Microplastics from tyre and road wear

A literature review

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Abstract

This literature review concerns microplastics from tyre and road wear caused by road traffic. As there is limited knowledge about microplastics in general, and microplastics from road traffic in particular, the Swedish Government commissioned the Swedish National Road and Transport Research Institute (VTI) to, during 2018-2020, develop and disseminate knowledge about microplastics from road traffic. The chapters in this report summarises existing knowledge about microplastics from road traffic with respect to the following aspects: sources, spread and presence; effects on and risk to the environment and human health; characteristics and chemical composition; tyre and road wear; sampling methods; analysis and sample preparation; and measures. The report also includes a chapter with overall conclusions, and a chapter about further research, development and investigation needs.

The purpose of this report is to provide a basis for reducing the generation and spread of microplastics from road traffic. One aim of the report is to collate and disseminate knowledge about microplastics generated by tyre and road wear, and to review the current level of knowledge. A second aim is to identify knowledge gaps and research requirements in relation to microplastics from road traffic. This literature review is based on a review of scientific articles and reports, as well as technical literature and some information from experts and industry.

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Referat

Denna kunskapssammanställning handlar om mikroplast från vägtrafikens däck- och vägslitage. Eftersom kunskapen om mikroplaster från vägtrafiken är begränsad samtidigt som däckslitage bedöms vara den största källan till emissioner av mikroplast i Sverige, gav regeringen inom ramen för sitt arbete med plast och mikroplast Statens väg- och transportforskningsinstitut (VTI) i uppdrag att under 2018–2020 ta fram och sprida kunskap om mikroplast från vägtrafiken. Varje kapitel i denna rapport sammanfattar befintlig kunskap om mikroplast från vägtrafiken avseende en eller flera aspekter. Dessa aspekter är: källor, spridning och förekomst; miljö- och hälsoeffekter samt risker; egenskaper och kemisk sammansättning; däck och vägslitage; provtagningsmetoder; analys- och provberedningsmetoder samt åtgärder. Dessutom finns ett kapitel med sammanfattande slutsatser och allra sist ett kapitel om forsknings-, utvecklings- och utredningsbehov.

Syftet med rapporten är att den ska utgöra ett underlag för att minska emissioner och spridning av mikroplast från vägtrafiken. Ett mål med rapporten är att sammanställa och sprida kunskap om mikroplast från däck- och vägslitage och att redogöra för nuvarande kunskapsläge. Ytterligare ett mål är att identifiera kunskaps- och forskningsbehov avseende mikroplast från vägtrafiken. Underlaget till denna kunskapssammanställning utgörs av vetenskapliga artiklar och rapporter samt facklitteratur och information från branschen och från experter.

Titel:	Mikroplast från däck- och vägslitage. En kunskapssammanställning
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Foreword

There is limited knowledge regarding microplastics, in particular microplastics from road traffic. At the same time, tyre wear particles are deemed to be the biggest source of microplastic emissions in Sweden. For this reason, the Swedish Government commissioned the Swedish National Road and Transport Research Institute (VTI) to, during 2018–2020, develop and disseminate knowledge about microplastics from road traffic. This literature review is one part of this task. The purpose of this report is to provide a basis for reducing the generation and spread of microplastics from road traffic. One aim of the report is to collate and disseminate knowledge about microplastics from tyre and road wear, and to review the current state of knowledge. Another aim is to identify knowledge gaps and research needs in relation to microplastics from road traffic.

This is an English translation of the VTI-rapport 1028 which was published in Swedish in February 2020. A few minor revisions have been made in this English edