to a 90th percentile lower confidence limit road fraction of 15%, and this value was chosen for conservativeness. The rubber fraction of TRWPs is therefore assumed to be 85%. This factor has been applied to literature data that contain a road fraction (i.e. TRWPs), so that the outputs of the model are given in terms of tyre-derived rubber particles only. If further data becomes available in the future, the exposure scenario could be updated to reflect this. The initial and adjusted values are presented in Annex 2.

To be conservative, it was decided to use the upper 90th percentile confidence limit of the collated emission data as the tyre rubber particle release quantity used for each vehicle type for urban roads. This approach could not be used for the other road types due to the

small sample size for rural roads and motorways, as it produced higher calculated emissions for rural and motorways than for urban roads. Given that reports which assessed each road type together showed that emission rates are always higher for urban roads, a different approach was therefore used to calculate the emission rates for rural roads and motorways.

The ratio of emission rates across each road type for a given vehicle type was calculated for each study that reported emission rates for all road types (for example, reports by Deltares and TNO (2016) and NAEI (2017) contained data for urban, rural and motorways as shown in Annex 2). An arithmetic mean emission rate relative to that of urban roads was calculated for each other road type. This value was multiplied by the upper 90th percentile limit for urban roads to give the emission rate for the vehicle on either rural roads or motorways. A higher emission rate for motorways compared urban roads has been calculated for BEVs due to the magnitude of the motorway emission rates reported by Woo *et al.* (2022a). The calculated ratios relative to the urban emission rates and overall emission rates (in milligram per kilometre driven, mg/vkm) used in the exposure scenario are shown in Table 1.

Table 1 Rubber particle emission rates for different types of vehicles used in the exposure scenario

Vehicle type	Urban emission rate (mg/vkm)	Ratio of rural to urban	Rural emission rate (mg/vkm)	Ratio of motorway to urban	Motorway emission rate (mg/vkm)
Car (ICE)	74	0.82	61	0.93	69
Electric car (BEV)	120	0.94	113	1.10	133
Motorbike	43	0.71	30	0.72	31
Van	155	0.71	111	0.72	113
Small lorry	508	0.64	327	0.79	399
Large lorry	913	0.61	555	0.72	660
Bus/coach	314	0.73	228	0.73	228

3.1.2.2 Uncertainties in tyre wear rates

The available literature varies in its reporting method, measurement methods and terminologies. Factors highlighted as being important to tyre wear rates were often lacking in supporting data and as a result several simplifications and assumptions were required in the exposure scenarios:

1. Tyre and particle considerations

    - Tyre age: The composition of a tyre will change during its normal use, and there is evidence to show changes in wear rate occur with increased tyre mileage (DfT, 2025b). As the change in composition of the tyre particles from a tyre over its lifetime has not been studied in detail, there is insufficient information to parameterise this factor in the exposure scenarios. In addition, as the exposure scenarios are intended to be used on a number of different

road types and locations it is assumed that there will be a wide range of tyre types and ages in use.

- Tyre type: The type of tyre also influences the rate of particle release. Seasonal tyres (e.g. for winter conditions) differ in tread composition and hardness, which can affect abrasion rates under different driving conditions. Wang *et al.* (2024c) notes that, compared to studless friction and summer tyres, studded tyres are more prone to wear and release more TRWPs (see also Hussein *et al.* (2008); Kupiainen and Pirjola (2011); Kupiainen *et al.* (2005)). This is attributed to the mechanical action of studs against the road surface, which accelerates tread abrasion. Because of their high anti-skid properties, studded tyres are widely used as snow tyres in some regions, but their elevated emissions have led to calls for restrictions on their use or the development of alternative designs. The model does not currently differentiate between tyre types. This factor may be particularly relevant in regions where studded tyres are common, as they could contribute to higher localised emissions. For GB, it is unusual for tyres to be changed between summer and winter compared to Europe.

- Tyre particle weathering: As with tyres, the composition of TRWPs is expected to change over time. The released particles will be leached by rainwater and further transformed by chemical, biological or photochemical action once in the environment (Li *et al.*, 2022; Liu *et al.*, 2022; Lu *et al.*, 2021). Particles with different degrees of weathering and the different environmental conditions that influence these processes will be present within any scenario modelled.

- Scale of release: Several reports provide a measurement or estimation of the rate of release of particles from tyres during use (for a review, see Baensch-Baltruschat *et al.* (2020)). Some address the annual quantity of rubber released on a national basis and others focus on the release from individual vehicles. As the goal of these exposure scenarios was to both predict regional release for long-term risk assessment and release at an individual site to understand the risk of URMS, it was considered that using data on individual vehicle release would be most appropriate to use as it could easily be scaled up for a regional assessment with knowledge of annual national traffic statistics. Therefore, the literature considered for designing the exposure scenario were those that reported a rate of release expressed as mass of rubber released per kilometre driven.

- Tyre particle type: Several different types of tyre particle can be examined and results can vary depending on the tyre type (Kreider *et al.*, 2010). It should also be noted that researchers often only collect a fraction of the tyre particulate for testing (e.g. PM_{10} or $PM_{2.5}$). This makes comparison across the different particle types difficult, especially when the different nomenclatures

are used interchangeably within the literature. Definitions for the particle types considered in this report are given in Section 2.1.

Recent evidence suggests that regardless of how particles are generated, their surface properties may become similar after environmental ageing and exposure to sewer water, as organic functional groups adhere to the particle surface (Li *et al*., 2024). This convergence is not accounted for in the exposure scenarios and model.

- Particle size distribution: It can be expected that the particle size distribution would have a significant impact on transport behaviour. Large particles are less likely to remain suspended in water while small particles may travel further when suspended in water or air (Zhang *et al.*, 2023).

  The International Organisation for Standardisation (ISO) has recently published standards for measurements of tyre particles (see, for example, ISO/TS 20593:2017 (2017) and ISO 22638:2024 (2024)). In some cases, the literature pre-dates these published methodologies and therefore the absence of a common methodology for reporting the measurement of particle size distribution makes it difficult to compare studies and obtain an overall assessment of rubber particle size distribution. Many studies use filtration or size exclusion to collect particles, which may exclude smaller particles in an assessment, or capture only the fine fraction. Particle size distributions often become skewed towards increased particle size following the initial release from the tyre. This could be due to particles agglomerating or the fine fraction being lost from the road environment due to atmospheric transport. Finally, inconsistency in the units used to report particle size distribution also limits comparability. Reporting distributions by mass or volume biases results towards larger particle sizes. If the only goal is to understand mass flow, this may be acceptable.

  The Committee on the Medical Effects of Air Pollutants (COMEAP) has highlighted that non-exhaust particles from sources such as tyre wear contribute to adverse health outcomes, particularly through fine and ultrafine fractions (COMEAP, 2020), although modelling human exposure from tyre particulates and additives is beyond the scope of this report**.** The current evidence base is limited, and a firm conclusion cannot be drawn from the literature search on the size of each particle fraction (see Section 3.2.1 for more details), so the exposure scenarios and model do not differentiate between different size fractions of TRWPs. The role of the air pathway in these exposure scenarios may be underestimated.

  Table 2 provides an indication of the size ranges measured in the literature.

Table 2 Reports of rubber particle size distribution in the academic literature

Reference	Type of particles analysed	Size	Range determination method and additional comments
Andersson-Skold *et al.* (2020)	Airborne	Range: 2.5 - 80 µm	Unclear whether distribution range is determined by number, mass or volume
Jarlskog *et al.* (2020)	Road dust collected during cleaning	Sweep sand: 0.6 – 2,000 µm Wash water: 100 – 300 nm Storm water: 2 – 100 µm	Distribution range based on volume
Kumar *et al.* (2013)	Nanomaterials	15 – 700 nm	Various
Knight *et al.* (2020)	Particles collected in drains/sewage treatment plant (STP)/soil	94 – 101 µm elongated	Unclear whether distribution range is determined by number, mass or volume
Kovochich *et al.* (2021)	Road dust and sediment	Dust: Range 6 – 649 µm; mean 158 µm Sediment: Mean 267 µm; 54% elongated Tunnel dust: Mean 54 µm; 74% elongated	Distribution range determined by number
Yan *et al.* (2021)	Lab simulation: fine fraction	Range 1 – 10 µm; mean 5 µm	Distribution range determined by mass of elongated particles
Wang *et al.* (2021)	Lab simulation	Mainly > 435 µm	Unclear whether value is determined by number, mass or volume
Liu *et al.* (2021)	Lab simulation and during driving	Lab: 1 – 10 µm (by mass); 15 – 50 nm (by number) Driving: 70 – 80 µm (mass)	
Kreider *et al.* (2010)	Road particles and TWPs	Road particles: 4 – 280 µm; modal average: 50 µm TWP: 5 – 220 µm	Distribution range determined by volume
Klockner *et al.* (2021a) (Klockner *et al.*, 2021b)	Tunnel dust	Mainly 20 – 50 µm	Distribution range determined by mass
Wagner *et al.* (2018)	TWPs, collected during driving, runoff	TWP: 0.001 – 100 µm Driving: 0.2 – 20 µm Runoff: 1 – 250 µm	Unclear whether distribution range is determined by number, mass or volume

Reference	Type of particles analysed	Size	Range determination method and additional comments
Zhong *et al.* (2024)	TWPs, lab simulation	6 nm – 0.1 µm, 94.8% of particles 0.1 µm – 2.5 µm, 5.18% of particles 2.5 µm – 10µm, 0.02% of particles	Distribution range determined by number
Parker-Jurd *et al.* (2021)	TRWPs, collected from storm drain, STP effluent and atmospheric deposition	Range: 15 – 415 µm Average Length (all particles): 43 µm Average Length (Storm drain): 42 µm Average Length (Atmospheric): 36 µm Average Length (STP): 21 µm Mode: 20 µm	Unclear whether distribution range is determined by number, mass or volume. LOD is 15 µm.
Schläfle *et al.* (2023)	TWPs, lab simulation	0.3 – 17 µm	Unclear whether distribution range is determined by number, mass or volume

2. Road and physical considerations

- Driving style: Aggressive driving increases the rate of tyre wear when compared to steady acceleration and braking (Rodland *et al.*, 2022). Cornering increases the lateral forces on the tyre which increases tyre wear, especially at speed. As the exposure scenario is targeted to the release of particles across a given geographical area (rather than for an individual tyre), it can be assumed that a range of driving styles would be present, which are not parameterised separately in the exposure scenarios.

- Distance-dependant pollutant attenuation: Concentrations of pollutants decline with distance from roads, but the rate of attenuation varies by pollutant type. Phillips *et al.* (2021) reported that concentrations of metals typically return to background levels within 10–50 m of the road verge, while PM_{10} and smaller particulate matter can disperse for several hundred metres (see Section 2.2). Given that 68% of land in England is used for agricultural purposes (DEFRA, 2025b; accessed 05/12/2025), 50% of land in GB lies within 216 m of a road and >70% of land is within a road-affected zone (Phillips *et al.*, 2021), agricultural soils are considered an appropriate receptor for airborne particulate in this exposure scenario. The exposure scenarios and model do not explicitly parameterise the concentration decrease with distance from the road, but assume that soils across the transport network are subject to representative levels of road-derived pollutants.

- Road material and condition: The material that the road surface is made from can have a significant impact on the wear rate of a tyre (He *et al.*, 2024). A softer road material, such as asphalt, generates fewer TRWPs than a harder road surface such as concrete. The road surface also alters the composition of the TRWP fraction in road debris. As there is little information on GB road surfaces and distribution, the impacts of road surface are not considered further. Damaged roads surfaces are expected to lead to greater tyre wear versus 'smooth' roads. It is assumed that there is a mixture of roads in good and poor condition, but the effect of road condition is not considered further.

- Temperature: Contact of the road surface with a tyre generates heat during use due to friction. Recent studies confirm that tyre emissions vary with temperature and tyre type (Miech *et al.*, 2024; Schläfle *et al.*, 2023), and that higher temperatures can accelerate TWP aging within the environment (Zhang *et al.*, 2024a). All tyres have a glass transition temperature (T_g), which is lower for winter tyres. Tyres used in conditions beyond or at the extremes of their T_g can become brittle and thus wear faster (e.g. a summer tyre used in winter). However, the exposure scenarios do not account for seasonal temperature, tyre-type variation or the heating effect caused by friction over long journeys.

- Seasonal deviations: Tyre wear rates can vary between wet and dry seasons, with higher wear observed in cold and wet weather due to increased material rigidity and rolling resistance (Chae *et al.*, 2024; Liu *et al.*, 2024). In addition, environmental concentrations of leached chemicals may increase during dry seasons due to reduced dilution. The exposure scenarios do not explicitly account for seasonal variation. At a local scale, using "days since rainfall" as a parameter accounts for some of this variability, although environmental concentrations would still be expected to be higher in dry periods due to increased accumulation. At the regional scale, such seasonal differences are assumed to average out over the annual timeframe considered in this scenario.

3. Vehicle considerations

- Vehicle class mass variations: No adjustments are made within the model for the variability of vehicle mass when passengers or goods are carried, even though the additional load increases vehicle weight and can influence tyre wear rates. For example, a car carrying three passengers of average weight (70 kg) increases the weight of an average car (1481 kg (ICCT, 2023)) by ~15%. This means that variability in load within a given vehicle class (e.g. an empty versus fully laden lorry, or sports utility vehicle (SUV) versus a small car) is not represented. However, the exposure scenarios do distinguish between broad vehicle categories (i.e. cars, vans, lorries, buses), with emission ranges for each collated from the literature (see Annex 2).

The terms “lorry” and “truck” were used by some authors. For the purposes of categorisation in the model It was assumed that “lorry” referred to a small lorry and “truck” referred to a larger vehicle based on the relative emission rates stated. In addition, the terms “van”, “small truck” and “large truck” are not defined using either a weight or number of axles as a unit. This is in contrast to the traffic figures used in the case study (see Section 3.4.1).

Based on the outline above, the exposure scenario has been parameterised for both a local and a regional scale. The local scale exposure scenario considers a defined length of road across a timescale of days (i.e. since last rainfall event) for the purpose of predicting URMS events. The regional scale exposure scenario considers the whole of the GB road network across an annual timescale. Both allow for calculation of released of TRWP and leachate mass. The two exposure scenarios are considered separate entities with different intended purposes, aside from shared input emission rates, partitioning fractions and assumptions.

A model has been developed based on these scenarios to allow for calculation of the local and regional exposure outputs. Input data and interception variables can be adjusted as required to best suit the location being modelled. The local exposure scenario and model development are discussed below in Section 3.2, the regional scenario is discussed in Section 3.3.

3.2 Local Scenario

A model was developed based on the local exposure scenario to estimate the total daily emission at a specific location, which can be used to compare release from different locations, relative peak/low traffic emissions, location-specific risk assessments and targeted interception measure placement. An annual estimation of partitioned releases is also calculated based on the daily emissions, although care should be taken interpreting this estimation as input of high or low traffic flow may result in under or overestimation of annual emissions. Each combination of vehicle type and road length is calculated and summed to estimate the total daily emission for a specific road type. Only one road type can be selected for each calculation. In geographical areas where more than one road type is to be assessed, the user must calculate and sum emissions for each road type. The distribution of tyre rubber to different environmental compartments differs between road types.

Figure 3 illustrates the cells within the model where data input is required; this can be found on the “Particle Exposure” tab of the model. The model requires input of actual daily traffic volume data. The user must input the type of road, length of road and the daily traffic volume.

Data made available from the DfT provide details on vehicle type and frequency. However, the data does not typically differentiate BEVs from ICE cars. It is reported that 1.06% of licensed cars in GB were electric in 2021, according to VEH0101 and VEH0141

(DfT, 2021; accessed 13/06/2024). The total number of cars from the traffic data can therefore be partitioned between BEVs and ICE cars based on this information if specific data are not available.

Equation 1 Calculating the total estimated tyre particle emission rate for a specific geographical area. Based on road type, road length and daily traffic volume

$$E_{daily,road\ type} = R_L\left(N_{vehicle} \cdot E_{vehicle,road\ type}\right) + R_L\left(N_{vehicle} \cdot E_{vehicle,road\ type}\right) + R_L\left(N_{vehicle} \cdot E_{vehicle,road\ type}\right) \ldots$$

Where: **$E_{daily,\ road}$** = Sum of estimated emissions from all vehicles within a specific road type (mg/day)

R_L = Length of road (km, data provided and input by model user)

$N_{vehicle}$ = Number of vehicles, based on daily traffic volume. Each vehicle type must be considered individually. $N_{vehicle}$ is the general symbol used to illustrate N_{car}, N_{bike}, N_{van}, $N_{small\ lorry}$, $N_{large\ lorry}$, N_{bus}, $N_{elec.\ car}$ (data provided and input by model user)

$E_{vehicle,road}$ = Volume of emissions estimated for a specific vehicle type on a specific road type (mg/km, no user input required as the values presented in Table 1 are built into the model).

$E_{vehicle,road}$ = specific emission values from the combinations of vehicle type and road type:

$E_{car,urban}$, $E_{bike,urban}$, $E_{van,urban}$, $E_{small\ lorry,urban}$, $E_{large\ lorry,urban}$, $E_{bus,urban}$, $E_{elec.\ car,urban}$

$E_{car,rural}$, $E_{bike,rural}$, $E_{van,rural}$, $E_{small\ lorry,rural}$, $E_{large\ lorry,rural}$, $E_{bus,rural}$, $E_{elec.\ car,rural}$

$E_{car,motorway}$, $E_{bike,motorway}$, $E_{van,motorway}$, $E_{small\ lorry,motorway}$, $E_{large\ lorry,motorway}$, $E_{bus,motorway}$, $E_{elec.\ car,motorway}$

Location characteristics	What is the type of road?	Motorway	
	What is the daily traffic volume?		
	Cars (ICE)	37759	
	Motorbikes	268	
	Vans	10244	
	Small lorries	2416	
	Large lorries	8310	
	Buses	202	
	Electric cars (BEV)	405	
	What is the length of road in question?	1	km
	Road surface type - Porous Asphalt?	no	
	Where does the road drain to?	Drain leading to Settlement Pond	
	Is the road cleaned regularly	no	

Figure 3 Model interface and user input for road type, traffic volume and length of road. All pale green boxes require a value. Values shown reflect the inputs used in the case study discussed in Section 3.4

3.2.1 Distribution of tyre particles

The exposure scenario assumes that a fraction of the particles released are sufficiently small to become airborne and are removed from the immediate road environment by wind. Different studies have stated a range of values for release to air (Table 3). There is evidence within the literature that suggests the residence time of ≤PM_{10} in the atmosphere can be multiple days (Brahney *et al.*, 2021). However, there is not sufficient data to parameterise this within the exposure scenario and particles released to air are assumed to remain in the atmosphere for the duration of the local scenario timeframe. Further refinement of atmospheric residence and transport could be carried out in a future review of the model. The exposure scenario does not account for particle resuspension from the road, which may lead to underestimation of the total amount of tyre rubber particles distributed to air.

Table 3 Literature estimates for the proportion of TRWPs released to the air

Reference	% TRWPs airborne
ten Broeke *et al.* (2008)	5
Unice *et al.* (2019)	2
Sieber *et al.* (2020)	0.6
Verschoor *et al.* (2016)	5
Prenner *et al.* (2021)	5.7
(Rounded) Arithmetic mean	**4**

The exposure scenario assumes that the proportion of tyre rubber particles released to air corresponds to the arithmetic mean of the literature values, rounded to the nearest integer. Therefore, it is assumed 4% of tyre rubber particles are released to air and the remaining 96% are deposited on to the road. Equation 2 and Equation 3 present the calculations used within the model.

Equation 2 Calculating the mass of rubber particles released to the air

$$\mathbf{M_{daily,air}} = \mathbf{0.04} \times \mathbf{E_{daily}}$$

Equation 3 Calculating the assumed mass of rubber particles deposited on the road

$$\mathbf{M_{daily,road}} = \mathbf{0.96} \times \mathbf{E_{daily}}$$

Where: **$M_{daily, air}$** = Estimated mass of particles released to the air compartment (mg/day)

$M_{daily, road}$ = Estimated mass of particles deposited on the road (mg/day)

E_{daily} = Sum of estimated emissions from all vehicles within a specific road type (mg/day, Equation 1)

The mass of particles released to the air is not included in the subsequent calculations in the local model for transport of particles into soil (verge), runoff or for leaching of substances from the tyre-derived rubber particles.

3.2.2 Correction factors for road cleaning and porous asphalt

Before calculating particle transport, two processes that can reduce the number of particles available for mobilisation are addressed:

1. Road cleaning: Jarlskog *et al.* (2020) examined sweep sand, wash water and road dust from urban streets in Sweden and estimated that road cleaning removes 10% of the annual load of tyre particles from the road surface. Some studies indicate that cleaning can remove certain size particles preferentially but there are contradictions around whether larger or smaller particles are removed (Polukarova *et al.*, 2020; Snilsberg *et al.*, 2017). As the exposure scenario does not address

particle size these results are not included in the exposure scenario. The user should provide input to the model on whether road cleaning takes places in the cases used for their exposure scenario. If cleaning is undertaken, the amount of tyre rubber remaining is calculated using the equation below. If road cleaning is not undertaken, no correction is made. The model assumes that cleaning waste is not released back into the environment after collection and is instead disposed of in accordance with GB waste legislation.

Equation 4 Calculating the particles removal by road cleaning processes

$$\mathbf{M}_{\mathbf{after\ cleaning}} = \mathbf{M}_{\mathbf{daily,road}} \times \mathbf{Correction\ Factor}_{\mathbf{cleaning}}$$

Where: $\mathbf{M}_{\mathbf{after\ cleaning}}$ = Estimated mass of particles remaining on the road after sweeping (mg/day)

$\mathbf{M}_{\mathbf{daily,\ road}}$ = Estimated mass of particles deposited on the road (mg/day, Equation 3)

$\mathbf{Correction\ Factor}_{\mathbf{cleaning}}$ = Correction factor applied depending on occurrence of road cleaning

Road cleaning occurs = 0.9

Road cleaning does not occur = 1

2. Porous road surfaces: A Dutch government report into particles released to the road network in the Netherlands (Verschoor and de Valk, 2018) includes a correction for tyre particles held within the surface of the road by porous asphalt (Zeer Open Asphalt Beton, ZOAB) which is used to surface motorways. No further details are given regarding the properties of this asphalt, so it is not clear whether this or similar porous asphalt is used on GB roads. However, one leading GB asphalt manufacturer does not appear to supply porous asphalt for use on roads, suggesting it is not widely used (Tarmac, 2024; accessed 17/05/2024). The study indicates that the porous asphalt holds 90% of tyre particles making them unavailable for transport into verges or drainage systems. There is no data available on whether other road surfaces immobilise tyre particles; therefore, the exposure scenario assumes they do not. No studies have been performed to investigate whether rubber held in the road surface can still leach substances as rainwater passes through the asphalt. If new information is made available, this part of the exposure scenario should be updated.

   The user should state whether the road surface under assessment is made of porous asphalt in the user entry portion of the model. If porous asphalt is used, the mass of tyre rubber available for mobilisation by rain is calculated using the equation below. If porous asphalt is not used, no correction is made.

Equation 5 Estimating the mobilisable particles on porous asphalt

$$\mathbf{M_{mobilisable}} = \mathbf{M_{after\ cleaning}} \times \mathbf{Correction\ Factor_{asphalt}}$$

Where: **$M_{mobilisable}$** = Estimated mass of mobilisable particles (mg/day)

$M_{after\ cleaning}$ = Estimated mass of particles remaining on the road after sweeping (mg/day, Equation 4)

Correction Factor$_{asphalt}$ = Correction factor applied depending on asphalt type

Non-porous = 1 (default setting)

Porous = 0.1

3.2.3 Particle mobilisation

The exposure scenario assumes that tyre particles are only mobilised for distribution into the environment by the action of rainfall. This may be by surface runoff into drainage systems, by movement of surface runoff onto roadside verges or by splashing of particle-containing standing water onto verges. Therefore, in the absence of rain there is accumulation of tyre rubber particles on the road surface. This assumption is unlikely to have a significant impact on the accuracy of the model despite the likelihood of some smaller particles being transported into verges by resuspension into the air from passing vehicles. In any case, in the absence of data on this type of distribution, the conservative approach is to assume all particles not made airborne are mobilised during rainfall events. Unice *et al.* (2019) state that particles are not mobilised by any rainfall below 2 mm/day and are only completely mobilised by rainfall exceeding 5 mm/day (i.e. heavy rain). To assess an individual release event at the local scale, as would be required to understand whether any acute effects seen during URMS is a potential issue in GB, the exposure scenario requires the user to input the number of days since a heavy rainfall event occurred (T_{rain}). Unice *et al.* (2019) do not estimate the efficiency of particle removal by rainfall events of 2 to 5 mm/day (i.e. light rain), so the exposure scenario assumes a 50% removal for these events.

To provide some context to these rainfall event values, the EUSES default values for the average precipitation rate at the regional scale is 700 mm/year (ECB, 2004) and the Met Office (2022; accessed 01/05/2024) has reported average rainfall in GB for the last twenty years (2000-2021) as:

- England 870 mm/year
- Wales 1,465 mm/year
- Scotland 1,573 mm/year

The mass of particles accumulated on the road available for mobilisation is calculated by multiplying the daily mass of mobilisable particles by the number of days since a heavy rainfall event.

Equation 6 Estimating the mass of accumulated particles, accounting for time since last rainfall event

$$\mathbf{M_{accumulated}} = \mathbf{M_{mobilisable}} \times \mathbf{T_{rain}}$$

Where: $\mathbf{M_{accumulated}}$ = Estimated mass of particles accumulated since last >5 mm/day rainfall event (mg)

$\mathbf{M_{mobilisable}}$ = Estimated mass of mobilisable particles (mg/day, Equation 5)

$\mathbf{T_{rain}}$ = Length of time since last heavy rainfall event (days)

As stated previously, the mass of particles mobilised by a rainfall event depends on the intensity of the rainfall event. If the user is interested in the impact of a single event, they should manually choose the intensity of the rainfall event as either < 2 mm/day, light rain or heavy rain. The choice prompts the following calculations:

Equation 7 Estimating the mass of particles mobilised during rainfall events of various intensity

< 2 mm/day	No particles are mobilised
Light rain (2 to 5 mm/day)	$\boldsymbol{M_{mobilised}} = \mathbf{0.5} \times \boldsymbol{M_{accumulated}}$
Heavy rain (> 5 mm/day)	$\boldsymbol{M_{mobilised}} = \boldsymbol{M_{accumulated}}$

Where: $\mathbf{M_{accumulated}}$ = Estimated mass of particles accumulated since last heavy rainfall event (mg, Equation 6)

$\mathbf{M_{mobilised}}$ = Estimated mass of particles that is mobilised during the rainfall event (mg)

The annual estimation of TRWPs released from a site does not consider the mobilisation of particles by rainfall events. All particles deposited to the road surface are considered to be mobilised over this timeframe.

3.2.4 Particle transportation away from the road surface

Particles can travel via the surface flow of water to artificial drainage, natural drainage channels or verges. Particles may also reach verges via physical action of spray from the road surface. The proportion of particles transported to either the watercourse or soil (verge) is dependent upon the road type.

Table 4 shows the values for relative proportion of TRWPs distributed into each receiving environmental compartment considered in the exposure scenario. The values were informed by available literature estimations of particle release to runoff and soil. The available estimations were normalised to total 100%, correcting for the proportion released to air, and an average value was calculated. The average normalised values

are presented in Table 4 and used in the exposure scenario. Details of the calculations and literature are available in Annex 3.

Table 4 Relative proportion of TRWPs distributed into each receiving environmental compartment used in the exposure scenario

Receiving Site	Proportion of particles released Urban roads (% w/w)	Proportion of particles released Rural roads (% w/w)	Proportion of particles released Motorways (% w/w)
Soil (verge)	44	75	67
Watercourse	56	25	33

The exposure scenario partitions the mobilised particles according to the values in Table 4 to give a mass transported to soil in the verge and to a receiving watercourse. The receiving watercourse can vary depending on the road type. Urban roads will have artificial drainage, rural roads may drain directly into streams but more likely into roadside ditches and motorways may drain into settlement or retention ponds. Soil sampling on verges of dual carriageways has shown that particles can reach up to 10 m from the carriageway with a greater concentration nearer to the road (Kibblewhite, 2018; Muller *et al.*, 2022a). As GB motorways usually have a hard shoulder that is approximately 3.5 m wide and dual carriageways do not, it can be expected that a greater proportion of particles will reach soil in the verge of dual carriageways than motorways where it will collect on the hard shoulder. Since there is no available data on this issue it is not addressed in the exposure scenario, but the scenario should be updated if new research is published.

3.2.5 Transport within the receiving site

The soil in verges is regarded as a sink for rubber particles, meaning they are not expected to be transported further into another environmental compartment (chemicals can still be leached from the particles and transported, and this is addressed in Section 4). The movement of soil to water bodies through erosion is not considered in the model.

Once particles are transported from the road in water, interception measures (drainage, roadside ditch, retention pond etc.) can trap particles and prevent their release into the wider environment (see Stang *et al.* (2022) for an overview). The interception measure in place will typically depend on the type of road and their effectiveness in removing particles has been examined:

1. Motorways: Settlement ponds are often constructed alongside motorways at sites expected to have a high traffic density combined with acceleration/braking (e.g. junctions). As with drainage ditches, these are relatively static waterbodies containing natural organic matter. As a result, a significant proportion of particles will settle into the sediment of these ponds. The 90th percentile upper confidence limit of the effectiveness of particle removal from water is estimated to be 80.4% (average value of efficacy estimations in the academic literature, see Annex 4 for

references). There are a number of interception measures that National Highways use on the SRN on a case-by-case basis. For the purposes of report, only settlement ponds are considered, but the model can be adjusted by the user to account for other measures and the expected removal efficiency adjusted accordingly.

2. Rural roads: It is assumed that the principal receiving body for surface water runoff from rural roads will be drainage ditches. These are generally small bodies of very slow running or static water containing natural organic matter. As particles from tyres have a density > 1 g/cm^3 (Klockner *et al.*, 2021a; Klockner *et al.*, 2021b) many particles, especially large particles, will sink and collect in the sediment in these ditches before they can be transported into rivers or streams (NH, 2023c). The effectiveness of particle removal from freshwater by settling into sediment has been estimated as 75% (singular efficacy estimation in the academic literature, see Annex 4 for references).

3. Urban roads: Drainage systems in the urban environment can direct road surface runoff to watercourses or to a STP through a combined sewer network before water is released to surface waters. Based on confidential data for one GB city, the rounded area coverage is 60% runoff sewers and 40% combined sewer (Gutierrez Dominguez, 2025). In the absence of other GB specific data, this assumption is used in the exposure scenario and model. Once entering the STP, the removal efficiency of rubber particles is expected to be high (96.3%, 90th percentile upper confidence limit) based on data for microplastics (see Annex 4 for references). Accounting for this interception, the partitioning of rubber particles mobilised in road runoff is 61.5% to surface waters and 38.5% to STP sludge. The figures have been rounded for simplicity and are conservative.

   Tian *et al.* (2021) do not state whether the sites where URMS is observed released the storm water to a STP or directly to a river, but if it is the latter this could explain why URMS is only observed in specific locations. Other interception measures can be used in specific situations (e.g. gully pots), but as their use frequency is not known they are not addressed in the scenario.

For the local exposure scenario, any rubber particles contained within sludge or sediment are assumed to remain within the respective interception measure due to the shortened calculation timeframe.

Data indicating the frequency of interception measures for rural roads and motorways was not available at the time of the literature search. NH (2023a) indicates that up to 254 outfalls on the SRN (which accounts for 3% of GB roads) present a high risk and require mitigation. The total number of outfalls and soakaways, and how they compare in number to settlement ponds or other interception methods, is not indicated within the report. To accommodate for this uncertainty and the potential worst-case scenario of an absence of interception measures, it is possible to bypass interception within the model. This may however lead to overestimation of releases to water and underestimation of releases to

other environmental compartments. The model should be updated if data becomes available that allows for determination of the frequency of interception measures.

3.2.6 Model output - Display of results

The model output reports the mass of rubber particles released from tyres found in different environmental compartments, from both a single rainfall event and on an annual basis. A single event does not necessarily represent a daily release as the exposure scenario considers accumulation during dry periods before the rainfall event. An example output is shown below in Figure 4.

Individual rainfall event	Rubber particle mass held in soil (verges)	**19.8**	**kg**
	Rubber particle mass released to air	**0.4**	**kg**
	Rubber particle mass trapped by runoff interception measures	**7.9**	**kg**
	Rubber particle mass released to surface waters (non-road environment)	**1.9**	**kg**

Annual releases	Rubber particle mass held in soil (verges)	**2406.1**	**kg**
	Rubber particle mass released to air	**150.3**	**kg**
	Rubber particle mass trapped by runoff interception measures (non-road environment)	**965.1**	**kg**
	Rubber particle mass released to surface waters	**235.6**	**kg**

Figure 4 Display of results of release of tyre-derived rubber particles in the exposure scenario (results displayed are related to the case study presented in Section 3.4)

The mass held in soil refers to the soil in the verges adjacent to the road. The nature of the interception measures where particles are held will depend on the type of road being examined (see Section 3.2.5). A watercourse is assumed to be a flowing body of water, such as a stream or river, that particles can enter after passing through a treatment measure. The exposure scenario does not consider the fate of the particles once released to a watercourse. However, there are other exposure models that have investigated the fate of microplastics in the environment and the mass of rubber particles released to watercourses can be used as the input value for these models (e.g. the Full-Multi model developed in the Nano2Plast project (Domercq *et al.*, 2022)).

3.3 Regional Scenario

To estimate releases of rubber particles that can be used for a more generic risk assessment across a larger geographic area, a regional approach is needed. Based on the exposure scenario discussed in Section 3.1, a regional scale model has been developed that considers the whole of the GB road network and calculates the national releases of TRWPs and environmental concentrations of leachates. There is no user

input for the regional model, but the annual vehicle travel distance detailed in Section 3.3.1 below can be updated by the end user.

3.3.1 Travel miles categorised by vehicle type and road type

National traffic data is required for the regional exposure scenario. Annual GB road and traffic data used for the exposure scenario was taken from DfT (2025a; TRA0204), which breaks down the distance travelled by each type of vehicle by the road types Motorways, 'A' Roads and Minor Roads (Table 5). The reported travel distance data has a category for HGVs, whereas the particle release data (Table 1) addresses lorries (small lorries) and trucks (large lorries) separately. To overcome this a particle release rate for HGVs was calculated for each road type by averaging the values for lorries and trucks. It should be noted that ICE and BEV cars are not differentiated in this data.

Table 5 Summary of the travel distance by different types of vehicles on each road class in GB for 2024

Vehicle type	Motorway Travel Distance ($x10^9$ km)	'A' Road Travel Distance ($x10^9$ km)	Minor Roads Travel Distance ($x10^9$ km)
Car	78.6	184.2	149.5
Van (LGV)	21.2	39.7	33.2
Lorry (HGV)	12.7	12.1	2.0
Motorcycles and scooters	0.3	1.9	2.5
Buses and coaches	0.3	1.4	1.4

In DfT (2025a; TRA0204), 'A' roads are subdivided into principle and trunk roads and then further subdivided into rural and urban categories, minor roads are subdivided into rural and urban. Motorways and dual carriageways are expected to have the same driving behaviour whether they are in an urban or rural situation but are included with the 'A' road data. Overall GB road length data published in DfT (2026; RDL0201) can be used to partition the 'A' road data between dual carriageways and other road types. The road length data is summarised below in Table 6.

Table 6 GB road length data

DfT Road Categories	Length (km)	DfT Road Categories Subcategories	Length of road type (km)
Motorways	3,751	**Motorways**	3,751
All 'A' Roads	47,783	**Rural 'A' road (centrally and locally managed)**	36,034
		Urban 'A' road (centrally and locally managed)	11,750
All Minor Roads	346,308	**Rural minor roads (B, C and U)**	205,644
		Urban minor roads (B, C and U)	140,665

The data indicates that of the 47,783 km of 'A' road length, there is 8,694 km of dual carriageway in GB, of which 5,809 km is rural and 2,886 km is urban, which is subtracted from the 'A' road data and summed with the motorway data. Dual carriageways can be calculated to account for 19.2% of rural A roads and 32.6% of urban 'A' roads, applying these fractions to the travel distance data (Table 5) gives the values presented in Table 7. This approach introduces uncertainty, but in the absence of more detailed data it is considered to be acceptable.

Table 7 Conversion of the travel distances of each type of vehicle into categories based on the location of the road

Vehicle Type	Motorway Travel Distance ($x10^9$ km)	Dual Carriageway ('A' Roads) Travel Distance ($x10^9$ km)	Rural A Road ('A' Roads) Travel Distance ($x10^9$ km)	Urban ('A' Road) Travel Distance ($x10^9$ km)	Rural Minor Road Travel Distance ($x10^9$ km)	Urban Minor Road Travel Distance ($x10^9$ km)
Car	78.6	43.6	98.9	41.7	60.5	89.0
Van (LGV)	21.2	9.2	22.9	7.6	17.2	16.0
Lorry (HGV)	12.7	2.6	7.9	1.6	1.1	0.9
Motorcycles	0.3	0.5	0.8	0.6	0.7	1.8
Buses	0.3	0.4	0.5	0.5	0.4	1.0

The data in Table 7 can then converted into travel distance for each road type used in literature studies for rubber particle release by summation of motorways and dual carriageways and of the rural and urban related categories. The travel distance of BEV is calculated as 1.06% of the travel distance of ICE cars as described in Section 3.2.

Table 8 Travel distances of different vehicle types on the categories of road used to predict TRWP emissions

Vehicle Type	Motorway Travel distance ($x10^9$ km)	Rural Travel distance ($x10^9$ km)	Urban Travel distance ($x10^9$ km)
Car	120.9	157.7	129.3
BEV	1.3	1.7	1.4
Van (LGV)	30.4	40.1	23.6
Lorry (HGV)	15.3	9	2.5
Motorcycles	0.8	1.5	2.4
Buses	0.7	0.9	1.5

3.3.2 Annual particle release across GB

The annual particle release from rubber tyres for each type of vehicle across each road type is calculated by multiplying the travel distance (km, Table 8) by the rate of particle release (mg/km, Table 1). This calculation can be used to estimate the total annual particle release prior to environmental portioning or interception across each road type and across each vehicle type (Table 9). It is important to calculate particle release for

each road type separately because of different risk management measures present and subsequent partitioning.

Table 9 Estimated TRWP emission from different types of vehicles on motorways, urban and rural roads

Vehicle Type	Motorway Particle release (t/y)	Rural Particle release (t/y)	Urban Particle release (t/y)	Total Particle release (t/y)
Car	8,314	9,593	9,586	**27,494**
BEV	173	192	169	**534**
Van (LGV)	3,385	4,438	3,660	**11,483**
Lorry (HGV)	8,102	3,970	1,776	**13,848**
Motorcycles	25	45	103	**173**
Buses	160	205	471	**836**
All vehicles	**20,159**	**18,444**	**15,765**	**54,369**

The regional exposure scenario estimates an annual release of 54,400 tonnes of rubber particles from tyres used on roads across GB. This is close to the Environment Agency's 1998 estimate of 53,000 tonnes across the GB (note that this estimate was calculated based on the loss of tyre mass from a lifecycle and traffic volumes have increased since 1998 from 274 billion vehicle miles to 338 billion vehicle miles in 2024 (DfT, 2022a; accessed 01/05/2024; EA, 1998); the data reported in 1998 also included Northern Ireland). Approximately 40 million tyres are recovered within the UK each year (TRA, 2024; accessed 04/07/2024). Assuming each tyres weighs 11 kg with 85% rubber-related content (i.e. not cord or textiles), and that 12% of this rubber is lost to wear prior to processing, the resulting mass balance indicates 44,900 tonnes of rubber released to the environment. As not all used tyres are recovered, this provides some support for the regional GB estimate.

3.3.2.1 Partitioning between environmental compartments

The partitioning approach and assumptions described in Section 3.2 for the local exposure scenario are used to calculate the annual regional release to each road type. However, there are some assumptions that are unique to the regional exposure scenario and model:

1) It is assumed that all particles dispersed into air are transported away from the road and subsequently deposited to agricultural soil in the wider environment (i.e. not roadside verges). Therefore, the regional model assumes 4% of particles are emitted to air (Section 3.2.1) and subsequently to land.

2) As a worst-case scenario, it is assumed that no porous asphalt is used in GB roads.

3) The regional exposure scenario considers a timeframe of a year, over which it would rain multiple times. Therefore, all released particles are assumed to be mobilised.

4) It is assumed that the vast majority of particles collected by each interception method, with the exception of street cleaning, are removed in the form of sludge

that is applied to agricultural soil or redeposited alongside the watercourse. This assumption may result in overestimation of releases to agricultural soil or soil within the wider environment (i.e. not immediately adjacent to a road). However, until new research or further data is published the model will use this assumption.

Based on these assumptions, the TRWP partition to different environmental compartments in the proportions described in Table 10.

Table 10 Normalised values used to predict the partitioning of particles into different sites within the road environment (see Section 3.2.4 for derivation)

Proportion in each Receiving Site	Motorway	Rural	Urban
% airborne (subsequently agricultural soil)	4	4	4
% removed by cleaning	0	0	9.6
% transported to soil in verge	64.0	72.0	38.0
% transported into watercourse within road environment	32.0	24.0	48.4

Application of these values to the annual quantity of rubber tyre particles released to each road type gives the total mass in each receiving compartment across GB. The effectiveness of street cleaning from the local exposure scenario is also assumed to apply to the regional model.

3.3.2.2 Removal of tyre particles from wastewater by interception before release to the environment

It is assumed that the effectiveness of the interception methods are the same for regional releases as for local releases (Section 3.2.5).

As noted in Section 3.3.2.1, it is assumed that the particles collected by each interception method are removed in the form of sludge if captured by STP from combined sewer, or dredged material. Sludge and dredged material may be applied to agricultural soil, subject to re-use suitability criteria (DEFRA, 2018; accessed 03/05/2024; EA, 2021; accessed 17/05/2024; IADC, 2018). Any unsuitable material is required to be disposed of in accordance with waste legislation in GB. Dredged material may be exempt from the Landfill Directive if it is both classed as non-hazardous and is deposited alongside the watercourse where it was dredged from. Based on the partitioning calculated in Section 3.2.5, and assuming that 93% of sludge is applied to land (BAS, 2020; accessed 24/10/2025), the partitioning of tyre-derived rubber particles removed by road runoff is 61.5% to surface waters, 35.8% to soils via STP sludge and 2.7% removed for other disposal, such as incineration. The figures have been rounded for simplicity and are conservative. This assumption is also applied to sediments dredged from settlement ponds and roadside ditches.

3.3.3 Regional exposure scenarios for the release of rubber particles from tyres

The scenarios are presented as REACH-style exposure scenarios in Section 3.3.3.1 to Section 3.3.3.3. The exposure scenarios are made separately for each road type (i.e.

motorway, urban and rural) and the estimated total regional accumulation is presented in Section 3.3.4.

The daily local widespread use amount is calculated from the respective regional use annual tonnages using the conversion factor presented within section R.16.2.2.1.2. of the R16 Guidance published by ECHA (2016a). The default assumptions are used without alteration except the “fraction of the tonnage for the use used in the region” which is adjusted to 1 to account of the region representing the whole of GB – the tonnage is the amount of rubber released for each road type. The conversion factor used is therefore 5.45×10^{-6} year/day. This daily local widespread use amount may be used as a proxy for the local scenario if insufficient data is available for the local exposure scenario.

3.3.3.1 Exposure scenario for the release of rubber particles from vehicle tyres on GB motorways

A calculation was performed to estimate values for the regional release and accumulation of rubber particles in different environmental compartments, deriving from the motorway. The estimated regional release, daily local widespread release, and the conditions assumed are described in Table 11. These assumptions inform the percentage interception values applied to the estimated release value, presented in Table 12. The estimated accumulation, adjusted for interception values, is presented in Table 13.

Table 11 An outline of the conditions used when estimating the regional release and partitioning in the motorway environment

Amount released, frequency and duration of use (or from service life)		**Source**
Regional use amount (mass of particle released from tyres):	20,159 tonnes/year	Table 9
Daily local widespread use amount:	109.9 kg/day	(ECHA, 2016a; R.16.2.2.1.2.)
Conditions and measures related to external treatment of waste (including article waste)		**Source**
Sludge removed from interception measures is applied to soil		Section 3.3.2.2
Other conditions affecting environmental exposure		**Source**
Regular road cleaning?:	No	Section 3.3.2.1
Type of interception method:	Settlement pond	Section 3.2.5
Effectiveness of interception methods:	80.4%	Section 3.2.5

Table 12 Partitioning factors applied to each environmental compartment in the motorway road environment

Environmental compartment	Release estimation method	Accumulation factor	Source
Water	Calculated	Before interception RMM: 32.0%	Table 10
		After interception RMM: 6.3%	80.4% reduction
		Intercepted: 25.7%	
Air	Calculated	4%	Table 10
Soil (verge)	Calculated	64.0%	Table 10
Soil (agricultural)	Calculated	27.9%	Assumptions according to Section 3.3.3.2. Assumption that 93% of intercepted particles released via water are applied to agricultural soil as sludge (23.9%) and all airborne particles (4%) eventually settle on agricultural soil.

Table 13 Estimated regional release values for the motorway environment

Environmental compartment	Accumulation rate	
Water (before interception)	Regional annual: Local daily:	6,443 tonnes/year 35.1 kg/day
Water (after interception)	Regional annual: Local daily:	1,264 tonnes/year 6.9 kg/day
Air	Regional annual: Local daily:	806 tonnes/year 4.4 kg/day
Soil (verge)	Regional annual: Local daily:	12,911 tonnes/year 70.4 kg/day
Soil (agricultural)	Regional annual: Local daily:	5,624 tonnes/year 26.4 kg/day

3.3.3.2 Exposure scenario for the release of rubber particles from vehicle tyres on rural roads in GB

A calculation was performed to estimate values for the regional accumulation of rubber particles originating from rural roads in different environmental compartments. The estimated regional use amount, daily local widespread use amount, and the conditions assumed are described in Table 14. These assumptions inform the percentage interception values applied to the estimated use amount, which are presented in Table

15. The estimated accumulation, adjusted for interception values, are then presented in Table 16.

Table 14 An outline of the conditions used when estimating the regional release and partitioning in the rural road environment

Amount used, frequency and duration of use (or from service life)		Source
Regional use amount (mass of particle released from tyres):	18,444 tonnes/year	Table 9
Daily local widespread use amount:	100.5 kg/day	(ECHA, 2016a; R.16.2.2.1.2.)
Conditions and measures related to external treatment of waste (including article waste)		**Source**
Sludge removed from interception measures is applied to soil		Section 3.3.2.2
Other conditions affecting environmental exposure		**Source**
Regular road cleaning?	No	Section 3.3.2.1
Type of interception method:	Drainage ditch	Section 3.2.5
Effectiveness of interception methods:	75%	Section 3.2.5

Table 15 Partitioning factors applied to each environmental compartment in the rural road environment

Environmental compartment	Release estimation method	Accumulation factor	Source
Water	Calculated	Before interception RMM: 24.0%	Table 10
		After interception RMM: 6.0%	75% reduction
		Intercepted: 18.0%	
Air	Calculated	4%	Table 10
Soil (verge)	Calculated	72.0%	Table 10
Soil (agricultural)	Calculated	20.7%	Assumptions according to Section 3.3.3.2. Assumption that 93% of intercepted TRWPs released via water are applied to agricultural soil as sludge (16.7%) and all airborne particles (4%) eventually settle on agricultural soil.

Table 16 Estimated regional release values for the rural road environment

Environmental compartment	Accumulation rate	
Water (before interception)	Regional annual: Local daily:	4,427 tonnes/year 24.1 kg/day
Water (after interception)	Regional annual: Local daily:	1,107 tonnes/year 6.0 kg/day
Air	Regional annual: Local daily:	738 tonnes/year 4.0 kg/day
Soil (verge)	Regional annual: Local daily:	13,280 tonnes/year 72.4 kg/day
Soil (agricultural)	Regional annual: Local daily:	3,818 tonnes/year 20.8 kg/day

3.3.3.3 Exposure scenario for the release of rubber particles from vehicle tyres on urban roads in GB

A calculation was performed to estimate values for the regional accumulation of rubber particles originating from urban roads in different environmental compartments. The estimated regional use amount, daily local widespread use amount, and the conditions assumed are described in Table 17. These assumptions inform the percentage interception values applied to the estimated use amount, which are presented in Table 18. The estimated accumulation, adjusted for interception values, are then presented in Table 19.

Table 17 An outline of the conditions used when estimating the regional release and partitioning in the urban road environment

Amount used, frequency and duration of use (or from service life)		Source
Regional use amount (mass of particle released from tyres):	15,765 tonnes/year	Table 9
Daily local widespread use amount:	85.9 kg/day	(ECHA, 2016a; R.16.2.2.1.2.)
Conditions and measures related to external treatment of waste (including article waste)		**Source**
Sludge removed from interception measures is applied to soil		Section 3.3.2.2
Other conditions affecting environmental exposure		**Source**
Regular road cleaning?	Yes	Section 3.3.2.1
Type of interception method:	40% drains diverted to STP	Section 3.2.5
Effectiveness of interception methods:	96.3%	Section 3.2.5

Table 18 Partitioning factors applied to each environmental compartment in the urban road environment

Environmental compartment	Release estimation method	Accumulation factor	Source
Water	Calculated	Before interception RMM: 48.1%	Table 10
		After interception RMM: 29.6%	40% of drains being diverted to STP with a 96.3% reduction
		Intercepted: 18.5%	
Air	Calculated	4%	Table 10
Soil (verge)	Calculated	38.3%	Table 10
Soil (agricultural)	Calculated	21.2%	Assumptions according to Section 3.3.3.2. Assumption that 93% of intercepted TRWPs released via water are applied to agricultural soil as sludge (17.2%) and all airborne particles (4%) eventually settle on agricultural soil.
Road cleaning waste	Calculated	9.6%	Table 10

Table 19 Estimated regional release values for the urban road environment

Environmental compartment	Accumulation rate	
Water (before interception)	Regional annual: Local daily:	7,581 tonnes/year 41.3 kg/day
Water (after interception)	Regional annual: Local daily:	4,661 tonnes/year 25.4 kg/day
Air	Regional annual: Local daily:	631 tonnes/year 3.4 kg/day
Soil (verge)	Regional annual: Local daily:	6,040 tonnes/year 32.9 kg/day
Soil (agricultural)	Regional annual: Local daily:	3,358 tonnes/year 18.3 kg/day
Road cleaning waste	Regional annual: Local daily:	1,513 tonnes/year 8.2 kg/day

3.3.4 Estimated total regional environmental accumulation of rubber particles deriving from the motorway, rural and urban scenarios

In the previous sections, Table 13, Table 16 and Table 19 present the estimated environmental accumulated mass of rubber particles from tyres derived from the motorway, rural and urban road environments respectively. As discussed above, the accumulation rate to air also contributes to the (agricultural) soil accumulation rate. The accumulation rate to air is presented to ensure clarity within the scenario and indicate the partitioning that occurs within the model. It should be noted that as a result of this, the mass appears twice within the above tables, but is counted only once in the overall assessment.

Table 20 presents a summary of the annual accumulation from each scenario. The estimated annual accumulation from each scenario were summed to provide a total, regional estimate that accounts for all three exposure scenarios and removal of particles due to interception. The values derived may be used as input values in microplastic environmental fate models.

Table 20 Summary of the combined accumulation rates (tonnes/year) of rubber particles in environmental compartments assuming interception measures on all road types

Environmental compartment	Motorway (t/y)	Rural (t/y)	Urban (t/y)	Total (t/y)
Surface water	1,264	1,107	4,661	**7,032**
Air[b]	806	738	631	**2,175**
Soil (verges)	12,911	13,280	6,040	**32,230**
Soil (agricultural)	5,624	3,818	3,358	**12,800**
Road cleaning waste	-[a]	-[a]	1,513[c]	**1,513**
Total	**19,799**	**18,205**	**14,059**	**52,063**

Note: [a] As explained in Section 3.2.2, motorway and rural roads are assumed to not be cleaned

[b] Particle mass partitioned to air is accounted for in the Soil (agricultural) value and is not included in the overall total

[c] Road Cleaning Waste is not included in the overall total or total row

In the worst-case scenario that no interception measures are installed on rural roads and motorways the combined accumulation rates accounting for removal due to interception can be seen in Table 21. As noted in Section 3.2.5, the prevalence of interception measures in GB is unknown.

Table 21 Summary of the combined accumulation rates (tonnes/year) of rubber particles in environmental compartments assuming no interception on motorways or rural roads

Environmental compartment	Estimated accumulation (tonnes/year)			
	Motorway (t/y)	Rural (t/y)	Urban (t/y)	Total (t/y)
Surface water (No interception)	6,443	4,427	4,661	**15,530**
Air[b]	806	738	631	**2,175**
Soil (verges)	12,911	13,280	6,040	**32,230**
Soil (agricultural)	806	738	3,347	**4,784**
Road cleaning waste	-[a]	-[a]	1,513[c]	**1,513**
Total	**20,160**	**18,445**	**14,048**	**52,653**

Note: [a] As per Section 3.2.2, motorway and rural roads are assumed to not be cleaned

[b] Particle mass partitioned to air is accounted for in the Soil (agricultural) value and is not included in the overall total

[c] Road Cleaning Waste is not included in the overall total or total row

3.3.4.1 Comparison of model output to the UKIAM approach

At 54,400 tonnes prior to interception and partitioning (see Table 9), the regional (GB) estimate is ~30% lower than the median UK-scale output of 79,100 tonnes derived from the UKIAM model (Zheng *et al.*, 2025), but is slightly lower than the 5th percentile (59,500 tonnes) of the range of UKIAM outputs. This suggests that the model could be underestimating emissions, but a discrepancy between a GB- versus UK-scale model is to be expected. However, the estimated release is of the same order of magnitude, which adds confidence in the predicted scale of this pollution.

In terms of the amounts released to different environmental compartments (see Tables 20 and 21), ~50% less is released to air compared to the UKIAM model, ~50% less to surface water and ~50% more to soil; the mass of rubber particles removed is less than 10% of the UKIAM model. In the UKIAM model, the emissions to water and soil are back calculated from the assumption that 5% of the total amount of TWPs generated are emitted to air. For the water and soil pathways, the fate of particles is based on assumptions derived from literature values, largely reflecting European methods of runoff interception and wastewater treatment. In the regional GB model, it is assumed that a portion these particles are captured effectively, preventing release to water, but that they are essentially recycled into the agricultural soil compartment as opposed to being removed entirely via waste disposal. The discrepancy is therefore due to different assumptions in the partitioning of releases to soil and water across road types.

In conclusion, the median UK-scale output from the UKIAM model is similar to the regional (GB) model output, with both estimates being in the order of tens of thousands of tonnes annually. This adds confidence in the prediction of the overall scale of release. The UKIAM model predicts a greater proportion of the rubber particles will reach watercourses, which indicates the exposure for the water compartment could be

underestimated in the GB model, depending on the assumed effectiveness of the mitigation measures. Given the sensitivity of the aquatic environment versus terrestrial for substances like 6PPD and 6PPD-Q, this could affect the conclusion about risks from chemical leachate.

3.4 Case Study – M6 Lowgill

To examine whether the model estimates reasonably realistic values for the release of both TRWPs, a case study was considered for a specific length of road in GB with known traffic volumes.

3.4.1 Estimation of release of TRWPs from vehicles from the M6 near Levens, Cumbria

A 1 km length of the M6 motorway near Levens in Cumbria was chosen for the case study due to the approximate 200 m distance from the River Lune. The River Lune supports a diverse range of fish, including migratory species like *Salmo salar* (Atlantic Salmon) and *Salmo trutta* (Sea Trout), as well as resident species such as *Salmo trutta* (brown trout) according to the Lancaster & District Angling Association (LDAA, 2025; accessed 28/10/2025).

Traffic information was extracted from data made available by the DfT (2022b; accessed 30/04/2024).

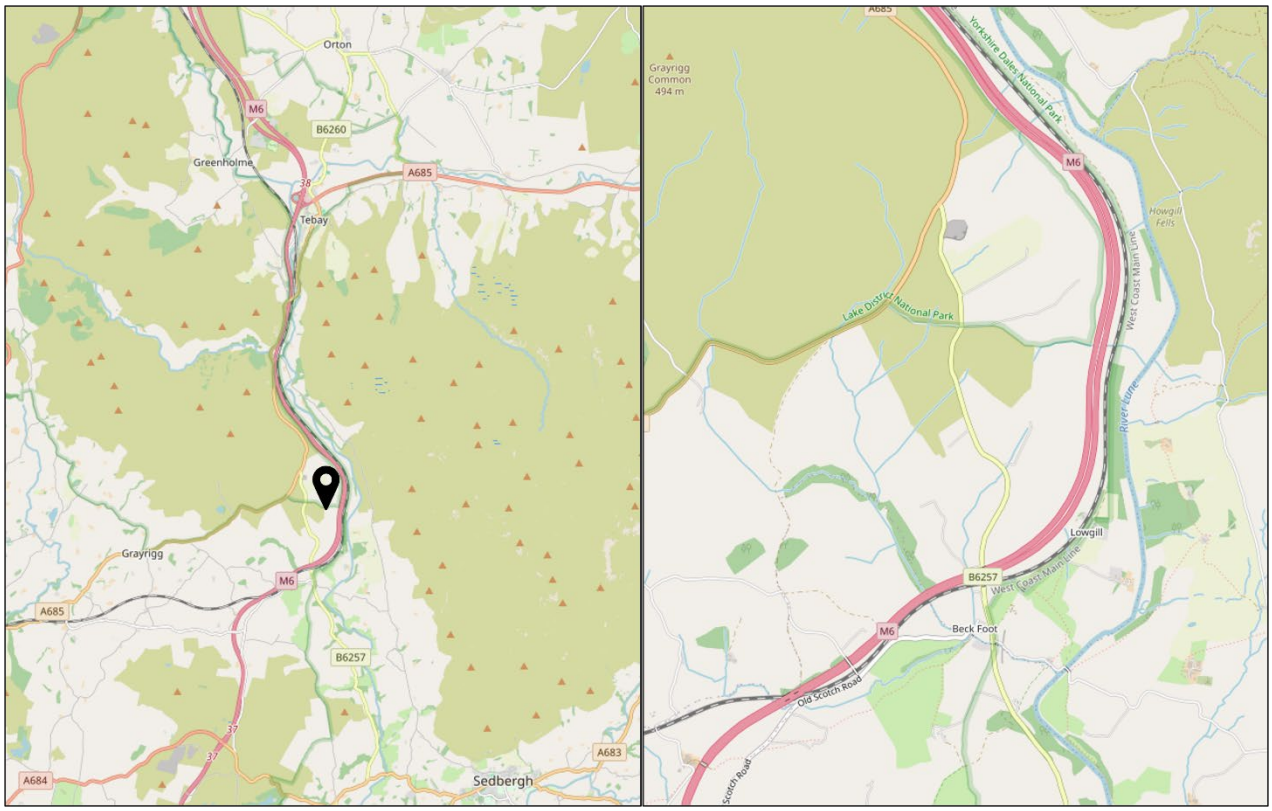


Figure 5 Location of the stretch of the M6 used as a case study for the exposure scenario. M6 between J37 and J38 (grid reference 54.382194, -2.582028) (OpenStreetMap, 2026; accessed 26/02/2026)

3.4.2 Release and exposure to rubber particles

The available data needed to be manipulated slightly to fit with the input requirements of the exposure scenario, as follows:

- The 1 km stretch of the M6 has three lanes in each direction, carrying both northbound and southbound traffic.
- Daily traffic volume: Traffic counts were reported separately for each direction; these values were combined to provide the inputs for the exposure scenario. Data from 15th May 2018 were used, as the most recent available dataset (April 2020) coincided with the COVID-19 pandemic and was therefore unrepresentative of normal traffic levels. Traffic was recorded over a 12-hour period between 07:00 and 18:00, and the total was doubled to estimate the total 24-hour traffic volume. No adjustment is made for variations in traffic frequency across the 24 hours, which may lead to overestimation of traffic levels.
- The traffic data refers to Light Goods Vehicles (LGV), which is assumed to be equivalent to vans in the exposure scenario.
- The traffic data is classified into six types of heavy goods vehicle (HGV) based on axle number and type (DfT, 2022c). It is assumed that all fixed axle HGVs are equivalent to small lorries and all articulated axle HGVs are heavy lorries (HGVs).
- The proportion of electric cars is assumed to be 1.06% of total cars, based the number of newly licensed BEVs in GB for 2021 (VEH0101 & VEH0141 (DfT, 2021; accessed 13/06/2024)), as discussed in Section 3.2. The total number of cars from the traffic data is partitioned between BEV cars and ICE cars based on this information.
- For simplicity it has been assumed that a heavy rainfall event occurs three days after a similar event, with no lighter rain in the intervening period.
- Data on road surface, drainage discharge and cleaning are not available so it is assumed that a motorway would not be cleaned and will have a settlement pond for the discharge of surface water before being released directly to the River Lune.

Table 22 Road and weather parameters used in the case study to predict TRWP release

Road type		Motorway
Daily traffic volume in 2018	Cars	37,759
	Motorbikes	268
	Vans (LGV)	10,244
	Small lorries (fixed)	2,416
	Large lorries (articulated)	8,310
	Buses	202
	Electric cars (1.06%)	405
Length of road		1 km
Porous asphalt?		Unknown, assume no
Where does drainage discharge?		Unknown, assume settlement pond
Road cleaning?		Unknown, assume to be no
Rainfall intensity		> 5 mm/day
Days since last rain?		3

The model estimates the following release and partitioning of rubber particles released from traffic.

Individual rainfall event	Rubber particle mass held in soil (verges)	19.8	kg
	Rubber particle mass released to air	0.4	kg
	Rubber particle mass trapped by runoff interception measures	7.9	kg
	Rubber particle mass released to surface waters (non-road environment)	1.9	kg
Annual releases	Rubber particle mass held in soil (verges)	2406.1	kg
	Rubber particle mass released to air	150.3	kg
	Rubber particle mass trapped by runoff interception measures (non-road environment)	965.1	kg
	Rubber particle mass released to surface waters	235.6	kg

Figure 6 Mass of TRWPs distributed in different receiving sites estimated by the exposure scenario

The exposure scenario estimates that approximately 1.9 kg of tyre rubber is released to the River Lune during this single rainfall event and 7.9 kg is held in the sediment of the settlement pond. In addition, 19.8 kg of rubber is released to soil along the 1 km stretch of road.

If this volume of traffic and rainfall frequency is representative of the whole year, the annual release of rubber to the River Lune would be 235.6 kg and 2,406 kg would be released to the soil in the verge of the road. When considering a standard 11 kg car tyre with a rubber content of 85%, the mass of rubber particles generated from this 1km stretch of motorway would be equivalent to the mass of rubber from 25 whole tyres released into the River Lune and 257 tyres into the soil verge.

3.4.3 Comparison with measured values

To examine whether this estimated mass is realistic relative to measured data for the concentration of rubber in soil, the concentration of rubber particles in verge soil from this release can be estimated with certain assumptions.

- The rubber is released to each side of the road, the central reservation is not included in the calculation.
- Most rubber is found within 2 m of the road.
- The rubber is found in the topsoil to a depth of 10 cm.
- The density of soil at this location is 0.43 g/cm^3 (UKSO, 2016; accessed 13/06/2024). This differs to the EUSES default density of 1.7 g/cm^3 (ECB, 2004). However, the chosen value is specific to the location of this scenario. If a location specific value is not available, the user should select an appropriate value or otherwise use the EUSES default value.

Using these values, the mass of soil that will contain rubber along the 1 km stretch of road will be:

Equation 8 Volume of soil located either side of a road

$$\boldsymbol{V_{soil} = 2 \times (L_{road} \times W_{verge} \times D_{Soil})}$$

Equation 9 Mass of soil located either side of a road

$$\boldsymbol{M_{soil} = V_{soil} \times \rho_{soil}}$$

Equation 10 Concentration of rubber particles found within soil located either side of a road

$$\boldsymbol{C_{rubber\ soil} = \frac{M_{rubber\ soil}}{M_{soil}} \times 1,000,000}$$

Where: **V_{soil}** = Volume of soil located adjacent to a road (m^3)

L_{road} = Length of road (m)

W_{verge} = Width of verge in which rubber particles are found (m)

D_{soil} = Depth of soil in which rubber is found (m)

M_{Soil} = Mass of the soil located adjacent to a road (kg)

ρ_{soil} = Density of the soil (kg/m^3)

$C_{rubber\ soil}$ = Concentration of rubber within the soil adjacent to a road (mg/kg)

$M_{rubber\ soil}$ = Mass of rubber held in soil (kg, Figure 7)

Therefore, along the kilometre of road in question, there would be 400 m^3 of soil with a mass of 172,000 kg. The concentration of rubber particles in virgin soil after a year would be 14,000 mg/kg of soil.

There is no GB data for soil rubber concentrations. Muller *et al.* (2022a) calculated the concentration of rubber in soils near a German motorway with comparable traffic levels to this case study by analysing for marker substances and then adjusting these results for quantity of rubber. When analysing for SBR rubber the concentration of tyre wear varied between 155 mg/kg soil to 15,898 mg/kg soil. The variation was due to distance from the road (0.3 – 5 m) and soil sampling depth (0 – 20 cm), the higher value is representative of the concentration calculated in this case study. In addition, it is likely that rubber will have been accumulating in the soil for longer than one year. The result shows that the amount of released rubber calculated by the exposure scenario is within the range of measured literature values.

4 Release and fate of chemicals from tyre rubber

4.1 Chemicals used in tyre rubber

As noted in Section 2.2, tyres contain a complex mixture of substances. Several groups of substances perform certain functions within a tyre, and the relative quantity of these groups can be estimated. Table 23 and Annex 5 present the approximate proportions (%) of the various groups present within tyre rubber and list some of the substances known to carry out this function. The model has been designed to allow the user to select a substance listed.

It is not clear if multiple substances with the same functionality are used within a single tyre, or if only one substance from each additive group is present. It is therefore not possible to calculate an average concentration for each individual substance with confidence. However, some examples of measured concentrations are provided in Annex 5.

A comprehensive review of concentrations of chemicals other than 6PPD in tyres and leachate is beyond the scope of this report. However, several key chemical groups are frequently reported in the literature such as benzothiazoles, benzotriazoles, guanidines and carbon black. A number of these substances were prioritised in EA (2025).

Table 23 Concentrations of substances that perform different functions within tyre rubber

Function	Approximate concentration (%)	Substances
Rubber	40 - 60	Butadiene rubber
		Styrene butadiene rubber
		Natural rubber
		Styrene-butadiene rubber
		Chlorobutyl rubber
Fillers and pigments	25 - 35	Carbon black
		Silicon dioxide
		Calcium carbonate
		Calcium silicate
		Clays
		Resins
Plasticisers and processing aids (oils)	15 - 20	Aromatic petroleum oils
		Mild extracted solvent oils
		Rape seed oils
		Alkylphenols
		tert-Octylphenol
Activators	2 - 5	Zinc oxide
Accelerators and vulcanising agents	0.5 - 2	Stearic acid
		Sulfur
		Hexamethylene tetramine (HMT)
		Thioureas
		Sulfenamides
		Various (see Annex 5)
Retarders	0.5	Nitrosophenyl amine
		Salicylic acid
		Benzoic acid
		Phthalic anhydride
Inhibitor	1	N-(Cyclohexylthio)phthalimide (CTP)
Antiozonant	2	Various (see Annex 5)
Antioxidants and other functions	2	Various (see Annex 5)

4.2 *para*-Phenylenediamine (PPD) derivatives

PPDs – also known as 4-aminodiphenylamine (4-ADPA) derivatives (DTSC, 2021) – are the most common antiozonants in tyres. Their function is to prevent tyre material from degrading during use (Cataldo, 2018). Some typical PPDs are presented in Table 24.

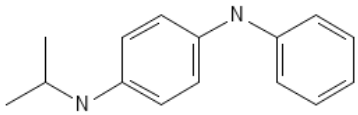
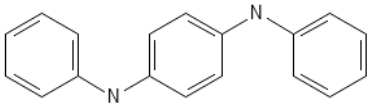
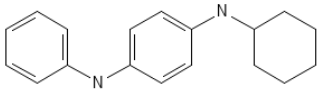
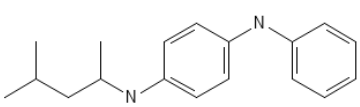
PPDs were selected as a case study in this report because one member of this group (6PPD) has been implicated in URMS events (Thorp, 2022; Tian *et al.*, 2022; Tian *et al.*, 2021). The toxicity is attributed to the quinone degradation product known as 6PPD-Q, one of many degradation products of 6PPD. Hu *et al.* (2022) indicate that 1 – 19% of the

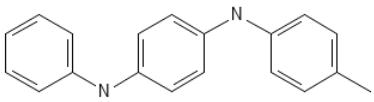
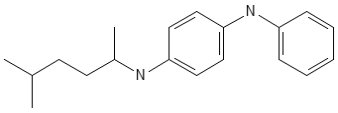
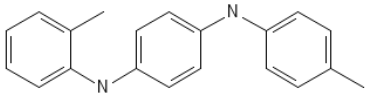
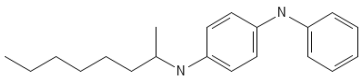
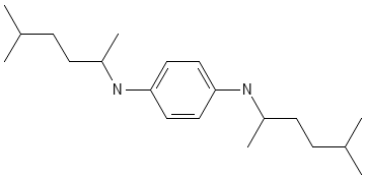
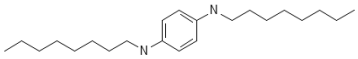
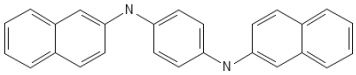
input mass of 6PPD is transformed into 6PPD-Q; the primary transformation products are 1,3-dimethylbutylamine (1,3-DMBA) and 4-hydroxydiphenylamine (4-HDPA). There is ongoing discussion and research regarding the transformation products formed and the impact of different conditions (Smithers, 2024; accessed 12/02/2026). Other PPDs might give rise to similar (or the same) transformation products (Hua and Wang, 2023). Zhao *et al.* (2023a) and Wang *et al.* (2024b) have detected a number of quinone transformation products in tyres.

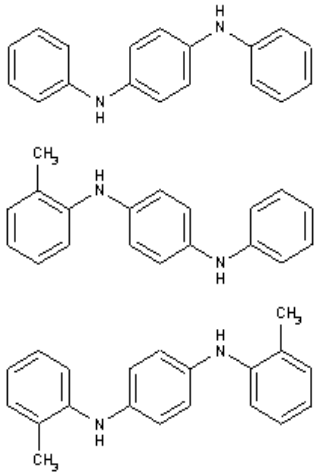
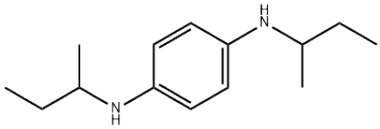
Most tyre formulations contain PPDs at 1–3% by weight (Fohet *et al.*, 2023); the specific concentrations and chemical varies between locality and manufacturer. Hu *et al.* (2022) and Sheridan (2010) estimate 6PPD concentrations in tyre tread range between 0.4 to 2% by weight while Kawakami *et al.* (2022) and Wang *et al.* (2024a) measured concentrations between 0 – 1,260 µg/g (0.13% by weight) of 6PPD within tyre tread samples from different manufacturers. Zhao *et al.* (2023a) and Wang *et al.* (2024b) have reported concentrations of various PPDs in TWP samples indicating concurrent use of different PPDs. Tyre type can also influence substance concentration. For example, Rodland *et al.* (2024) measured 6PPD concentrations in TP ranging between 2800 and 33,000 µg/g (0.28 – 3.3%) for different seasonal tyres.

Multiple aspects of the lifecycle of 6PPD and 6PPD-Q are under investigation, including factors that influence the formation of 6PPD-Q in tyres and TWPs in the environment, leaching rates from TWPs, and its persistence and bioaccumulation potential (HSE, 2025; ITRC, 2023; Lane *et al.*, 2024; Xu *et al.*, 2023).

Table 24 Examples of phenylenediamines (PPDs)

Substance name	Abbreviation	CAS number	Chemical structure	Molecular weight (g/mol)
N-isopropyl-N′-phenyl-1,4-phenylene-diamine	IPPD	101-72-4		226.3
N,N′-diphenyl-p-phenylene-diamine	DPPD	74-31-7		260.3
N-phenyl-N′-cyclohexyl-p-phenylene-diamine	CPPD	101-87-1		266.4
N-(1,3-dimethylbutyl)-N′-phenyl-p-	6PPD	793-24-8		268.4

Substance name	Abbreviation	CAS number	Chemical structure	Molecular weight (g/mol)
phenylene-diamine				
N-phenyl-N′-(o-tolyl)-p-phenylene-diamine	PTPD	24124-30-9		274.4
N-(1,4-dimethylpentyl)-N'-phenyl-benzene-1,4-diamine	7PPD	3081-01-4		282.4
N,N′-di(o-tolyl)-p-phenylene-diamine	DTPD	27417-40-9		288.4
N-(1-methyl-heptyl)-N′-phenyl-p-phenylene-diamine	8PPD	15233-47-3		296.4
N-(1,4-dimethylpentyl)-N′-phenyl-benzene-1,4-diamine	77PD	3081-14-9		304.5
N,N-dioctyl-p-phenylene-diamine	88PD	1241-28-7		332.6
N,N′-di-2-naphthyl-p-phenylene-diamine	DNPD	93-46-9		360.4

Substance name	Abbreviation	CAS number	Chemical structure	Molecular weight (g/mol)
Reaction mass of N-phenyl,N'-o-tolyl-phenylene diamine, N,N'-diphenyl-p-phenylene diamine and N,N'-di-o-tolyl-phenylene diamine	BENPAT	68953-84-4		260.3 – 288.4
N,N'-di-sec-butyl-p-phenylene diamine	44PD	101-96-2		220.4

4.2.1 UK REACH registrations

A search of the UK REACH database (UK Government, 2023) was conducted for the PPDs listed in Table 25 in November 2025. Two PPDs (6PPD and 7PPD) are UK REACH registered and three further PPD (DPPD, BENPAT and 44PD) have transitional registrations, meaning they are being imported or manufactured in amounts above 1 tonne/year by one or more individual companies within GB (see Annex 6).

The other PPDs in Table 24 do not have UK REACH registrations; they might not be supplied in GB, or may be manufactured or imported in amounts below 1 tonne/year, or imported within articles where release is unintended. Alternatively, they may be being imported by GB-based companies from EU-based suppliers who were previously classed as “downstream users” (DUs) under EU REACH. A transitional measure allows former DUs to suspend registration until one of three deadlines is met (depending on tonnage and hazard). To benefit from this provision, companies must have submitted a Downstream User Import Notification (DUIN). These have not been considered for the purposes of this report, but interrogation of DUIN data for tyre additives is recommended if future work is performed.

4.2.2 EU REACH registrations

A search of the EU REACH database (ECHA, 2023c) was conducted for the PPDs listed in Table 24 in November 2025. Seven PPDs are registered: 6PPD at ≥10,000 tonnes/year; IPPD, BENPAT and 77PD at ≥1,000 tonnes/year; 44PD at ≥100

tonnes/year; and 7PPD and DPPD at ≥10 tonnes/year (see Annex 6). They might be imported into GB either as substances, in mixtures or in articles but either subject to DUINs or not meeting the requirements for UK REACH registration.

According to the Public Activities Coordination Tool (PACT), these seven registered PPDs have been considered under various EU REACH work streams as of November 2025, as follows (ECHA, 2023b):

- 6PPD: Regulatory Management Options Analysis carried out by the Netherlands, concluding that a REACH restriction is necessary;
- IPPD: Dossier evaluation;
- 77PD: Substance evaluation, concluding no need for regulatory follow-up action at EU level;
- 7PPD: Substance evaluation, concluding no need for regulatory follow-up action at EU level;
- DPPD: Dossier evaluation;
- BENPAT: Harmonised classification;
- 44PD: Dossier evaluation.

A broader Assessment of Regulatory Needs (ARN) for the PPD group has been undertaken (ECHA, 2023a) and Austria has indicated that 7PPD should be included within the 6PPD restriction proposal based on human health and environmental concerns and to avoid regrettable substitution of 6PPD (ECHA, 2025). The ARN identified ten further substances that are part of this grouping, of which three appear to be supplied in amounts above 1 tonne per year (see Table 25, one substance has no identified data). The ARN identifies a range of further regulatory investigations for various group members, although it is not clear whether all of these substances are used in tyres.

Table 25 Further PPDs identified in the ARN registered in the EU

Substance name	Abbreviation	CAS number	EU REACH supply level
N-(4-aminophenyl)aniline	-	101-54-2	≥1 tonnes/year
N-(1,3-dimethylbutyl)-N'-(phenyl)-1,4-benzoquinonediimine	6QDI	52870-46-9	Not publicly available (former “NONS”* substance)
No public name available	-	-	Not publicly available (former “NONS”* substance)

Note: *Notification of new substance (NONS)

4.3 Leaching of substances from rubber

Tyres and TRWPs will release some of their chemical constituents and transformation products into the environment over time through leaching by rainwater, soil pore water

and surface water. It has been reported in the literature that significant numbers of chemicals are found in tyre leachate, for example, Muller *et al.* (2022b) identified 145 different substances. Tian *et al.* (2021) reported over 2,000 different electrospray ionisation peak (ESI+) detections in leachate samples, however, the number of substances will be lower than the number of ionisation fragments due to the nature of the analytical method. The rate and availability of leaching is substance specific; some chemicals (e.g. PPDs) bloom to the rubber surface to fulfil their intended purpose during the tyre surface life.

6PPD and its transformation product 6PPD-Q are frequently detected after storm events due to runoff transporting the TRWPs and leachate from the road surface, leading to short-term increases in concentrations and the occurrence of URMS (Cao *et al.*, 2022; Tian *et al.*, 2021). In colder climates, snowmelt significantly contributes to peak release events of 6PPD-Q into the aquatic environment; for example, Ren *et al.* (2024) reported that snowmelt contained 3 – 6.5% more 6PPD-Q than river waters due to dilution. Examples of measured environmental 6PPD-Q concentrations are summarised in Table 26.

Table 26 Summary of reported aquatic environmental concentrations of 6PPD-Q

Reference	Sampling site	Number of samples	Environmental sample type	6PPD-Q concentrations
Tian *et al.* (2021) and Erratum, Thorp (2022)	Seattle, USA	16	Road runoff	0.096-2.23 µg/L
	Seattle, USA	6	Watershed during storm events	<0.036-0.39 µg/L
	Los Angeles, USA	2	Road runoff	0.49-0.73 µg/L
	San Francisco, USA	4	Creek affected by urban runoff	0.12-0.42 µg/L
Peter *et al.* (2024)	San Francisco, USA	8	Urban stormwater	97 µg/L (median)
Johannessen *et al.* (2022)	Don River, Greater Toronto Area, Canada	42	Surface water, 2-44 h after rain	0.93-2.85 µg/L
Cao *et al.* (2022)	Hong Kong	9	Urban runoff	0.21-2.43 µg/L
Rauert *et al.* (2022a)	Cubberla Creek,	32	Surface water (grab) samples	0.4-88 ng/L

Reference	Sampling site	Number of samples	Environmental sample type	6PPD-Q concentrations
	Brisbane, Australia		were collected during major storm events	
Rauert *et al.* (2022b)	5 urban centres, Queensland, Australia	21	Surface water (grab) samples from stormwater drains, creeks, rivers, tributary, estuary, ponds/reservoirs	<0.05–24 ng/L (18 out of 21 sites)
Helm *et al.* (2024)	Greater Toronto Area, Canada	60	Surface water samples from stormwater entering streams, grab samples at low flows, grab samples of lake water	<2.0 – 8.4 ng/L (dry flow) <2.0 – 82.3 ng/L (wet flow)
Ren *et al.* (2024)	Yantai, China	12	Snowmelt samples	272 ng/L (maximum)
Zeng *et al.* (2023)	Pearl River Delta & Estuary, South China Sea, China	85	Estuarine and river sediment	9.03 ng/g (urban rivers, dry weight) 2 ng/g (estuary, dry weight) 1.27 ng/g (coastal, dry weight) 2.71 ng/g (deep sea, dry weight)
Zhang *et al.* (2024c)	55 Urban trunk roads in 55 different major Cities in China	55	Road dust	28.5 – 1327.1 ng/g (service area, n= 5) 8.6 – 43.5 ng/g (suburban road, n=5) 16.6 -545.5 ng/g (urban tunnel, n = 14) 15.4 – 240.6 ng/g (urban trunk road, n = 23)
Jin *et al.* (2023)	Urban roads (n=16), Agricultural (n=32),	83	Road dust	9.75 ng/g (median)

Reference	Sampling site	Number of samples	Environmental sample type	6PPD-Q concentrations
	Forest (n=35)			
Mao *et al.* (2024)	Beijing, China		Road dust	132 – 8,911 ng/g
Wang *et al.* (2024b)	Taiyuan, China	18	Air	34.9 pg/m^3
		20	Soil	141 ng/g

4.4 Development of local and regional leaching exposure scenarios and model

4.4.1 Leaching in the local exposure scenario

To investigate the possibility of URMS occurring (local scenario) or estimate longer-term environmental releases (regional scenario), the release of leachate from TRWPs and the subsequent environmental partitioning of the substances has to be considered within the exposure scenario and resultant model. Based on available literature data on leaching and leachates and modelled estimates of TRWPs released, environmental concentrations can be calculated.

Information on the concentration of substances within tyres and their availability for leaching is required to determine the mass of leachate released from TRWPs. The exposure scenario assumes that all the available substance (described in Section 4.4.2) that could be leached from the TRWPs is leached once the TRWPs have reached soils and watercourses in close proximity to the road environment, prior to any interception of TRWPs that may occur in these environments. The substances in the leachate can then be subsequently partitioned based on their respective physicochemical properties. It is important to recognise that URMS arises as a result of acute toxicity, so available substances must be leached from TRWPs with sufficient rapidity to cause this.

Estimations of the leaching rate, transformation rate and partitioning fractions were collected during the literature review. The volume of directly relevant research is limited and there are considerable differences in the test methods and results reported. Typically, the research focuses on substances that are known to be toxic to the aquatic environment (e.g. zinc and 6PPD-Q). The exposure scenario development for leaching has therefore focused on this small sub-set of substances. This has the potential to be extrapolated to other tyre components, recognising that measured leaching data will be limited for almost all the chemicals likely to be used or associated with tyres. This complexity and data limitations mean that the leachate exposure scenario includes several assumptions. In addition, the quality of data available on the small proportion of chemicals investigated is difficult to assess for the following reasons:

1. Inconsistency in leaching test method: Despite there being standardised protocols for generating leachates, their use by researchers is inconsistent (Mohajerani *et al.*, 2022). This means different studies use leaching methods that differ in:

    a. Type of solvent: Distilled water and natural water from different sources are used in some studies, while other reports use organic solvents. It is expected that the use of different solvents would result in different leaching rates.

    b. Temperature of leaching: Kida *et al.* (2023) and Li *et al.* (2023) have demonstrated that increased temperature results in an increase in leaching rate. However, the temperature in leaching studies can vary from 15 to 40 °C which makes direct comparison of leaching rate difficult. Foscari *et al.* (2023) reported that exposure of TRWPs to elevated temperature and sunlight prior to leaching led to a decrease in total leachate due to a combination of evaporation and chemical transformation; some chemicals were affected more by the incubation temperature. The average GB temperature between 1991 and 2020 was 9 °C (Met Office, Undated) which is generally below the temperature used in the laboratory tests identified.

    c. Duration of leaching: The time used for leaching varies from hours to months, it is reasonable to expect that the concentration of chemicals within the leachate may increase with time. Nevertheless, Foscari *et al.* (2024) indicated that abiotic transformation or biodegradation may lead to a decrease in leachate concentration in extended leaching experiments.

    These methodological inconsistencies make it difficult to compare studies and develop an overall understanding of how substances leach from rubber tyre particles. In addition, it is not clear which leaching method is most representative of environmental processes, and over what timescales.

2. Lack of information on tyre composition: Tyre composition is proprietary information for the tyre manufacturer, so exact data on the ingredients and their quantities used in specific tyre models and across all tyre types is not available. Some chemicals may only be used in the tread (which contacts the road surface), while others may only be present in the sidewall of the tyre (which are not typically present in TRWPs). The variability of substance concentration across tyres for different vehicle types is also unknown. This means that estimates of chemical concentrations must be used in the exposure scenario, as well as assumptions on their presence in TRWPs.

3. Lack of information on degradation and transformation of chemicals during manufacture and use of tyres: Although information can be found for some tyre ingredients given their intended role, this is not necessarily comprehensive, and data for other chemical types might be missing or difficult to predict. For example, 6PPD-Q was only identified as a degradation product of 6PPD relatively recently (Tian *et al.*, 2021). Other studies have shown that 6PPD can also transform into a

number of other chemicals during the manufacture and use of a tyre (Mao *et al.*, 2024; Seiwert *et al.*, 2022). On the other hand, vulcanisation agents are intended to react during manufacture, which is expected to limit their presence in TRWP leachates (ETRMA, 2013).

4. Limited data on leaching mechanisms and impact of chemical structure on rate of leaching: Leaching of chemicals from a matrix such as rubber may be influenced by several factors such as the organic carbon-water adsorption/desorption coefficient, mobility within cross-linked rubber, water solubility, and the particle's location in the environment (e.g. in a soil matrix or lying on the road surface). However, there has been little research into predictive models to estimate how quickly chemicals will leach and whether they can be exhaustively leached.

5. Effect of particle morphology on leaching rate: Although it is generally accepted that the rate of leaching should increase as particle size decreases (Stack *et al.*, 2023), some studies have indicated this may not hold true for all chemicals (Selbes *et al.*, 2015). Most research articles investigating leaching only report the longest dimension of the particle, but leaching is largely expected to occur across the whole surface of a particle. Therefore, surface area may be a more relevant parameter to measure. This metric has been suggested for the measurement of toxicity of nanoparticles (Schmid and Stoeger, 2016).

As highlighted in Section 3.1.2.2, there are also a number of characteristics of tyre particle generation and transport, which can also impact the leaching potential. To ensure the exposure scenarios are representative of a number of tyre and vehicle types and can be used on both a local and regional scale, the following aspects and their potential impact on leachate are not parameterised within the exposure scenarios:

- Tyre age: The composition of a tyre will change during its normal use and the effect of this change on the toxicity of tyre leachates has been examined (Halle *et al.*, 2021; Lu *et al.*, 2021). As the change in composition of the tyre particles or the leachates from a tyre over its lifetime has not been studied in detail, there is insufficient information to parameterise this factor in the exposure scenarios.

- Tyre particle weathering: As with tyres, the composition of TRWPs is expected to change over time. Although there is research into the impact of particle weathering on the toxicity of leachates and changes in the chemical composition (Fohet *et al.*, 2023; Foscari *et al.*, 2024; Weyrauch *et al.*, 2023; Zhang *et al.*, 2024a), there is currently insufficient data to parameterise the model.

- Particle size distribution: Leaching occurs at a higher rate for smaller particles due to the increased surface area, leading to higher leaching potential, higher concentrations of substances within the leachate within a shorter time period and increases in toxicity for certain biota (Stack *et al.*, 2023). This is also affected by particle weathering processes, such as photolysis or mechanical abrasion (Zhang

et al., 2024b). The exposure scenarios and model do not differentiate between different size fractions of TRWPs in terms of leachate generation.

These uncertainties mean the exposure scenarios rely on several assumptions when estimating chemical release from tyre rubber particles through leaching. These are described in the following section.

4.4.2 Concentration of chemicals in tyres

This project identified 114 different substances that may be used in the manufacture of tyre tread (see Annex 5). The model accounts for different substances in different ways based on their function. The user can select the substance that they are interested in using a dropdown menu located in the “Chemical Exposure” tab of the model. The “Chemicals” tab details the function of the substance in the tyre, the approximate concentration used in the tyre, and whether it is intended to be consumed during manufacture. The following assumptions are used in the exposure scenario and model:

1. Only substances which function as a vulcanising agent are consumed during the tyre manufacturing process (NOCIL, 2010b).

2. The concentration associated with a specific substance is based on the function of the substance, as most of the data available is based on the class of ingredient rather than individual substances. While this may overestimate the concentration of the chemical within the tyre, as discussed above, there is insufficient data on tyre concentrations and leaching rate to provide chemical-specific values. However, the user can input specific concentrations if more information becomes available.

3. The substance list only covers the rubber ingredients as named, not individual constituents of these ingredients. For example, one ingredient of tyre rubber is “aromatic petroleum oils” which may contain many constituents.

When the user has chosen the chemical of interest on the “Chemical Exposure” tab, they should manually fill in the following boxes shown in Figure 7 below.

	Intentionally added component	
Chemical parameters	What is the substance of interest?	N-(1.3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD)
	Is the substance organic or a metal?	Organic
	Concentration used in tyre manufacture (%, $Conc_{man}$)	2
	Is the substance intended to be consumed during manufacture?	no
	Concentration in tyre tread after manufacture (%) ($Conc_{afterman}$)	2
	Does the substance transform or degrade during use?	yes
	If degradation does occur, what fraction remains ($F_{ingredient}$)?	0.4
	What is the Log K_{ow} of the substance?	4.68

Figure 7 User input for a substance that is intentionally added during the manufacture of tyres, 6PPD is used as an example

1. Is the substance organic or a metal?: If the ingredient is organometallic or an organic salt (e.g. zinc dibenzyldithiocarbamate (ZDBC)), the user should decide whether they are interested in the metal fraction or the organic fraction of the ingredient and complete the box accordingly.

2. Concentration used in manufacture (%, $Conc_{man}$): Refer to Annex 5 for a typical value based on the chemical class. Measured concentrations are available for specific chemicals, although caution should be exercised when selecting these due to the limitations discussed above.

3. Is the substance intended to be consumed during manufacture?: Refer to Annex 5 for an expected value.

4. Concentration in tyre tread after manufacture (%, $Conc_{afterman}$): If the substance is not consumed during manufacture, this should be set to equal $Conc_{man}$. If the substance is consumed during manufacture, the user should enter a suitable remaining concentration to account for any residual substance.

5. Does the substance transform or degrade during use? If so, what fraction remains? ($F_{ingredient}$): Users will need to use expert judgment. For example, based on literature data it can be calculated that if the rubber contains 2% of 6PPD (20 mg/g) at the point of manufacture and the 90th percentile confidence limit of measurements of 6PPD in tyres is 8.2 mg/g, then the remaining fraction of the input mass is 0.40 (Kawakami *et al.*, 2022; Mao *et al.*, 2024; Rodland *et al.*, 2024; Wang *et al.*, 2024a; Wang *et al.*, 2024b; Zhao *et al.*, 2023a). As noted in the

uncertainties and assumptions discussion above, there is a high degree of variance in the literature due to measurement methods, tyre brand and TRWP age, and this value should be updated if further information becomes available. If no information is available, the conservative assumption would be to assume no degradation occurs and the fraction remaining is 1.

6. What is the n-octanol-water partition coefficient (log K_{OW}) of the substance?: The user needs to enter this manually. If the substance has been registered under REACH, publicly available registration data should be available for this parameter.

The user can also assess a degradation product of an ingredient instead. The information about the degradant is entered into the "Chemical Exposure" tab (see Figure 8).

The user will need to manually fill in all the boxes highlighted in pale green other than *Concentration of degradation product in tyre rubber particles ($Conc_{deg}$)*, which is completed automatically.

Degradation product	
What is the degradation product?	6PPD-quinone
Is the degradation product organic or a metal?	organic
From which tyre ingredient is it sourced?	6PPD
Concentration of source component in tyre (%)	2
Efficiency of transformation (%)	1
Concentration of degradation product in tyre rubber particles ($Conc_{deg}$, %)	0.02
Log K_{OW} of degradation product	3.98

Figure 8 User input for a degradation product formed during either manufacture or use of tyres, 6PPD-Q is used as an example

1. Is the degradation product organic or a metal? Refer to the guidance above for assessing ingredients.

2. From which tyre ingredient is it sourced?: This is intended to support the completion of the subsequent boxes. It should be noted that some degradation products are common to multiple ingredients. For example, benzothiazole can be a degradation product of all the thiazole and sulfenamide groups of vulcanising agents (NOCIL, 2010b).

3. Concentration of source component in tyre (%): Refer to Annex 5 for a value based on the chemical class or a measured concentration. It should be noted that while a tyre is unlikely to contain every vulcanising agent, it may contain several. Therefore, the user should use their expert judgment to complete this section if the degradation product could be generated from multiple ingredients.

4. Efficiency of transformation: Efficiency is expressed as the percentage (w/w) of degradation product formed relative to the amount of the ingredient used in tyre

manufacture. This will need expert judgement, and data might not be available for many substances.

5. Concentration of degradation product in tyre rubber particles ($Conc_{deg}$, %): Concentrations of degradation products are not widely reported in the literature and vary based on environmental conditions. The concentration of the degradation product is calculated from the concentration of the source component within the tyre and the efficiency of transformation of the source component.

6. n-Octanol-water partition coefficient (log K_{OW}) of degradation product: This will need expert judgement. As degradation products may not be manufactured and hence do not require REACH registration, public registration data are unlikely to be available (ECHA, 2008a). In the absence of experimental data, there is software available that can predict a log K_{OW} from a molecular structure (Cappelli *et al.*, 2015).

Once the user has completed the input of these variables, the model will estimate the total amount of the chemical that could be leached from the particles and the subsequent partitioning. Studies have shown that exhaustive leaching of all the chemical in the rubber matrix is very unlikely within the given timeframes of the exposure scenarios, so only a fraction is available to be leached ($F_{leachable}$). Unfortunately, there is very little substance-specific information on the proportion that can be leached from rubber. Some examples are given in Annex 5, but as noted above, the literature is inconsistent in approach.

As a placeholder until further research can be carried out, Unice *et al.* (2015) and Verschoor (2007) indicate that 20% of organic chemicals can be leached from tyre rubber after 0.8 years and 0.01% of metals are available for leaching. It may be surprising that inorganics leach more slowly than organic components, but the value is largely based on measured information on zinc, and it is known that zinc becomes incorporated into the polymeric structure during vulcanisation and desorbs slowly due to the presence of organic functional groups (Li *et al.*, 2024). These values are based on a very limited number of studies so this part of the exposure scenario should be updated if more information becomes available in the future. Unice *et al.* (2015) measured the fraction of a limited number of substances available for leaching to the environment but these vary, and the authors do not propose a method to predict this parameter.

The fraction of the chemical originally used as an ingredient that can be released to the environment from leaching by water ($F_{ingredient\ leachable}$) is calculated using the following equations.

Equation 11 Estimated leaching of a parent compound into water

$$F_{ingredient\ leachable} = Conc_{afterman} \times F_{ingredient} \times F_{leachable}$$

Where: **$F_{ingredient\ leachable}$** = Fraction of the chemical that can be released to the environment by leaching into water

$Conc_{afterman}$ = Concentration of the ingredient in the tyre rubber after manufacture (mg/kg)

$F_{ingredient}$ = Fraction of the ingredient that remains after any degradation or transformation occurs

$F_{leachable}$ = Fraction of chemical that is available for leaching (0.2 for organics and 0.0001 for inorganics)

Equation 12 Estimated leaching of a degradation product into water

$$F_{deg\ leachable} = Conc_{deg} \times F_{leachable}$$

Where: **$F_{deg\ leachable}$** = Fraction of degradation product that is available for leaching to water

$Conc_{deg}$ = Concentration of the degradation product in tyre rubber particles (mg/kg, Figure 8)

$F_{leachable}$ = Fraction of chemical that is available for leaching (0.2 for organics and 0.0001 for inorganics)

The mass of the substance that can be leached ($M_{ingredient\ leachable}$ or $M_{deg\ leachable}$) from the particles released to a given environmental compartment is then calculated as follows. These calculations should be performed for both the particles that are partitioned to the soil (verge) and to a watercourse (see Table 4).

Equation 13 Estimated mass of ingredients and relevant degradants that are available for leaching within a given environmental compartment

$$M_{ingredient\ leachable} = F_{ingredient\ leachable} \times M_{particle}$$

or

$$M_{deg\ leachable} = F_{deg\ leachable} \times M_{particle}$$

Where: $M_{ingredient\ leachable}$ & $M_{deg\ leachable}$ = Mass of ingredient or degradant that is available for leaching to the given environmental compartment (mg)

$F_{ingredient\ leachable}$ & $F_{deg\ leachable}$ are defined as in Equation 11 and Equation 12

$M_{particle}$ = Mass of particles available within the given environmental compartment (mg, Section 3.3.4)

Once leached, the chemical can adsorb onto organic carbon in the roadside compartment (e.g. soil in the verge or sediment in the interception measures). This needs to be accounted for in the model. The proportion of a substance that adsorbs to organic carbon will depend on the physicochemical characteristics of the substance and the type of soil or sediment. The variability of soil or sediment organic carbon content is too complex to include in the exposure scenarios, so a simplified algorithm is used based on the log K_{OW} as reported by Unice *et al.* (2015), summarised in Table 27. Users can also consider using the soil-organic carbon partition coefficient (K_{OC}) where available and an assumed nominal organic carbon content for environmental media (ECHA, 2016b). The leached substance can also adsorb onto organic carbon in particles in surface water but only where sediment is expected in the receiving waters. This means this correction is only applied when the road is either rural or a motorway. Some sediment might be present in urban drainage systems connected to STPs, but the conservative approach means that all the chemical dissolved in water is assumed to be released from the road environment into the STP.

Table 27 Simplified approach to predict the proportion of the leached substance that will adsorb to soil or sediment

log K_{OW}	Fraction retained by soil/sediment ($F_{retained}$)
Urban Roads	0
< 1.1	0.1
1.1 – 4	0.5
> 4	0.9

The final calculation assumes that any chemical released from soil in roadside verges is transported to the same roadside watercourses that tyre particles are transported to. It is assumed that the soil does not reach its water holding capacity during a rainfall event and that all runoff partitioned to soil percolates through the soil. Therefore, the total mass

of the chemical released to the environment ($M_{substance\ water}$) is a sum of the mass released from the soil after leaching from tyre particles transported to the verge ($M_{substance\ soil}$), plus the mass not retained in the sediment from particles released to roadside drainage ($M_{substance\ drainage}$). In other words, what is freely mobile in water.

Equation 14 Mass of substance released to water from soils and road runoff. $M_{deg\ leachable}$ can be used in place of $M_{ingredient\ leachable}$

For substances that originate from particles that have partitioned to the soil located within the verge of roads (see Table 4):

$$M_{substance\ soil} = M_{ingredient\ leachable} - (M_{ingredient\ leachable} \times F_{retained})$$

For substances that originate from particles that have partitioned to watercourses (see Table 4):

$$M_{substance\ drainage} = M_{ingredient\ leachable} - (M_{ingredient\ leachable} \times F_{retained})$$

$$M_{substance\ water} = M_{substance\ drainage} + M_{substance\ soil}$$

Where:

$F_{retained}$ = Fraction of the chemical retained by soil or sediment (Table 27)

$M_{ingredient\ leachable}$ & **$M_{deg\ leachable}$** = Mass of ingredient or degradant that is available for leaching to the given environmental compartment (mg, Equation 13)

$M_{substance\ soil}$ = Mass of the substance leached to surface waters from soil verges (mg)

$M_{substance\ drainage}$ = Mass of substance leached from particles held in watercourses and roadside drainage (mg)

$M_{substance\ water}$ = Total mass of substance released to water (mg)

4.5 Regional Exposure Scenarios for 6PPD and 6PPD-Q

The results of the regional exposure scenario for release of tyre particles during vehicle use (Section 3.3.4) can be used to predict the leaching and release of substances in the rubber using the assumptions described above (Section 4.4) The output values of this section can be used as an input quantity for EUSES (ECB, 2004); a summary is provided within the “EUSES Input” tab of the model and details of data entry into EUSES can be found in Annex 7.

Examples of how this exposure scenario works in practice on a regional scale are described in the following sections for 6PPD and 6PPD-Q. Hu *et al.* (2022) and Zhao *et*

al. (2023b) indicate transformation ratios of 6PPD to 6PPD-Q of 9.7% and 10% in laboratory ozonation experiments respectively, although there is evidence to suggest it may be lower (Seiwert *et al.*, 2022; Shen *et al.*, 2025). Hu *et al.* (2022) also measured a transformation rate of 0.95% for 6PPD within TRWPs, which is rounded to 1% for simplicity and used within the model until more data is available. Log K_{OW} values of 4.68 and 3.98 for 6PPD and 6PPD-Q, respectively, have been sourced from Hu *et al.* (2022), and it is assumed there is no further degradation of 6PPD to 6PPD-Q. The reliability of this information has not been critically assessed, so this is just an illustrative calculation. Daily local widespread use amounts are calculated as described in Section 3.2 and the R.16 Guidance (ECHA, 2016a), different values are presented for equivalent annual tonnages due to rounding.

4.5.1 Release of the tyre ingredient 6PPD from rubber tyre particles released from motorways

Table 28 The estimated properties and values used as inputs when estimating the regional leaching of 6PPD and 6PPD-Q in the motorway scenario

	6PPD	6PPD-Q	Source
Properties and mass of substance released via leaching from tyre particles			
Concentration in tyre rubber particle ($Conc_{AfterMan}$ and $Conc_{Deg}$)	2%	0.02%	Figure 7, Figure 8 and "Chemical" tab of model
Fraction of the ingredient that remains after any degradation or transformation occurs ($F_{ingredient}$)	0.40	N/A	Figure 7
Fraction of the chemical that can be released to the environment by leaching into water ($F_{ingredient\ leachable}$)	0.0016	0.00004	Equation 11 and Equation 12
log K_{OW}	4.68	3.98	Hu *et al.* (2022)
Regional mass of substance in tyre particles available for leaching, $M_{ingredient\ leachable}$)	31 tonnes/year	0.8 tonnes/year	Table 9 & Equation 13
Daily local widespread use amount (mass of substance in tyre particles)	0.17 kg/day	4.2 g/day	ECHA (2016a; R.16.2.2.1.2.)
Other conditions affecting environmental exposure			
Fraction available for release from tyre particles ($F_{leachable}$)	0.2	0.2	Section 4.4.2
Fraction retained by soil (verge) and/or sludge in interception RMM ($F_{retained}$)	0.9	0.5	Table 27

Table 29 Releases of chemicals to watercourses for motorways

Release route	6PPD Release rate	6PPD-Q Release rate
Water (regional annual)	3 tonnes/year	0.4 tonnes/year
Water (local daily)	17 g/day	2.1 g/day

4.5.2 Release of the tyre ingredient 6PPD from rubber tyre particles released from rural roads

Table 30 The estimated properties and values used as inputs when estimating the regional leaching of 6PPD and 6PPD-Q in the rural roads scenario

	6PPD	6PPD-Q	Source
Amount used, frequency and duration of use (or from service life)			
Concentration in tyre rubber particle ($Conc_{AfterMan}$)	2%	0.02%	Figure 7, Figure 8 and "Chemical" tab of model
Fraction of the ingredient that remains after any degradation or transformation occurs ($F_{ingredient}$)	0.40	N/A	Figure 7
Fraction of the chemical that can be released to the environment by leaching into water ($F_{ingredient\ leachable}$)	0.0016	0.00004	Equation 11 and Equation 12
log K_{OW}	4.68	3.98	Hu *et al.* (2022)
Regional mass of substance in tyre particles available for leaching, $M_{ingredient\ leachable}$)	28 tonnes/year	0.7 tonnes/year	Table 9 & Equation 13
Daily local widespread use amount (mass of substance in tyre particles)	0.18 kg/day	4.4 g/day	ECHA (2016a; R.16.2.2.1.2.)
Other conditions affecting environmental exposure			
Fraction available for release from tyre particles ($F_{leachable}$)	0.2	0.2	Section 4.4.2
Fraction retained by soil (verge) and/or sludge in interception RMM	0.9	0.5	Table 27

Table 31 Releases of chemicals to watercourses for rural roads

Release route	6PPD Release rates	6PPD-Q Release rates
Water (regional annual)	3 tonnes/year	0.4 tonnes/year
Water (local daily)	15 g/day	1.9 g/day

4.5.3 Release of the tyre ingredient 6PPD from rubber tyre particles released from urban roads

Table 32 The estimated properties and values used as inputs when estimating the regional leaching of 6PPD and 6PPD-Q in the urban roads scenario

	6PPD	6PPD-Q	Source
Amount used, frequency and duration of use (or from service life)			
Concentration in tyre rubber particle ($Conc_{AfterMan}$)	2%	0.02%	Figure 7, Figure 8 and "Chemical" tab of model
Fraction of the ingredient that remains after any degradation or transformation occurs ($F_{ingredient}$)	0.40	N/A	Figure 7
Fraction of the chemical that can be released to the environment by leaching into water ($F_{ingredient\ leachable}$)	0.0016	0.00004	Equation 11 and Equation 12
log K_{OW}	4.68	3.98	Hu *et al.* (2022)
Regional mass of substance in tyre particles available for leaching, $M_{ingredient\ leachable}$)	22 tonnes/year	0.5 tonnes/year	Table 9 & Equation 13
Daily local widespread use amount (mass of substance in tyre particles)	0.12 kg/day	2.9 g/day	ECHA (2016a; R.16.2.2.1.2.)
Other conditions affecting environmental exposure			
Fraction available for release from tyre particles ($F_{leachable}$)	0.2	0.2	Section 4.4.2
Fraction retained by soil (verge) and/or sludge in interception RMM	0.9	0.5	Table 27

Table 33 Releases of chemicals to watercourses for urban roads

Release route	6PPD Release rates	6PPD-Q Release rates
Water (regional annual)	13 tonnes/year	0.4 tonnes/year
Water (local daily)	71.4 g/day	2.3 g/day

4.5.4 Combined uses

These three exposure scenarios can be combined to estimate the amount of substance released either directly to watercourses (motorways and rural roads) or to STP (urban roads), which are summarised separately in Table 34 to differentiate the receiving water type.

Table 34 Combined releases of chemicals to watercourses

Release route	Scale of release	Release rates	
		6PPD	6PPD-Q
Motorway and Rural Road	Regional, annual	6 tonnes/year	0.8 tonnes/year
	Local, daily	32 g/day	4.0 g/day
Urban Road	Regional, annual	13 tonnes/year	0.4 tonnes/year
	Local, daily	71.4 g/day	2.3 g/day

Annex 7 contains instructions for entering the model outputs into EUSES for further modelling of PECs. It must be noted that as 6PPD-Q is not REACH registered, several basic parameters required for EUSES modelling are not available (vapour pressure, biodegradability, hydrolysis rate, photolysis rate) and so the user must use expert judgement when selecting values (using software predictions where appropriate).

4.6 Case Study - Leaching and release of substances

Estimates of 6PPD and 6PPD-Q leachate masses released can be calculated from the TRWP mass determined in the M6 Lowgill case study (see Section 3.4).

Table 35 Substance related parameters used as input values in the case study

Parameter	Input
What is the substance of interest?	N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD)
Is the substance organic or a metal?	Organic
Concentration used in manufacture (%)	2
Is the substance intended to be consumed during manufacture?	No
Concentration in tyre tread after manufacture (%)	2
Does the substance transform or degrade during use?	Yes
If degradation does occur, what fraction remains?	0.40
What is the log K_{OW} of the substance?	4.68

Table 36 Degradation product related parameters used as input values in the case study

Parameter	Input	Source
What is the degradation product?	6PPD-Q	
Is the degradation product organic or a metal?	organic	
From which tyre ingredient is it sourced?	6PPD	
Concentration of source component in tyre (%)	2	NOCIL (2010a, 2010b)
Efficiency of transformation (%)	1	Hu *et al.* (2022)
Concentration of degradation product in tyre rubber particles (%)	0.02	
What is the log K_{OW} of the substance?	3.98	Hu *et al.* (2022)

The releases of 6PPD from both the single rainfall event and annual releases estimated by the local exposure scenario are shown in Figure 9.

For a single rainfall event

Chemical released from TWRPs in soils **Chemical released from particles in run-off**	Mass of substance in soil available to environment	**3.16E+04**	**mg**
	Mass of substance retained in soil	**2.85E+04**	**mg**
	Mass released to surface water	**3.16E+03**	**mg**
	Mass of substance in particles in runoff available to environment	**1.58E+04**	**mg**
	Mass of substance leached from particles held in water	**1.58E+03**	**mg**
	Mass of Substance Bypassing STP (Urban Only)	**N/A**	**mg**
	Mass of Substance Entering STP (Urban Only)	**N/A**	**mg**
	Mass of substance held in treatment measure	**1.42E+04**	**mg**
Chemical released to environment	Total mass of substance in released water	**4.74E+03**	**mg**

Over the period of a year

Chemical released from TWRPs in soils **Chemical released from particles in run-off**	Mass of substance in soil available to environment	**3.85E+06**	**mg**
	Mass of substance retained in soil	**3.46E+06**	**mg**
	Mass released to surface water	**3.85E+05**	**mg**
	Mass of substance in particles in runoff available to environment	**1.92E+06**	**mg**
	Mass of substance leached from particles held in water	**1.92E+05**	**mg**
	Mass of Substance Bypassing STP (Urban Only)	**N/A**	**mg**
	Mass of Substance Entering STP (Urban Only)	**N/A**	**mg**
	Mass of substance held in sediment	**1.73E+06**	**mg**
Chemical released to environment	Total mass of substance in runoff water	**5.77E+05**	**mg/year**

Figure 9 Estimated releases of 6PPD from TRWPs as calculated by the local exposure scenario

It is estimated that 4.7 g of 6PPD would be released to the River Lune from this stretch of road during the single rainfall event and 577 g would be released over a year to the river assuming the road drained into it.

The amount of 6PPD-Q released using the same parameters is shown in Figure 10.

For a single rainfall event

Chemical released from TWRPs in soils	Mass of substance in soil available to environment	**791.0**	**mg**
	Mass of substance retained in soil	**395.5**	**mg**
	Mass released to surface water	**395.5**	**mg**
Chemical released from particles in run-off	Mass of substance in particles in runoff available to environment	**394.7**	**mg**
	Mass of substance leached from particles held in water	**197.4**	**mg**
	Mass of Substance Bypassing STP (Urban Only)	**N/A**	**mg**
	Mass of Substance Entering STP (Urban Only)	**N/A**	**mg**
	Mass of substance held in treatment measure	**197.4**	**mg**
Chemical released to environment	Total mass of substance in released water	**592.9**	**mg**

Over the period of a year

Chemical released from TWRPs in soils	Mass of substance in soil available to environment	**9.62E+04**	**mg**
	Mass of substance retained in soil	**4.81E+04**	**mg**
	Mass released to surface water	**4.81E+04**	**mg**
Chemical released from particles in run-off	Mass of substance in particles in runoff available to environment	**4.80E+04**	**mg**
	Mass of substance leached from particles held in water	**2.40E+04**	**mg**
	Mass of Substance Bypassing STP (Urban Only)	**N/A**	**mg**
	Mass of Substance Entering STP (Urban Only)	**N/A**	**mg**
	Mass of substance held in sediment	**2.40E+04**	**mg**
Chemical released to environment	Total mass of substance in runoff water	**7.21E+04**	**mg/year**

Figure 10 Estimated releases of 6PPD-Q from TRWPs as calculated by the local exposure scenario

The key outputs from the exposure scenario are that 0.59 g of 6PPD-Q would be released to the river during the single rainfall event and 72.1 g would be released on an annual basis.

Assuming all rain that falls on the road during a heavy rainfall event can transport the substance and no further dilution occurs before reaching the watercourse, the volume of water can be calculated as follows:

Equation 15 Calculation to determine the volume of rain that falls upon the road

$$V_{rain} = L_{road} \times W_{lane} \times n \times D_{rain}$$

Where: V_{rain} = Volume of rain that falls onto the road surface (m^3)

L_{road} = Length of road (m)

W_{lane} = Width of lane on the road (m)

n = Number of lanes in the road

D_{rain} = depth of rainfall deposited during the event (m)

In this scenario, assuming six 3.7 m wide lanes and a 5 mm rainfall instance, 111 m^3 or 111,000 L of rain falls on the stretch of road. Using this value, the concentrations of 6PPD and 6PPD-Q estimated by the exposure scenario in the runoff would be 42.7 µg/L and 5.3 µg/L, respectively, as calculated using Equation 16.

Equation 16 Concentration of the substance present within rainfall event road runoff

$$C_{sub} = \frac{M_{sub}}{V_{rain}}$$

Where: V_{rain} = Volume of rain that falls onto the road surface (L, Equation 15)

M_{sub} = Mass of the substance present within the road runoff (mg, Figure 10 or Equation 14)

C_{sub} = Concentration of the substance present within the road runoff (mg/L)

Freshwater predicted environmental concentrations (PECs) of 6PPD and 6PPD-Q can be calculated from the concentration in the runoff and accounting for the flow rate of the River Lune. The average and Q95 low flow rate of the River Lune between May 2018 and April 2020 were calculated as being 7.86 m^3/s and 0.51 m^3/s, respectively (DEFRA, 2026). Assuming the rainfall event took place over the course of an hour, a flow rate of 0.031 m^3/s can be calculated based on the calculated volume of road runoff. This results in dilution factors of 255 and 17 for the average and Q95 low flow rates of the River Lune, respectively. The dilution is conservative as it assumes the upstream flow of the River Lune is unchanged by the rainfall. The PECs were calculated using Equation 17 below.

Indicative thresholds were calculated using ecotoxicity data from the HSE (2025) mandatory classification and labelling (MCL) report for 6PPD using the approach described for intermittent releases published by ECHA (2008b). The thresholds were calculated as being 0.28 µg/L for 6PPD and of 0.00041 µg/L for 6PPD-Q. Comparison to the calculated PECs can be seen in Table 37.

Equation 17 PECs of the substance calculated from concentration in the road runoff and dilution factor

$$PEC = \frac{C_{Sub}}{DF}$$

Where: C_{sub} = Concentration of the substance present within the road runoff (µg/L)

DF = Dilution factor calculated from the river flow rate and runoff volume

Table 37 Calculated local $PEC_{surfacewater}$ and risk characterisation ratio (RCR) based on the mass of 6PPD and 6PPD-Q released from the M6 Lowgill case study

Substance	Flow Rate	$PEC_{surfacewater}$ (µg/L)	Freshwater Indicative Threshold (µg/L)	RCR
6PPD	Average	0.17	0.28	0.6
6PPD	Q95	2.51	0.28	9.0
6PPD-Q	Average	0.02	0.00041	756
6PPD-Q	Q95	0.31	0.00041	48.8

The concentration of 6PPD-Q has been measured in stormwater runoff and nearby surface waters in several countries (not within GB) between 0.4 ng/L and 6.1 µg/L (Cao *et al.*, 2022; Rauert *et al.*, 2022a; Tian *et al.*, 2021; Zhao *et al.*, 2023b). This is a wide range of concentrations but there is little information on the sampling locations (road type, distance of road serviced by the sampled watercourse, etc.) or prevailing weather conditions for each of the sampled sites (days since rain, rain volume, etc.). Therefore, while the calculated concentration in the runoff and River Lune in this case study falls within the range of literature values, direct comparison is not possible as there is currently no 6PPD or 6PPD-Q monitoring data for this site. The RCRs exceed 1 for a number of flow scenarios, indicating that there is a potential risk to surface water from the release of 6PPD and 6PPD-Q at this location when using the specified conservative parameters. Other tyre additives and degradation products may add to the risk and the use of an additional mixture assessment factor may be appropriate (EA, 2022b).

4.7 UK Monitoring Data

The EA (2022a; accessed 12/02/2026, last updated 02/2026) aquatic monitoring programme has included 6PPD-Q in routine target screening since late 2021. Between January 2024 and January 2026, 6PPD-Q was detected 8 times in surface waters at 4 sites (River Ouse, River Douglas, River Chelt and Bourne Rivulet) in the range of 0.0047 to 0.1 µg/L (at a limit of detection (LOD) of 0.001 µg/L, detection frequency ≤1.3 %). These data confirm the presence of 6PPD-Q in the aquatic environment in England. The concentrations reported are the same order of magnitude as the concentrations calculated from the exposure model outputs for the local scenario (0.02 – 0.31 µg/L). However, as the data are semi-quantitative, the values have significant uncertainty. It is possible that this type of substance is under-reported because the EA monitoring

programme is not currently designed to capture rain-induced pollution events and the locations sampled do not necessarily represent locations where 6PPD-Q might be expected (i.e. in proximity to roads or receiving discharges from highways outfalls).

HE (2020) collected fifteen road runoff samples between 23 May and 30 September 2022 across seven different locations, in which a number of tyre related chemicals were identified (NH, 2023c), as summarised in Table 38. Most of the substances were present along with TRWPs which could indicate that they originate from the same source, or tyre particles have contributed to their presence. The authors identified that further sampling and analysis was needed to increase confidence in concluding on whether TRWPs are the primary source of the substances detected in the water samples.

Table 38 Summary of reported concentrations from NH (2023c)

Substance	LOD (µg/L)	Number of positive detections from 15 samples	Concentration (mean, µg/L)	Concentration (maximum, µg/L)
1,3-Diphenylguanidine (DPG)	<0.1	13	2.24	16.20
N-(1,3-Dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD)	<0.1	15	1.16	4.36
Benzothiazole-2-sulfonic acid (BTSA)	<1	13	28.25	75.10
Cyclohexyl-3-phenylurea (CPU)	<1	4	0.85[a]	2.50
Cyclohexylamine	<0.1	4	0.14	0.50
N, N'-Dicyclohexylurea (DHU)	<1	4	0.82[a]	2.10
Hexa(methoxymethyl)melamine	<10	4	7.27	20.00
Hydroxybenzothiazole	<1	6	1.93	10.40
1-Indanone	<1	15	2.67	5.00
2-Methylthiobenzothiazole	<1	2	0.69[a]	2.57

Note: [a]Sample concentrations below the LOD were assigned a concentration equivalent to 50% of the LOD by the author

5 Conclusions and Recommendations

5.1 Conclusions

In response to the known environmental concerns around the release of 6PPD-Q and its precursor 6PPD from roads, the Environment Agency has used published data on tyre wear rates and particle transport values to develop exposure scenarios and an associated model for the environmental release of rubber particles from tyres. By incorporating the potential leaching of chemicals from the particles, the model can be used to predict PECs for chemicals present in tyres at the local and regional scales at a screening level. This should be useful for prioritisation purposes.

The regional exposure scenarios for tyre use predicts that 54,400 tonnes of tyre rubber particles are released from GB roads annually. Annual releases of rubber are predicted to be 7,000 tonnes into surface waters, 2,200 tonnes into air, 32,000 tonnes into roadside verges and 12,800 tonnes onto other soils partly due to spreading of sludge removed from interception measures. The annual mass released is similar to that predicted by a recent, national-scale UK estimate, which adds confidence in the output. The model developed from the exposure scenarios also allows a user to predict tyre rubber release from a geographically specific stretch of road if traffic volumes are known. A case study on 1 km of the M6 motorway predicted that 235.6 kg of rubber could be released annually into the River Lune and 2,400 kg might be released to roadside soils from this stretch of road. When considering a standard 11 kg car tyre, the released rubber particle mass could be visualised as being the same mass as the rubber from 25 and 257 whole tyres deposited into the River Lune and adjacent soils respectively. The calculated concentration of rubber particles within the soil of 14,000 mg/kg is within the ranges of measured values reported in the literature for European sites, but there is no GB data to compare it to.

Over 100 potential tyre ingredients were identified from the literature and can be selected from a dropdown list in the model. Log K_{OW} values are provided where available. The report focusses on 6PPD and 6PPD-Q to provide an illustration of how the model may be used. 6PPD was detected in 15 road runoff samples taken as part of the NH (2023c) microplastic investigation, at a mean and maximum concentration of 1.16 µg/L and 4.36 µg/L, respectively. Further sampling and analysis were recommended to increase confidence in these data. These values are nevertheless broadly consistent with average and Q95 flow PECs of 0.17 and 2.51 µg/L for surface water calculated in the M6 Lowgill case study (Section 4.6). EA monitoring has detected 6PPD-Q in a small number of freshwater samples at a concentration range of 0.0047 to 0.1 µg/L by semi-quantitative analysis. Though subject to significant uncertainty, they are also broadly consistent with the 6PPD-Q PECs calculated from the exposure model outputs for case study average and Q95 river flows (0.02 – 0.31 µg/L). While this provides reassurance that the model is not overly conservative, any comparison with measured data from different sites is complicated by factors such as the unknown amounts of rubber at the sampling sites,

differing traffic densities and weather events associated with sampling (as the local model assumes a rainfall event has occurred). For 6PPD-Q at both flow rates under examination and 6PPD at a Q95 low flow, the calculated PECs exceed intermittent thresholds derived from ecotoxicity data reported in the 6PPD MCL report (HSE, 2025). Therefore, the model output indicates that 6PPD and 6PDD-Q could potentially pose a risk to aquatic organisms at this location, but this would need to be confirmed (for example through monitoring appropriately linked to weather events) as the model is intended as a prioritisation and screening tool only.

5.2 Uncertainties

The exposure scenario and model rely on a series of inputs for which relatively little information is available. Several assumptions have therefore been made as a result. Key limitations include the following:

- Whilst general information is available about the types of chemicals used in tyres and their respective concentrations, actual composition data is proprietary information that is specific to tyre type (e.g. summer versus winter or vehicle type) and tyre manufacturer. Due to this lack of publicly available data we have made some simple assumptions about the likely levels of common components in tyres, which can be updated if better information becomes available.
- Leaching rate plays a significant role in the actual release of substances to the environment both for single event and annual scenarios. However, there is a lack of consistent leaching methodology. This meant a basic model was used to predict the quantity of a substance available for leaching and the exposure scenario assumes that all this quantity is available for environmental partitioning immediately upon rainfall and mobilization. For organic substances this is 20% of the concentration in the tyre after manufacture, less any degradation. It is important to recognise that URMS arises as a result of acute toxicity, so available substances must be leached from TRWPs with sufficient rapidity to cause this. Conversely, at the regional scale, the figure of 20% is based on a 10- month period, so annual releases could be proportionally higher. As rubber particles are expected to persist in the environment for multiple years, they potentially could release more leachate for several years before the amount available is exhausted. The model does not take any ‘baseline’ contamination from previous years into account.
- The impact of particle size on transport or leaching rate is not considered either. Particles released to air are generally considered to be <PM10. Particle weathering is not considered beyond the assumption that 20% of organics and 0.01% of inorganics are available to be leached from particles over the course of approximately one year. The distribution of expected size fractions is currently unknown, but finer particles are expected to be leached more rapidly due to increased surface area.
- Road types are grouped into Urban, Rural and Motorway for simplicity to reflect road characteristics, differences in driving styles and traffic volume. There is limited TRWP emission data for vehicles on rural roads and motorways, so the emission data

available for these road types was normalised against the urban road data in this report. This may over- or underestimate releases on certain roads and lead to uncertainty when deciding about the type of road being modelled for specific locations.

- Tyre (and subsequently TRWPs) age will impact the leaching rate and emission rate of TRWPs and is not often reported in the literature. No adjustments are made in the exposure scenario for tyre age.
- The mass of rubber in the TRWPs is assumed to be 85% (w/w) as a conservative estimate, but this can vary.
- The impact of driving style, road material and surface properties are not considered due to the scales involved and lack of data.
- Vehicle mass is not considered in the exposure scenario. Heavier vehicles within a specific vehicle class will generate TRWPs at an increased rate compared to lighter vehicles. The transition to electric vehicles may require a review of assumptions in future.
- The impact of seasonal variation (i.e. temperature and sunlight) on rubber properties, generation of TRWPs, and leaching rate are not considered.
- Different nomenclature is used for HGVs, LGVs and vans depending on the data source. In most cases it is not clear which vehicle type the data relate to. These vehicle classes are addressed within the local and regional sections differently due to the different underlying data.

5.3 Recommendations

The exposure scenario and model presented in this report can be considered to represent a first step in modelling rubber and chemical emissions from tyres on GB roads. Additional data and research could improve the reliability and accuracy of future assessments. Relevant activities are suggested below.

1. **Better reporting of TRWP size fractions and leaching rates:** Studies vary in test methodologies and units. In many cases, methods may bias results towards specific size fractions. Whilst this provides information on the total amount of rubber released, the potential for fine particles to be more bioavailable and to allow quicker leaching of substances mean that improved knowledge of this fraction would strengthen risk assessment.

   Although there are some standardised methods to measure leaching from solid particles (ISO, 2018), they are not commonly used by researchers. Leaching methods reported in the literature vary by media, duration, temperature and particle type.

   Standardisation of experimental methods and terminology would help improve reporting and consistency of data generated in the laboratory. If the volume and

quality of the available literature improves, the exposure scenarios and model could be updated.

2. **A more comprehensive monitoring programme for priority substances:** A monitoring programme for roadside soils, discharges from the GB road network and surface waters adjacent to major roads would improve the evidence base available, particularly for locations heavily impacted by road runoff. This would ideally use appropriate limits of detection relative to environmentally relevant concentrations (such as PNECs), and reflect the importance of weather events. In addition to providing more reliable information for risk assessment purposes, measured concentrations would help to benchmark the model.

   Various substances have been flagged in EA (2025) and are suggested in Annex 6 – PPDs and their quinones in particular are of significant regulatory interest. It should be noted that EA (2025) was based on a preliminary version of this exposure model, so could be updated to reflect the revised leachate masses calculated. This might identify additional substances of interest.

3. **Improved modelling of TRWP emissions to air and their subsequent transport within the environment:** The regional model currently assumes that all tyre particle matter suspended to air is deposited to agricultural soil near to the road, after which it contributes to the mass of TRWPs in soil for any subsequent leaching calculations. There is evidence to suggest that TRWPs may be subject to long range transport and impact environments other than those considered in the model. Resuspension of particles from the road surface may also be an important vector for transport of TRWPs into the environment. Further research, including a literature review, could determine the potential for long range transport and resuspension of particles. If sufficient data are collected the exposure scenario and model could be updated.

4. **Future developments:** Under the DEFRA (2025a) Environmental Improvement Plan, DfT are taking a leading role in developing regulations for emissions from tyre and break wear. It is anticipated that the planned EURO 7 legislation will reduce tyre wear rates (European Parliament and Council, 2023). Tyre formulations are expected to change to meet the requirements of EURO 7, so new chemicals may emerge or the relative proportions of existing chemicals could change. This will need to be considered when applying the model.

   NH are responsible for the SRN, which accounts for approximately 3% of GB roads and are currently assessing and implementing mitigation strategies for outfalls that pose the greatest risk. Emissions from outfalls not managed under the SRN are likely to be proportional to the traffic volume and the type of road, and the importance of this will depend on the sensitivity of the receiving environment. The model developed in this report could be considered as a screening tool to support this work, and user feedback could help to identify potential refinements.

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Glossary

ARN	Assessment of regulatory needs
BEV	Battery electric vehicle
BTMA	British Tyre Manufacturers Association
CAS	Chemical abstracts service number
CMTT	Cryomilled tyre tread
COMEAP	Committee on the Medical Effects of Air Pollutants
CSO	Combined sewer overflow
DEFRA	Department for Environment, Food and Rural Affairs
DFT	Department for Transport
DU	Downstream users
DUIN	Downstream user import notification
EA	Environment Agency
EC	Enzyme Comission numers
ECHA	European Chemicals Agency
EEA	European Environment Agency
ESI+	Electrospray Ionisation peaks
ETRMA	European Tyre and Rubber Manufacturers Association
EU	European Union
EUSES	European Union System for the Evaluation of Substances
GB	Great Britain
GIS	Geographic Information System
GRG	General rubber goods
HE	Highways England
HGV	Heavy goods vehicle
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ISO	International Organisation for Standardisation

ITRC	Interstate Technology and Regulatory Council
K_{OC}	Organic carbon-water partition coefficient
K_{OW}	Octanol-water partition coefficient
LDAA	Lancaster & District Angling Association
LGV	Light goods vehicle
LOD	Limit of detection
LOQ	Limit of quantisation
mph	Miles per hour
NAEI	National Atmospheric Emissions Inventory
NH	National Highways
NOCIL	National Organic Chemcal Industries Limited
NONS	Notification of new substances
MCL	Mandatory classification and labelling
OECD	Organisation for Economic Co-Operation and Development
PACT	Public activities coordination tool
PEC	Predicted environmental concentration
PM_{10}	Particulate matter with a diameter of 10 µm or less
$PM_{2.5}$	Particulate matter with a diameter of 2.5 µm or less
PNECs	Predicted no-effect concentration
PYGCMS	Pyrolysis gas chromatrography-mass spectrometry
RCR	Risk characterisation ratio
REACH	Registration, evaluation, authorisation and restriction of chemicals
RMM	Risk management measure
SpERCs	Specific environmental release category
SRN	Strategic road network
STP	Seweage treatment plant
SUV	Sports utility vehicle

SVHC	Substance of very high concern
T_g	Glass transition temperature
TNO	Netherlands Organisation for Applied Scientific Research
TP	Tyre particle
TRWP	Tyre and road wear particle
TWP	Tyre wear particle
UK	United Kingdom
UKIAM	United Kingdom Integrated Assessment Model
UKSO	United Kingdom Soil Observatory
URMS	Urban runoff mortality syndrome
ZOAB	Zeer Open Asfalt Beton (Very open asphalt concete)

Annex 1: Literature search terms

All data used in this study were taken from literature sources and available GB specific monitoring data. The literature search was performed using the principles outlined by Collins *et al.* (2015) for DEFRA. Three separate topics were investigated:

1. Tyre composition, market size and tyre production statistics.

2. Particles released from vehicle tyres and substances leached from these particles. This literature search was intended to identify data sources on the following topics:
    - Rate of particle loss from tyres during use.
    - Distribution of particles once released.
    - Rate of transport of particles from road into other environmental compartments.
    - Identity and effectiveness of measures intended to capture rubber particles.
    - Rate of leaching of substances from tyre rubber.
    - Measurement of particles and leachates in the environment.

3. Identification and measurement of 6PPD, its degradation products and similar substances. This literature search was intended to identify data sources on the following topics:
    - Measurement of 6PPD and 6PPD-Q in the environment.
    - Identity of other degradation products of 6PPD.
    - Occurrence of other phenylenediamine based substances used in tyres.

Relevant search terms were used in a range of literature databases. The abstracts of these initial hits were screened and references not relevant to the project were excluded. The literature search was undertaken in the period October 2022 to January 2023. A second search was conducted in October 2024 to ensure data published after the drafting and revision of this document were captured. A number of sources were provided by stakeholders.

Tyre composition and market size

This literature search was intended to identify data sources on the following topics

- Tyre composition
- Tyre market size
- Tyre production statistics

Search terms

No.	Search Terms	Results (Google Scholar)
1	Tyre composition AND Tire composition	No. of hits (Title): 158
2	Rubber AND chemicals AND composition	No. of hits (Title): 1
3	Tyre AND market size AND Tire market size	No. of hits (Title): 0
4	Tyre AND production statistics AND UK	No. of hits (Title): 0
5 (2024)	TITLE-ABS-key (("GB" OR "UK") AND ("Tyre" OR "Tire") AND ("Volumes " OR "Import" OR "Export" OR "Repurposing" OR "Disposal" OR "Production"))	No. of hits (TITLE-ABS-key): 84

Google Scholar was searched for academic literature and a general search was conducted using Google to access government reports plus tyre manufacturer and trade association websites for composition, market size and production data. Scopus was searched in October 2024.

Exclusion criteria

- Papers that did not provide specific information on tyre composition were excluded.
- Papers published prior to 2021 (2024 search)

Particle and leachate release from tyre particles and rubber crumb

This literature was intended to identify data sources on the following topics

- Rate of particle loss from tyres during use.
- Distribution of particles once released.
- Rate of transport of particles from road into other environmental compartments.
- Identity and effectiveness of measures intended to capture rubber particles.
- Rate of leaching of substances from tyre rubber.
- Measurement of particles and leachates in the environment.

Search terms

No.	Search Terms	Results
General Search		
1	Tire particles AND Tyre particles	No. of hits (Title): 319 No. of hits (Abstract): 2,342 No. of hits (Title OR Abstract): 2,386 **No. of hits (Title AND Abstract): 275**
1 (2024)	Title-ABS ("tire particles" AND "tyre particles") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 111**
2	Tire wear particle AND Tyre wear particle	No. of hits (Title): 119 No. of hits (Abstract): 460 No. of hits (Title OR Abstract): 477 **No. of hits (Title AND Abstract): 102**
2 (2024)	TITLE-ABS ("Tire wear particle" AND "Tyre wear particle") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 255**
3	Tire tread wear particle AND Tyre tread wear particle	No. of hits (Title): 6 No. of hits (Abstract): 60 No. of hits (Title OR Abstract): 61 **No. of hits (Title AND Abstract): 5**
3 (2024)	TITLE-ABS ("Tire tread wear particle" AND "Tyre tread wear particle") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 9**
4	Tire tread and road wear particles AND Tyre tread and road wear particles	No. of hits (Title): 1 No. of hits (Abstract): 40 No. of hits (Title OR Abstract): 40 **No. of hits (Title AND Abstract): 1**
4 (2024)	TITLE-ABS ("Tire tread and road wear particles" AND "Tyre tread and road wear particles") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
5	TRWP	No. of hits (Title): 4 No. of hits (Abstract): 39 No. of hits (Title OR Abstract): 39 **No. of hits (Title AND Abstract): 4**

No.	Search Terms	Results
5 (2024)	TITLE-ABS ("TRWP") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 59**
6	Tire tread wear particle leachate AND Tyre tread wear particle leachate	No. of hits (Title): 1 No. of hits (Abstract): 4 No. of hits (Title OR Abstract): 4 **No. of hits (Title AND Abstract): 1**
6 (2024)	TITLE-ABS ("Tire tread wear particle leachate" AND "Tyre tread wear particle leachate") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
7	Tire particles leachate AND Tyre particles leachate	No. of hits (Title): 1 No. of hits (Abstract): 22 No. of hits (Title OR Abstract): 24 **No. of hits (Title AND Abstract): 5**
7 (2024)	TITLE-ABS ("Tire particles leachate" AND "Tyre particles leachate ") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 5**
8	Environmental risk AND tires OR Environmental risk AND tyres	No. of hits (Title): 3 No. of hits (Abstract): 190 No. of hits (Title OR Abstract): 191 **No. of hits (Title AND Abstract): 2**
8 (2024)	TITLE-ABS ("Environmental risk" AND "tires" OR "Environmental risk" AND "tyres") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 56**
9	Environmental risk AND Tyre particles leachate OR Environmental risk AND Tire particles leachate	No. of hits (Title): 0 No. of hits (Abstract): 2 No. of hits (Title OR Abstract): 2 **No. of hits (Title AND Abstract): 0**
9 (2024)	TITLE-ABS ("Environmental risk" AND "Tyre particles leachate" OR "Environmental risk" AND "Tire particles leachate") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
10	Environmental risk AND Tyre particles OR Environmental risk AND Tire particles	No. of hits (Title): 0 No. of hits (Abstract): 44 No. of hits (Title OR Abstract): 44

No.	Search Terms	Results
		No. of hits (Title AND Abstract): 0
10 (2024)	TITLE-ABS ("Environmental risk" AND "Tyre particles" OR "Environmental risk" AND "Tire particles") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 2**
11	Environmental risk AND TRWP	No. of hits (Title): 0 No. of hits (Abstract): 3 No. of hits (Title OR Abstract): 3 **No. of hits (Title AND Abstract): 0**
11 (2024)	TITLE-ABS ("Environmental risk" AND "TRWP") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 4**
12	(Ecotox* AND tires OR Ecotox* AND tyres) OR (Ecotoxicity AND tires OR Ecotoxicity AND tyres) OR (Toxic* AND tires OR Toxic* AND tyres) OR (Toxicity AND tires OR Toxicity AND tyres) OR (Toxicity AND Tyre particles leachate OR Toxicity AND Tire particles leachate) OR (Toxicity AND Tyre particles OR Toxicity AND Tire particles) OR (Toxicity AND TRWP)	No. of hits (Title): 65 No. of hits (Abstract): 512 No. of hits (Title OR Abstract): 540 **No. of hits (Title AND Abstract): 46**
12 (2024)	TITLE-ABS ((("Ecotox*" AND "tires") OR ("Ecotox*" AND "tyres")) OR (("Ecotoxicity" AND "tires") OR ("Ecotoxicity" AND "tyres")) OR (("Toxic*" AND "tires") OR ("Toxic*" AND "tyres")) OR (("Toxicity" AND "tires") OR ("Toxicity" AND "tyres")) OR (("Toxicity" AND "Tyre particles leachate") OR ("Toxicity" AND "Tire particles leachate")) OR (("Toxicity" AND "Tyre particles") OR ("Toxicity" AND "Tire particles")) OR (("Toxicity" AND "TRWP"))) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 678**
13	(Toxicity AND tires OR Toxicity AND tyres) AND (Toxicity AND Tyre particles leachate OR Toxicity AND Tire particles leachate) AND (Toxicity AND Tyre particles OR Toxicity AND Tire particles) AND (Toxicity AND TRWP)	No. of hits (Title): 0 No. of hits (Abstract): 1 No. of hits (Title OR Abstract): 1 **No. of hits (Title AND Abstract): 0**
13 (2024)	TITLE-ABS ((("Toxicity" AND "tires") OR ("Toxicity" AND "tyres")) AND (("Toxicity" AND "Tyre particles leachate") OR	**No. of hits (TITLE-ABS-key): 0**

No.	Search Terms	Results
	("Toxicity" AND "Tire particles leachate")) AND (("Toxicity" AND "Tyre particles") OR ("Toxicity" AND "Tire particles")) AND (("Toxicity" AND "TRWP"))) AND PUBYEAR > 2020	
14	(Stormwater runoff AND tires OR Stormwater runoff AND tyres) OR (Stormwater runoff AND Tyre particles leachate OR Stormwater runoff AND Tire particles leachate) OR (Stormwater runoff AND Tyre particles OR Stormwater runoff AND Tire particles) OR (Stormwater runoff AND TRWP) OR (Urban runoff AND tires OR Urban runoff AND tyres) OR (Urban runoff AND Tyre particles leachate OR Urban runoff AND Tire particles leachate) OR (Urban runoff AND Tyre particles OR Urban runoff AND Tire particles) OR (Urban runoff AND TRWP)	No. of hits (Title): 5 No. of hits (Abstract): 96 No. of hits (Title OR Abstract): 98 **No. of hits (Title AND Abstract): 3**
14 (2024)	TITLE-ABS ((("Stormwater runoff" AND "tires") OR ("Stormwater runoff" AND "tyres") OR ("Stormwater runoff" AND "Tyre particles leachate") OR ("Stormwater runoff" AND "Tire particles leachate") OR ("Stormwater runoff" AND "Tyre particles") OR ("Stormwater runoff" AND "Tire particles") OR ("Stormwater runoff" AND "TRWP")) OR (("Urban runoff" AND "tires") OR ("Urban runoff" AND "tyres") OR ("Urban runoff" AND "Tyre particles leachate") OR ("Urban runoff" AND "Tire particles leachate") OR ("Urban runoff" AND "Tyre particles") OR ("Urban runoff" AND "Tire particles") OR ("Urban runoff" AND "TRWP"))) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 57**
15	(Environmental discharge AND tires OR Environmental discharge AND tyres) OR (Environmental discharge AND Tyre particles leachate OR Environmental discharge AND Tire particles leachate) OR (Environmental discharge AND Tyre particles OR Environmental discharge AND Tire particles) OR (Environmental discharge AND TRWP)	No. of hits (Title): 0 No. of hits (Abstract): 27 No. of hits (Title OR Abstract): 27 **No. of hits (Title AND Abstract): 0**

No.	Search Terms	Results
15 (2024)	TITLE-ABS (("Environmental discharge" AND "tires") OR ("Environmental discharge" AND "tyres") OR ("Environmental discharge" AND "Tyre particles leachate") OR ("Environmental discharge" AND "Tire particles leachate") OR ("Environmental discharge" AND "Tyre particles") OR ("Environmental discharge" AND "Tire particles") OR ("Environmental discharge" AND "TRWP")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
16	(Environmental risk AND tires OR Environmental risk AND tyres) OR (Environmental risk AND Tyre particles leachate OR Environmental risk AND Tire particles leachate) OR (Environmental risk AND Tyre particles OR Environmental risk AND Tire particles) OR (Environmental risk AND TRWP)	Same results as Search 7
16 (2024)	TITLE-ABS (("Environmental risk" AND "tires") OR ("Environmental risk" AND "tyres") OR ("Environmental risk" AND "Tyre particles leachate") OR ("Environmental risk" AND "Tire particles leachate") OR ("Environmental risk" AND "Tyre particles") OR ("Environmental risk" AND "Tire particles") OR ("Environmental risk" AND "TRWP")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 56**
17	(Environmental risk AND tires OR Environmental risk AND tyres) OR (Environmental risk AND Tyre particles leachate OR Environmental risk AND Tire particles leachate) OR (Environmental risk AND Tyre particles OR Environmental risk AND Tire particles) OR (Environmental risk AND TRWP) OR (Environmental discharge AND tires OR Environmental discharge AND tyres) OR (Environmental discharge AND Tyre particles leachate OR Environmental discharge AND Tire particles leachate) OR (Environmental discharge AND Tyre particles OR Environmental discharge AND Tire particles) OR (Environmental discharge AND TRWP)	No. of hits (Title): 3 No. of hits (Abstract): 212 No. of hits (Title OR Abstract): 213 **No. of hits (Title AND Abstract): 2** Similar results as Search 7
17 (2024)	TITLE-ABS (("Environmental risk" AND "tires") OR ("Environmental risk" AND "tyres") OR ("Environmental risk" AND "Tyre particles leachate") OR ("Environmental risk" AND "Tire	**No. of hits (TITLE-ABS-key): 56**

No.	Search Terms	Results
	particles leachate") OR ("Environmental risk" AND "Tyre particles") OR ("Environmental risk" AND "Tire particles") OR ("Environmental risk" AND "TRWP") OR ("Environmental discharge" AND "tires") OR ("Environmental discharge" AND "tyres") OR ("Environmental discharge" AND "Tyre particles leachate") OR ("Environmental discharge" AND "Tire particles leachate") OR ("Environmental discharge" AND "Tyre particles") OR ("Environmental discharge" AND "Tire particles") OR ("Environmental discharge" AND "TRWP")) AND PUBYEAR > 2020	
18	(TWP loading AND soil OR TRWP loading AND soil OR Tyre particle loading AND soil OR Tire particle loading AND soil) OR (TWP leaching AND soil OR TRWP leaching AND soil OR Tyre particle leaching AND soil OR Tire particle leaching AND soil)	No. of hits (Title): 0 No. of hits (Abstract): 53 No. of hits (Title OR Abstract): 53 **No. of hits (Title AND Abstract): 0**
18 (2024)	TITLE-ABS (("TWP loading" AND "soil") OR ("TRWP loading" AND "soil") OR ("Tyre particle loading" AND "soil") OR ("Tire particle loading" AND "soil") OR ("TWP leaching" AND "soil") OR ("TRWP leaching" AND "soil") OR ("Tyre particle leaching" AND "soil") OR ("Tire particle leaching" AND "soil")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
19	TWP release AND environmental exposure OR TWP emission AND environmental exposure OR TRWP release AND environmental exposure OR TRWP emission AND environmental exposure OR Tyre particle release AND environmental exposure OR Tyre particle emission AND environmental exposure OR Tire particle release AND environmental exposure OR Tire particle emission AND environmental exposure OR Tyre Leachate AND environmental exposure OR Tire Leachate AND environmental exposure	No. of hits (Title): 0 No. of hits (Abstract): 25 No. of hits (Title OR Abstract): 25 **No. of hits (Title AND Abstract): 0**
19 (2024)	TITLE-ABS (("TWP release" AND "environmental exposure") OR ("TWP emission" AND "environmental exposure") OR ("TRWP release" AND "environmental exposure") OR	**No. of hits (TITLE-ABS-key): 1**

No.	Search Terms	Results
	("TRWP emission" AND "environmental exposure") OR ("Tyre particle release" AND "environmental exposure") OR ("Tyre particle emission" AND "environmental exposure") OR ("Tire particle release" AND "environmental exposure") OR ("Tire particle emission") AND ("environmental exposure") OR ("Tyre Leachate" AND "environmental exposure") OR ("Tire Leachate" AND "environmental exposure")) AND PUBYEAR > 2020	
20	TWP release AND toxicity OR TWP emission AND toxicity OR TRWP release AND toxicity OR TRWP emission AND toxicity OR Tyre particle release AND toxicity OR Tyre particle emission AND toxicity OR Tire particle release AND toxicity OR Tire particle emission AND toxicity OR Tyre Leachate AND toxicity OR Tire Leachate AND toxicity	No. of hits (Title): 9 No. of hits (Abstract): 49 No. of hits (Title OR Abstract): 51 **No. of hits (Title AND Abstract): 7**
20 (2024)	TITLE-ABS (("TWP release" AND "toxicity") OR ("TWP emission" AND "toxicity") OR ("TRWP release" AND "toxicity") OR ("TRWP emission" AND "toxicity") OR ("Tyre particle release" AND "toxicity") OR ("Tyre particle emission" AND "toxicity") OR ("Tire particle release" AND "toxicity") OR ("Tire particle emission" AND "toxicity") OR ("Tyre Leachate" AND "toxicity") OR ("Tire Leachate" AND "toxicity")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 5**
21	Tyre leachate sensitivity OR Tire leachate sensitivity	No. of hits (Title): 0 No. of hits (Abstract): 3 No. of hits (Title OR Abstract): 3 **No. of hits (Title AND Abstract): 0**
21 (2024)	TITLE-ABS ("Tyre leachate sensitivity" OR "Tire leachate sensitivity") AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
22	(Rubber particle AND tyres AND toxicity OR Rubber particle AND tires AND toxicity) OR (Rubber particle AND tyres AND environmental risk OR Rubber particles AND tires AND environmental risk) OR (Rubber particle AND	No. of hits (Title): 1 No. of hits (Abstract): 27 No. of hits (Title OR Abstract): 27

No.	Search Terms	Results
	tyres AND environmental discharge OR Rubber particles AND tires AND environmental discharge)	**No. of hits (Title AND Abstract): 1**
22 (2024)	TITLE-ABS (("Rubber particle" AND "tyres" AND "toxicity") OR ("Rubber particle" AND "tires" AND "toxicity") OR ("Rubber particle" AND "tyres" AND "environmental risk") OR "Rubber particle" AND "tires" AND "environmental risk") OR ("Rubber particle" AND "tyres" AND "environmental discharge") OR ("Rubber particle" AND "tires" AND "environmental discharge")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 5**
23	(Microplastic AND tyres AND toxicity OR Microplastic AND tires AND toxicity) OR (Microplastic AND tyres AND environmental risk OR Microplastic AND tires AND environmental risk) OR (Microplastic AND tyres AND environmental discharge OR Microplastic AND tires AND environmental discharge)	No. of hits (Title): 0 No. of hits (Abstract): 19 No. of hits (Title OR Abstract): 19 **No. of hits (Title AND Abstract): 0**
	TITLE-ABS (("Microplastic" AND "tyres" AND "toxicity") OR ("Microplastic" AND "tires" AND "toxicity") OR ("Microplastic" AND "tyres" AND "environmental risk") OR ("Microplastic" AND "tires" AND "environmental risk") OR ("Microplastic" AND "tyres" AND "environmental discharge") OR ("Microplastic" AND "tires" AND "environmental discharge")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 25**
24	(Rubber particle loading AND tyres AND soil OR Rubber particle loading AND tires AND soil) OR (Rubber particle leaching AND tyres AND soil OR Rubber particle leaching AND tires AND soil)	No. of hits (Title): 0 No. of hits (Abstract): 18 No. of hits (Title OR Abstract): 18 **No. of hits (Title AND Abstract): 0**
24 (2024)	TITLE-ABS (("Rubber particle loading" AND "tyres" AND "soil") OR ("Rubber particle loading" AND "tires" AND "soil") OR ("Rubber particle leaching" AND "tyres" AND "soil") OR ("Rubber particle leaching" AND "tires" AND "soil")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**

No.	Search Terms	Results
25	(Microplastic particle loading AND tyres AND soil OR Microplastic particle loading AND tires AND soil) OR (Microplastic particle leaching AND tyres AND soil OR Microplastic leaching AND tires AND soil)	No. of hits (Title): 1 No. of hits (Abstract): 8 No. of hits (Title OR Abstract): 9 **No. of hits (Title AND Abstract): 0**
25 (2024)	TITLE-ABS (("Microplastic particle loading" AND "tyres" AND "soil") OR ("Microplastic particle loading" AND "tires" AND "soil") OR ("Microplastic particle leaching" AND "tyres" AND "soil") OR ("Microplastic leaching" AND "tires" AND "soil")) AND PUBYEAR > 2020	**No. of hits (TITLE-ABS-key): 0**
26 (2024)	TITLE-ABS-key (("Battery electric vehicles" AND "tyres" AND "emissions") OR ("Battery electric vehicles" AND "tires" AND "emissions") OR ("Battery electric vehicles" AND "tyre particles" AND "emissions") OR ("Battery electric vehicles" AND "tire particles" AND "emissions") OR ("BEV" AND "tyres" AND "emissions") OR ("BEV" AND "tires" AND "emissions") OR ("BEV" AND "tyre particles" AND "emissions") OR ("BEV" AND "tire particles" AND "emissions") OR ("electric vehicles" AND "tyres" AND "emissions") OR ("electric vehicles" AND "tires" AND "emissions") OR ("electric vehicles" AND "tyre particles" AND "emissions") OR ("electric vehicles" AND "tire particles" AND "emissions"))	**No. of hits (TITLE-ABS-key): 142**
27 (2024)	TITLE-ABS-key (("GB" OR "UK") AND ("Rural" OR "Urban" OR "Motorway") AND ("Interception Methods" OR "Interception efficien*" OR "runoff" OR "run off" OR "Drain" OR "settlement pond" OR "mitigation") AND ("Tyres" or "Tires"))	**No. of hits (TITLE-ABS-key):3**
28 (2024)	TITLE-ABS-key (("GB" OR "UK") AND ("Rural" OR "Urban" OR "Motorway") AND "Road" AND ("Interception Methods" OR "Interception efficien*" OR "runoff" OR "run off" OR "Drain" OR "settlement pond" OR "mitigation"))	**No. of hits (TITLE-ABS-key): 82**

Databases

- Web of Science
- Google Scholar

- Scopus (2024)

Exclusion criteria

Papers that focused on the following topics were excluded.

- Human toxicity of rubber particles.
- Inhalation exposure of humans to PM_{10} rubber particles
- Technical examination of the function of tyres and rubber
- Papers published prior to 2021 (2024 search)

6PPD, degradation products and other key chemicals

This literature search was focused on data regarding the following topics

- Ecotoxicity of 6PPD, 6PPD-Q and other key chemicals.
- Measurement of 6PPD, 6PPD-Q and other key chemicals in the environment.
- Mechanism of Action of ecotoxicity of 6PPD-Q.
- Identity of other degradation products of 6PPD, 6PPD-Q and other key chemicals
- Occurrence and ecotoxicity of other phenylenediamine based substances used in tyres.

Search terms

No.	Search Terms	Results
1	(6PPD AND tires OR 6PPD AND tyres) OR (6PPD AND Tyre particles leachate OR 6PPD AND Tire particles leachate) OR (6PPD AND Tyre particles OR 6PPD AND Tire particles) OR (6PPD AND TRWP)	No. of hits (Title): 5 No. of hits (Abstract): 25 No. of hits (Title OR Abstract): 26 **No. of hits (Title AND Abstract): 4**
2	(6PPD-quinone AND tires OR 6PPD-quinone AND tyres) OR (6PPD-quinone AND Tyre particles leachate OR 6PPD-quinone AND Tire particles leachate) OR (6PPD-quinone AND Tyre particles OR 6PPD-quinone AND Tire particles) OR (6PPD-quinone AND TRWP)	No. of hits (Title): 4 No. of hits (Abstract): 14 No. of hits (Title OR Abstract): 15 **No. of hits (Title AND Abstract): 3**
3 (2024)	TITLE-ABS-KEY((("4-tert-octylphenol" OR "OPN" OR "t-OP") OR ("Zinc Oxide" OR "oxozinc") OR "Aniline" OR ("1,4-benzenediamine, N,N'-mixed Ph and tolyl derivs." OR "1,4-benzenediamine" OR "BENPAT") OR ("N-(1,3-dimethylbutyl)-N'-phenyl-1,4-benzenediamine" OR "6PPD") OR ("Dibutyl phthalate" OR "DBP") OR ("N,N-dicyclohexylbenzothiazole-2-sulphenamide" OR "DCBS" OR "N-(1,3-benzothiazol-2-ylsulfanyl)-N-cyclohexylcyclohexanamine") OR ("1H-Benzotriazole" OR "BTA") OR ("Triphenylphosphate" OR "TPP") OR ("Diethyl	**No. of hits (TITLE-ABS-key): 216**

No.	Search Terms	Results
	phthalate" OR "diethyl benzene-1,2-dicarboxylate" OR "DEP") OR ("2-Mercaptobenzothiazole" OR "MBT" OR "1,3-benzothiazole-2-thiol") OR ("Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with & 0.1% w/w of 4-nonylphenol, branched and linear (4-NP)" OR "4-NP" OR "TNPP") OR ("N-Cyclohexylbenzothiazol-2-sulfenamide" OR "CBS") OR ("N-(1,4-dimethylpentyl)-N'-phenylbenzene-1,4-diamine" OR "7PPD") OR ("N,N'-diphenyl-p-phenylenedi-amine" OR "DPPD")) AND "Concentration" AND ("Tyres" OR "Tires"))	

Databases

- PubMed
- Google Scholar
- Scopus (2024)

Exclusion criteria

- Very few hits were excluded, mainly because the narrow focus of the search terms and the recent interest in the topic meant most hits were directly related to the project. It was assumed that any similar substances would contain the "PPD" acronym and would refer to 6PPD in the abstract.
- Papers published prior to 2021 (2024 search)

Annex 2: Particle emission data

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
Car	Urban	132	112.2	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		88*	74.8	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		50*	42.5	US EPA (1995) cited in Baensch-Baltruschat *et al.* (2020)
		35*	29.8	CEPMEIP (2020, accessed 30/01/2020) cited in Baensch-Baltruschat *et al.* (2020)
		53	45	Gebbe and Hartung (1997) cited in Baensch-Baltruschat *et al.* (2020)
		61*	51.9	Rauterberg-Wulff (1998) cited in Baensch-Baltruschat *et al.* (2020)
		100	100	Luhana *et al.* (2004) cited in Baensch-Baltruschat *et al.* (2020)
		74	74	Luhana *et al.* (2004) cited in Baensch-Baltruschat *et al.* (2020)
		50	42.5	Gustafsson *et al.* (2008) cited in Baensch-Baltruschat *et al.* (2020)

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
		33	33	Baensch-Baltruschat *et al.* (2020)
		90	90	Hillenbrand *et al.* (2005) cited in Baensch-Baltruschat *et al.* (2020)
		100	85	Kole *et al.* (2017)
		50	42.5	Kole *et al.* (2017); Magnusson *et al.* (2017)
		80	68	Baumann and Ismeier (1998); Kole *et al.* (2017)
		61*	51.9	Timmers and Achten (2016)
		68*	57.8	Beddows and Harrison (2021)
		128	108.8	Woo *et al.* (2022a)
		58*	49.3	Mun *et al.* (2023)
	Rural	85	72.3	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		68*	57.8	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		53*	45.1	Beddows and Harrison (2021)
		139	118.2	Woo *et al.* (2022a); Woo *et al.* (2022b)
	Motorway	104	88.4	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		58*	49.3	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
				et al. (2020) and NH (2023b)
		45*	38.3	Beddows and Harrison (2021)
		205	174.3	Woo *et al.* (2022a)
Electric car	Urban	72*	61.2	Timmers and Achten (2016)
		161	136.9	Woo *et al.* (2022a)
		74	62.9	Beddows and Harrison (2021)
	Rural	57	48.5	Beddows and Harrison (2021)
		178	151.3	Woo *et al.* (2022a)
	Motorway	50	42.5	Beddows and Harrison (2021)
		247	210	Woo *et al.* (2022a)
Motorbike	Urban	60	51	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		46	46	Hillenbrand *et al.* (2005)
		38	32.3	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		17.2	14.6	US EPA (1995) cited in Baensch-Baltruschat *et al.* (2020)
		7	6	Aatmeeyata *et al.* (2009)
	Rural	39	33.2	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		29*	24.7	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
				et al. (2020) and NH (2023b)
	Motorway	47	40	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		25*	21.3	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
Van	Urban	159	135.2	Baensch-Baltruschat *et al.* (2020)
		204	173.4	Kole *et al.* (2017); Lassen *et al.* (2015)
		140*	119	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		107	91	Gebbe and Hartung (1997) cited in Baensch-Baltruschat *et al.* (2020)
		180	153	Kole *et al.* (2017) and Baumann and Ismeier (1998), cited in Baensch-Baltruschat *et al.* (2020)
	Rural	102	86.7	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		110*	93.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
				et al. (2020) and NH (2023b)
	Motorway	125	106.3	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		91*	77.4	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
Small lorry	Urban	658	559.3	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		495	420.8	Kole *et al.* (2017)
		189	160.7	Kole *et al.* (2017) and Baumann and Ismeier (1998), cited in Baensch-Baltruschat *et al.* (2020)
		539	458.2	Gebbe and Hartung (1997) cited in Baensch-Baltruschat *et al.* (2020)
		700	700	Hillenbrand *et al.* (2005) cited in Baensch-Baltruschat *et al.* (2020)
		178	178	Baensch-Baltruschat *et al.* (2020)
		320*	272	Rauterberg-Wulff (1998) cited in Baensch-Baltruschat *et al.* (2020)
	Rural	423	359.6	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
	Motorway	517	439.5	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
Large lorry	Urban	850	722.5	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		712	605.2	Kole *et al.* (2017); Sundt *et al.* (2014)
		1092	928.2	Gebbe and Hartung (1997) cited in Baensch-Baltruschat *et al.* (2020)
		1200	1200	Hillenbrand *et al.* (2005) cited in Baensch-Baltruschat *et al.* (2020)
		600	510	Kole *et al.* (2017)
		470*	399.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		1068	907.8	Kole *et al.* (2017)
	Rural	546	464.1	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		270*	229.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
	Motorway	668	567.8	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)

Vehicle type	Road type	Emission rate (mg/km driven)	Road Fraction Removed (mg/km driven)	Reference
		310*	263.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
Bus	Urban	415	352.8	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		210*	178.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
		204	173.4	Kole *et al.* (2017)
	Rural	267	227	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		170*	144.5	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)
	Motorway	326	277.1	Deltares and TNO (2016) cited in Baensch-Baltruschat *et al.* (2020)
		140*	119	NAEI (2017; accessed 30/04/2024) cited in Baensch-Baltruschat *et al.* (2020) and NH (2023b)

Note: *Corrected from PM_{10} data. PM_{10} assumed to be 10% of total mass.

Annex 3: Particle distribution data

Type of road	% Released to Watercourse	% Released to soil (verge)*	Reference
Urban	63	37	ten Broeke *et al.* (2008)
	50	50	Unice *et al.* (2019)
	67	33	Blok (2005)
	60	40	Kaufmann *et al.* (2007)
	40	60	Sieber *et al.* (2020)
	60	40	Verschoor *et al.* (2016)
Rural	10	90	ten Broeke *et al.* (2008)
	50	50	Unice *et al.* (2019)
	30	70	Kaufmann *et al.* (2007)
	10	90	Verschoor *et al.* (2016)
Motorway	63	37	ten Broeke *et al.* (2008)
	50	50	Unice *et al.* (2019)
	10	90	Verschoor *et al.* (2016)
	10	90	Kaufmann *et al.* (2007)

Note: *Normalised to total 100%, correcting for proportion released to air

Annex 4: Effectiveness of particle removal measures

Type of road	Type of measure	Effectiveness (%)	Reference
Urban	STP	17 – 100 (particles < 63 µm) 90 (particles > 300 µm)	Unice *et al.* (2019)
		70	Andersson-Skold *et al.* (2020)
		95	Unice *et al.* (2019)
		99	Andersson-Skold *et al.* (2020)
		95 - 96	Baensch-Baltruschat *et al.* (2020)
		90.1	Bayo *et al.* (2020)
		93.7	Edo *et al.* (2020)
		84	Magni *et al.* (2019)
		67	Maw *et al.* (2024)
		99.5	UKWIR (2023)
Rural	Roadside ditch	75	Unice *et al.* (2019)
Motorway	Settling pond or wetland	21 - 86	Unice *et al.* (2019)
		28	Monira *et al.* (2021)
		98	Meland *et al.* (2023)
		46 - 97	García-Haba *et al.* (2023)
		63	Rodland *et al.* (2022)
		72.6	Parker-Jurd *et al.* (2024)
		81.6	Ziajahromi *et al.* (2023)
		95 (100, 100, 100, 80.1)	Rasmussen *et al.* (2024)

Annex 5: Substances used in the manufacture of rubber

Chemicals are sourced from Kawakami *et al.* (2022); Nishi *et al.* (2022); NOCIL (2010a, 2010b). The stoichiometry for each chemical class is adapted from ETRMA (2013, 2019); NOCIL (2010a, 2010b), where specific concentrations are provided in the literature this is noted in the reference column. CAS and EC numbers can be found in the "Chemicals Tab" of the model.

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
Rubber	**Butadiene rubber**	-	50		No	
	Styrene butadiene rubber	-	Chemical Class: 50 Measured: 28.9		No	Mao *et al.* (2024)
	Natural rubber	-	Chemical Class: 50 Measured: 9.4		No	Rodland *et al.* (2024)
Fillers	**Carbon Black**	-	Chemical Class: 30 Measured: 15.3		No	Ntziachristos and Boulter (2019)
	Silicon dioxide	-	30		No	
	Calcium carbonate	-	30		No	
	Calcium silicate	-	30		No	
	Clays	-	30		No	
	Resins	-	30		No	
Plasticisers	**Aromatic petroleum oils**	-	6		No	
	Mild extracted solvent oils	-	6		No	
	Rape seed oils	-	6		No	
	Alkyl phenols	-	1		No	
	tert-Octylphenol	-	1		No	
	Alkylphenol ethoxylates	-	1		No	
	Sulfur	-	2		Yes	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	Hexamethylene tetramine (HMT)	Amine accelerant	2		Yes	
	Heptaldehyde-aniline condensation product (BA)	Amine accelerant	1		Yes	
	Hexa(methoxymethyl)melamine	Amine accelerant	1		Yes	
	Diphenyl guanidine (DPG)	Guanidine	Chemical Class: 1 Measured: 0.0044 – 0.0103	66 – 95	No	Boisseaux *et al.* (2024); Foscari *et al.* (2023); Weyrauch *et al.* (2023)
	Diphenylamine (DPA)	Guanidine	1		No	
	N,N'-Di-ortho-tolyl guanidine (DOTG)	Guanidine	1		No	
	Benzothiazole (BTZ)	Thiazole	Chemical Class: 1 Measured: 0.00393 – 0.059		Yes	Avagyan *et al.* (2014); Boisseaux *et al.* (2024)
	2-Mercaptobenzo-thiazole (MBT)	Thiazole	Chemical Class: 1 Measured: $3x10^{-5}$ - 0.09	$5x10^{-5}$ – $8x10^{-4}$	Yes	Avagyan *et al.* (2014); Boisseaux *et al.* (2024); Foscari *et al.* (2023); Zhang *et al.* (2018)
	2-2'-Dithiobis-(benzothiazole) (MBTS)	Thiazole	Chemical Class: 1		Yes	Avagyan *et al.* (2014)

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
			Measured: $9.9x10^{-4}$			
	Zinc 2-mercapto-benzothiazole (ZMBT)	Thiazole	1		Yes	
	2-(4-Morpholinyl)benzothiazole (24MoBT)	Thiazole	1		Yes	
	2-Benzothiazolesulfenamide	Thiazole	1		Yes	
	2-Methylbenzothiazole	Thiazole	1		Yes	
	2-Methylthiobenzothiazole (MeSBT)	Thiazole	1		Yes	
	Benzothiazole-2-sulfonic acid (BTSA)	Thiazole	1		Yes	
	Hydroxybenzothiazole (HOBT)	Thiazole	1		Yes	
	N-Cyclohexyl-2-benzothiazolamine (NCBA)	Thiazole	1		Yes	
	Zinc O,O-di-N-phosphorodithioate (ZBDP)	Thio-phosphate	1		Yes	
	N-Cyclohexyl-2-benzothiazole sulfenamide (CBS)	Sulfenamide	Chemical Class: 1 Measured: $6.6x10^{-5}$ – $1.4x10^{-3}$		Yes	Avagyan *et al.* (2014); Zhang *et al.* (2018)
	N-tert-Butyl-2-benzothiazole sulfenamide (TBBS)	Sulfenamide	1		Yes	
	2-(4-Morpholino-thio)benzothiazole (MBS)	Sulfenamide	1		Yes	
	N,N-Dicyclohexylbenzothiazole-2-sulfenamide (DCBS)	Sulfenamide	1		Yes	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	Ethylene thiourea (ETU)	Thiourea	1		Yes	
	Di-pentamethylene thiourea (DPTU)	Thiourea	1		Yes	
	Dibutyl thiourea (DBTU)	Thiourea	1		Yes	
	Tetramethylthiuram monosulfide (TMTM)	Thiuram	1		Yes	
	Tetramethylthiuram disulfide (TMTD)	Thiuram	1		Yes	
	Dipentamethylene-thiuram tetrasulfide (DPTT)	Thiuram	1		Yes	
	Tetrabenzylthiuram disulfide (TBzTD)	Thiuram	1		Yes	
	Zinc dimethyldithio-carbamate (ZDMC)	Dithio-carbamate	1		Yes	
	Zinc diethyldithio-carbamate (ZDEC)	Dithio-carbamate	1		Yes	
	Zinc dibutyldithio-carbamate (ZDBC)	Dithio-carbamate	1		Yes	
	Zinc dibenzyldithio-carbamate (ZDBC)	Dithio-carbamate	1		Yes	
	Zinc isopropyl xanthate (ZIX)	Xanthate	1		Yes	
	N,N-Caprolactam disulfide (CLD / DTDC)	Sulfur donor	1		Yes	
	2-Morpholino-dithio benzothiazole (MBSS)	Sulfur donor	1		Yes	
	N-Oxydiethylene thiocarbamyl-N'- oxydiethylene sulfenamide (OTOS)	Sulfur donor	1		Yes	
	4,4'-Dithiodimorpholine (DTDM)	Sulfur donor	1		Yes	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	para-Benzo-quinonedioxime	Sulfur alternative	1		Yes	
	Dibenzoyl quinine dioxime	Sulfur alternative	1		Yes	
	Stearic acid	-	2		No	
	Zinc oxide	-	Chemical Class: 4 Measured: 0.017 – 17.4		No	Adachi and Tainosho (2004); Boisseaux *et al.* (2024); Degaffe and Turner (2011); Li *et al.* (2023); Ntziachristos and Boulter (2019); Rodland *et al.* (2024); Samešová *et al.* (2023); Wang *et al.* (2024a)
	Nitrosophenyl amine	Retarder	0.5		No	
	Salicylic acid	Retarder	0.5		No	
	Benzoic acid	Retarder	0.5		No	
	Phthalic anhydride	Retarder	0.5		No	
	N-(Cyclohexylthio)-phthalimide (CTP)	Inhibitor	1		yes	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	1H-Benzotriazole (BTA)	Inhibitor	0.5		No	
	5-Methyl-1H-benzotriazole (5-MTBR)	Inhibitor	0.5		No	
	2,2'-Dibenzamido-diphenyldisulfide (DBD)	-	0.5		Yes	
	Pentachlorothio-phenol	-	0.5		No	
	Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w of 4-nonylphenol, branched and linear (4-NP)		0.5		No	
	6,6'-Di-tert-butyl-2,2'-methylenedi-p-cresol (DBMC)		0.5		No	
	Ethoxyquin		0.5		No	
Antiaging and other chemicals	**N-(1,3-dimethyl-butyl)-N′-phenyl-p-phenylenediamine (6PPD)**	Antiozonant	Chemical Class: 2 Measured: 0.4 – 2	0.3 – 5	No	Fohet *et al.* (2023); Hu *et al.* (2023); Muller *et al.* (2022b); Weyrauch *et al.* (2023)
	N-Isopropyl-N′-phenyl-1,4-phenylenediamine (IPPD)	Antiozonant	2		No	
	N-Phenyl-N′-cyclohexyl-p-phenylenediamine (CPPD)	Antiozonant	Chemical Class: 2 Measured: $8.9x10^{-5}$ – $7.3x10^{-4}$		No	Mao *et al.* (2024); Wang *et al.* (2024b)

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	N,N′-Diphenyl-p-phenylenediamine (DPPD)	antiozonant	Chemical Class: 2 Measured:$7.1x10^{-5}$ – $1.4x10^{-3}$		No	Mao *et al.* (2024); Wang *et al.* (2024b)
	N-Phenyl-N′-(o-tolyl)-p-phenylene-diamine (PTPD)	Antiozonant	2		No	
	N,N'-Di(2-methylphenyl)benzene-1,4-diamine (DTPD)	Antiozonant	Chemical Class: 2 Measured: $5x10^{-6}$ – $1.34x10^{-4}$		No	Wang *et al.* (2024b)
	N-(1,4-Dimethyl-pentyl)-N′-phenyl-benzene-1,4-diamine (77PD)	Antiozonant	Chemical Class: 2 Measured: $4.5x10^{-5}$		No	Wang *et al.* (2024b)
	N,N′-Di-2-naphthyl-p-phenylenediamine (DNPD)	Antiozonant	2		No	
	N-(1-methylheptyl)-N′-phenyl-p-phenylenediamine (8PPD)	Antioxidant	Chemical Class: 2 Measured: $3.86x10^{-5}$		No	Wang *et al.* (2024b)
	N,N-Dioctyl-p-phenylenediamine (88PD)	Antioxidant	2		No	
	N,N'-Di-sec-butyl-p-phenylenediamine (44PD)	Antioxidant	2		No	
	2,2,4-Trimethyl-1,2-dihydroquinoline polymer (TMQ)	Antiozonant	Chemical Class: 2 Measured: $1.5x10^{-5}$ – $4.6x10^{-4}$		No	Rodland *et al.* (2024)

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	1,4-Benzenediamine, N,N'-mixed Ph and tolyl derivs. (BENPAT)	Antiozonant	2		No	
	Phenylguanidine (PG)	Antioxidant	2		No	
	1,3-Dicyclohexyl-urea (DCU)	Antioxidant	Chemical Class: 2 Measured:$3.3x10^{-5}$ - $2.6x10^{-3}$		No	Boisseaux *et al.* (2024); Zhao *et al.* (2023a)
	N-Methyl-dicyclohexylamine (DCHA)	Antioxidant	Chemical Class: 2 Measured: $5.9x10^{-5}$		No	Boisseaux *et al.* (2024)
	Dicyclohexylamine (DCH)	Antioxidant	2		No	
	Cyclohexyl-3-phenylurea (CPU)	Antioxidant	Chemical Class: 2 Measured: $3.6x10^{-5}$ – $1.3x10^{-5}$		No	Boisseaux *et al.* (2024)
	Paraffin wax	Antioxidant	2		No	
	MC-wax	Antioxidant	2		No	
	Polyethylene (PE) Wax	Antioxidant	2		No	
	Polypropylene (PP) Wax	Antioxidant	2		No	
	Styrenated phenol	Antioxidant	2		No	
	Butylated hydroxyphenol	Antioxidant	2		No	
	2,2-Methylene-bis-(4-methyl-6-tert-butylphenol) (DBMC)	Antioxidant	2		No	
	4,4'-Thio-bis(2-tert-butyl-m-cresol) (TBMC)	Antioxidant	2		No	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	Butylated reaction product of para-cresol and dicyclopentadiene (Wingstay L)	Antioxidant	2		No	
	Tetrakis(methylene 3-(3,5-di-tert-butyl-4-hydroxy)-propionatemethane) (Irganox 110)	Antioxidant	2		No	
	p-Orientated styrenated diphenylamine (Wingstay 29)	Antioxidant	2		No	
	Octylated diphenylamine (ODP)	Antioxidant	2		No	
	4,4'-Bis(dimethyl-benzyl)diphenylamine (DCDPA)	Antioxidant	2		No	
	Trisnonylphenyl-phosphate	Antioxidant	2		No	
	Triphenylphosphate (TPP)	Antioxidant	2		No	
	Acetone diphenylamine condensate (ADPA)	Antioxidant	2		No	
	6-Ethoxy-2,2,4-trimethyl-1,2-dihydro-quinoline (ETMQ)	Antioxidant	2		No	
	Phenyl-alpha-naphthylamine (PAN)	Antioxidant	2		No	
	Phenyl-beta-naphthylamine (PBN)	Antioxidant	2		No	
	Didodecyl-3,3'-thiopropionate	Antioxidant	2		No	
	Dioctadecyl-3,3'-thiodipropionate	Antioxidant	2		No	
	Nickel dibutyl dithiocarbamate	Antioxidant	2		No	
	Isononylphenol	Antioxidant	2		No	
	2-(2H-Benzotriazol-2-yl)-6-(1-methyl-1-phenylethyl)-4-	Antioxidant	2		No	

Technical function	Chemical	Chemical group	Stoichiometry in rubber manufacture (when used, %)	Measured Leaching Amount (%)	Consumed in manufacture?	Reference
	(1,1,3,3-tetramethylbutyl)phenol (UV-928)					
	2,2′-Methylenebis(4-ethyl-6-tert-butylphenol) (o-MBp24)	Antioxidant	2		No	
	Methyl isobutyl ketone (MIBK)	Antioxidant	2		No	

Annex 6: Candidate substances for further prioritisation

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
1,3-Dicyclohexylurea	DCU	2387-23-7	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
1,3-Diphenylguanidine	DPG	102-06-7	Positive detection in surface-water runoff (NH, 2023c)	1,000 - 10,000
1,3-Diphenylurea	DPU	102-07-8	Reported in Annex 2 of EA (2025)	1 - 10
1,4-Benzenediamine, N,N'-mixed Ph and tolyl derivs.	BENPAT	68953-84-4	Reported in Annex 2 of EA (2025)	1,000 – 10,000
1H-Benzotriazole	BTA	95-14-7	Reported in Annex 2 of EA (2025)	1,000 – 10,000
1-Indanone	-	83-33-0	Positive detection in surface-water runoff (NH, 2023c)	-
2-(2H-Benzotriazol-2-yl)-6-(1-methyl-1-phenylethyl)-4-(1,1,3,3-tetramethylbutyl)phenol	UV-928	73936-91-1	Reported in Annex 2 of EA (2025)	1,000 – 10,000
2-(4- Morpholinyl)benzothiazole	24MoBT	4225-26-7	Reported in Annex 2 of EA (2025)	-
2,2,4-Trimethyl-1,2-dihydroquinoline polymer	TMQ	26780-96-1	Reported in Annex 2 of EA (2025)	10,000 – 100,000
2,2′-Methylenebis(4-ethyl-6-*tert*-butylphenol)	*o*-MBp24	88-24-4	Identified as a candidate for further investigation as a result of TRWP release to the environment	1 - 10
2,2'-Methylene bis(4-methyl-6-tert-butylphenol)	DBMC	119-47-1	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 – 10,000
2,6-Di-*tert*-butyl-4-methylphenol	BHT	128-37-0	Identified as a candidate for further investigation as a result of TRWP release to the environment	10,000 - 100 000

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
2-Anilino-5-(4-methylpentan-2-ylamino)cyclohexa-2,5-diene-1,4-dione	6PPD-Q	2754428-18-5	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
2-Anilino-5-(propan-2-ylamino)cyclohexa-2,5-diene-1,4-dione	IPPD-Q	68054-73-9	Reported in Annex 2 of EA (2025)	-
2-Benzothiazolesulfenamide	-	2801-21-0	Reported in Annex 2 of EA (2025)	-
2-Mercaptobenzothiazole	MBT	149-30-4	Reported in Annex 2 of EA (2025)	1,000 – 10,000
2-Mercaptomethylbenzimidazole	MMBI	27231-36-3	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
2-Methylbenzothiazole	MeBT	120-75-2	Reported in Annex 2 of EA (2025)	-
2-Methylthiobenzothiazole	MeSBT	615-22-5	Positive detection in surface-water runoff (NH, 2023c)	-
2-N,2-N,4-N,4-N,6-N,6-N-Hexakis(methoxymethyl)-1,3,5-triazine-2,4,6-triamine	HMMM	3089-11-0	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
4-(1-Methyl-1-phenylethyl)-N-[4-(1-methyl-1-phenylethyl) phenyl]aniline		10081-67-1	Reported in Annex 2 of EA (2025)	1,000 – 10,000
4,4′-Butylidenebis(3-methyl-6-*tert*-butylphenol)	*p*-BBp14	85-60-9	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
4,4′-Methylenedianiline	MDA	101-77-9	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 -10,000
4,4'-Bis(dimethylbenzyl)diphenylamine	DCDPA	10081-67-1	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 - 10,000

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
4-Hydroxy-3-*tert*-butylanisole	BHA	121-00-6	Identified as a candidate for further investigation as a result of TRWP release to the environment	10 - 100
5-Methyl-1H-benzotriazole	5-MBTR	136-85-6	Reported in Annex 2 of EA (2025)	1 -10
6,6'-Di-tert-butyl-2,2'-methylenedi-p-cresol	DBMC	119-47-1	Reported in Annex 2 of EA (2025)	1,000 – 10,000
6,6'-Di-tert-butyl-4,4'-thiodi-m-cresol	*p*-TBp14	**96-69-5**	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 - 10,000
6-Ethoxy-1,2-dihydro-2,2,4-trimethylquinoline	Ethoxyquin	91-53-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	1 - 10
Acetone diphenylamine condensate	ADPA	101-54-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
Benzimidazole-2-thiol	MBI	583-39-1	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
Benzothiazol-2(3H)-one	HOBT	934-34-9	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
Benzothiazole	BTZ	95-16-9	Identified as a candidate for further investigation as a result of TRWP release to the environment	1 - 10
Benzothiazole-2-sulfonic acid	BTSA	941-57-1	Positive detection in surface-water runoff (NH, 2023c)	-
Benzyl butyl phthalate	BBP	85-68-7	Reported in Annex 2 of EA (2025)	1 - 10
Bis(2,2,6,6-tetramethyl-4-piperidyl)sebacate	BTPS	52829-07-9	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 – 10,000

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
Butylated reaction product of paracresol and dicyclopentadiene	Wingstay L	68610-51-5	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 – 10,000
Cyclohexyl-3-phenylurea	CPU	886-59-9	Positive detection in surface-water runoff (NH, 2023c)	-
Cyclohexylamine	-	108-91-8	Positive detection in surface-water runoff (NH, 2023c)	1,000 – 10,000
Di-2-ethylhexylphthalate	DEHP	117-81-7	Reported in Annex 2 of EA (2025)	10,000 – 100,000
Di(benzothiazol-2-yl) disulfide	MBTS	120-78-5	Reported in Annex 2 of EA (2025)	10,000 – 100,000
Dibutylphthalate	DBP	84-74-2	Reported in Annex 2 of EA (2025)	1,000 – 10,000
Dicyclohexylamine	DCH	101-83-7	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 - 10,000
Didodecyl-3,3'-thiopropionate	-	123-28-4	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 – 10,000
Diethylphthalate	DEP	86-66-2	Reported in Annex 2 of EA (2025)	1,000 – 10,000
Di-isobutylphthalate	DIBP	84-69-5	Reported in Annex 2 of EA (2025)	1 - 10
Dioctadecyl-3,3'-thiodipropionate	-	693-36-7	Identified as a candidate for further investigation as a result of TRWP release to the environment	1,000 – 10,000
Dioctyl phthalate	DnOP	117-84-0	Reported in Annex 2 of EA (2025)	-
Di-*o*-tolylguanidine	DOTG	97-39-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	10 - 100
Diphenylamine	DPA	122-39-4	Identified as a candidate for further investigation as a result of TRWP release to the environment	10 - 100
Isononylphenol	-	11066-49-2	Reported in Annex 2 of EA (2025)	-

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
Methyl isobutyl ketone	MIBK	108-10-1	Reported in Annex 2 of EA (2025)	10,000 – 100,000
N-(1,3-Dimethylbutyl)-N′-phenyl-*p*-phenylenediamine	6PPD	793-24-8	Member of PPD group, quinone degradation product 6PPD-Q of potential concern Positive detection in surface-water runoff undertaken by NH (2023c)	10,000 - 100,000
N-(1,4-Dimethylpentyl)-N′-phenylbenzene-1,4-diamine	77PD	3081-14-9	Member of PPD group, structural similarities to 6PPD	1,000 - 10,000
N-(1,4-Dimethylpentyl)-N'-phenylbenzene-1,4-diamine	7PPD	3081-01-4	Member of PPD group, structural similarities to 6PPD	-
N-(1-Methylheptyl)-N′-phenyl-p-phenylenediamine	8PPD	15233-47-3	Member of PPD group, structural similarities to 6PPD	-
N, N'-Dicyclohexylurea	DHU	2387-23-7	Positive detection in surface-water runoff (NH, 2023c)	-
N,N′-Di-2-naphthyl-*p*-phenylenediamine	DNPD	93-46-9	Member of PPD group, structural similarities to 6PPD	-
N,N'-Di(2-methylphenyl)benzene-1,4-diamine	DTPD	27417-40-9	Member of PPD group, structural similarities to 6PPD	-
N,N-Dicyclohexylbenzothiazole-2-sulfenamide	DCBS	4979-32-2	Reported in Annex 2 of EA (2025)	1,000 – 10,000
N,N′-Diphenyl-p-phenylenediamine	DPPD	74-31-7	Member of PPD group, structural similarities to 6PPD	-
N,N-Dioctyl-p-phenylenediamine	88PD	1241-28-7	Member of PPD group, structural similarities to 6PPD	-
N,N'-Di-sec-butyl-p-phenylenediamine	44PD	101-96-2	Reported in Annex 2 of EA (2025)	100 – 1,000
N-2-Naphthylaniline	PBN	135-88-6	Identified as a candidate for further investigation as a result of TRWP release to the environment	Intermediate

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
N-Cyclohexyl-2-benzothiazolamine	NCBA	28291-75-0	Reported in Annex 2 of EA (2025)	-
N-Cyclohexyl-2-benzothiazole sulfenamide	CBS	95-33-0	Reported in Annex 2 of EA (2025)	10,000 – 100,000
Nickel dibutyl dithiocarbamate	-	13927-77-0	Identified as a candidate for further investigation as a result of TRWP release to the environment	10 - 100
N-Isopropyl-N′-phenyl-1,4-phenylenediamine	IPPD	101-72-4	Member of PPD group, structural similarities to 6PPD	1,000 - 10,000
N-Methyl-dicyclohexylamine	DCA	7560-83-0	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
N-Phenyl-1-naphthylamine	PAN	90-30-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
N-Phenyl-N′-(o-tolyl)-p-phenylenediamine	PTPD	24124-30-9	Member of PPD group, structural similarities to 6PPD	-
N-Phenyl-N′-cyclohexyl-p-phenylenediamine	CPPD	101-87-1	Member of PPD group, structural similarities to 6PPD	-
N-Tert-butylbenzothiazole-2-sulfenamide	TBBS	95-31-8	Reported in Annex 2 of EA (2025)	10,000 – 100,000
Octylated diphenylamine	ODP	4175-37-5	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
Phenylguanidine	PG	2002-16-6	Identified as a candidate for further investigation as a result of TRWP release to the environment	-
Phthalimide	Pcyl	84-41-6	Identified as a candidate for further investigation as a result of TRWP release to the environment	1 - 10

Substance	Abbreviation	CAS No.	Reason	EU REACH (tonnes/year) (ECHA, 2023c)
P-Orientated styrenated diphenylamine (Wingstay 29)	-	68442-68-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 - 1,000
Stearic acid	-	57-11-4	Reported in Annex 2 of EA (2025)	10,000 – 100,000
4-Tert-octylphenol	t-OP	140-66-9	Reported in Annex 2 of EA (2025)	10,000 – 100,000
Tetramethyl thiuram disulfide	TMTD, Thiram	137-26-8	Reported in Annex 2 of EA (2025)	1,000 – 10,000
Thiodiphenylamine	TDPA	92-84-2	Identified as a candidate for further investigation as a result of TRWP release to the environment	100 – 1,000
Triphenylphosphate	TPP	115-86-6	Reported in Annex 2 of EA (2025)	100 – 1,000
Tris(4-nonylphenyl, branched and linear) phosphite (TNPP) with ≥ 0.1% w/w of 4-nonylphenol, branched and linear (4-NP)	-	799-976-5	Reported in Annex 2 of EA (2025)	-
Zinc oxide	-	1314-13-2	Reported in Annex 2 of EA (2025)	100,000 – 1,000,000

Note: UK REACH transition deadlines have not yet passed, as such there is not a complete picture of UK tonnages. It can be assumed that UK tonnages are 10% of EU tonnages. Chemicals may have multiple uses, the total registered tonnage does not necessarily reflect the tonnage used in tyres

Annex 7: Input of model outputs into EUSES V2.1.2

The outputs of the exposure scenarios developed in this report can be used as inputs for higher tier models to determine PECs and RCRs where applicable. The following instructions relate to the use of the regional scale of the tyre exposure model with EUSES V2.1.2 without significant modification of the default parameters. EUSES requires release fractions and tonnage to perform the required calculations, the “EUSES Input” tab of the model contains a summary of the regional exposure scenario outputs and calculates the required values for entry into EUSES.

The tyre exposure model estimates released mass of substances from urban roads to STP but does not calculate the subsequent partitioning that would occur within the STP to air, water or sludge as this is beyond the scope of the project. Therefore, estimates for urban wastewater must first be processed separately using Simpletreat or similar model before entry into EUSES to determine the partitioning that occurs with the STP (Struijs, 2014). The masses to be processed within Simpletreat for urban releases are provided within the “EUSES Input” tab for intentionally added products and degradation products. The partitioning fractions calculated by Simpletreat for the substance can then be re-entered into the “EUSES Input” tab.

Releases to settlement ponds and roadside ditches from motorways and rural roads do not need further processing to determine partitioning and further release, there is no emission to STP. Modelling of PECs in EUSES should therefore be carried out with the STP bypassed as the wastewater has either been pre-processed (urban releases) or does not pass through an STP (motorway and rural).

The “EUSES Input” tab provides a total input mass that should be set as the production volume of the chemical in EUSES. The different road types are summed to allow for EUSES modelling of all roads at once. The model will provide a mass for input to Simpletreat, as shown in Figure 11 below. The Simpletreat results should be re-entered into the pale green boxes highlighted in the model. The model will provide release fractions of the total input mass that can be entered into the “Release Fractions and Emissions Days” screen of EUSES to account for the environmental partitioning calculated in the leachate sections of the exposure scenario.

STP Modelling - Simpletreat Outputs		
Mass to Process within Simpletreat (Urban, Leachate)	4	tonnes/year
% Removal	16	%
% to air	25	%
% to sludge	16	%
% to Water	43	%
Mass Removed in STP	0.60	tonnes/year
Mass to Air from STP	0.93	tonnes/year
Mass to Sludge from STP	0.60	tonnes/year
Mass to Water from STP	1.60	tonnes/year
Regional Intentionally Added Product EUSES Input Values		
Mass released to Surface Waters	14	tonnes/year
Fraction of Total Mass released to Surface Waters	0.18	
Mass released to Industrial soil	44	tonnes/year
Fraction of Total Mass released to Industrial Soil	0.59	
Mass released to Agricultural soil	14	tonnes/year
Fraction of Total Mass released to Agricultural Soil	0.19	
Mass released to Wastewaters	0	tonnes/year
Fraction of Total Mass released to Wastewaters	0	
Mass released to Air	0	tonnes/year
Fraction of Total Mass released to Air	0	

Figure 11 The regional exposure scenario Simpletreat Outputs and EUSES Input Values section of the EUSES Inputs tab in the model. The provided values in this case are arbitrary

Instructions on the detailed use of EUSES are beyond the scope of this report however a brief example of the use and parameter choices are provided below. The ECB (2004) manual should be consulted for further detail.

i. When performing regional scenario modelling the local scale can be deselected from the “Assessment Types” screen.
ii. Where available, all identifiers should be entered into the “Substance identifier” and “Study Identification” screen.
iii. “Physico-chemical properties”, “partition coefficients and bioconcentration factors”, “Degradation and Transformation Inputs” and “Removal Rate Constants Soil” should be filled in chemical specific data.
iv. The total calculated tonnage of leachate determined using the model should be entered into the production volume of Chemical in EU field of the “Characterisation and Tonnage” screen. No other fields need to be changed. The masses for this field can be found in the “EUSES Inputs” tab of the model.
v. On the “Use Patterns” screen, an appropriate life cycle step should be set up with a 100 % fraction of the tonnage.
vi. On the “Release Fractions and Emission days” screen, the fractions of total released leachate tonnage should be entered in the corresponding boxes. This is provided on the EUSES Inputs tab of the model.
vii. If the local STP Input Configuration screen appears, the STP should be bypassed for both marine and freshwater options.

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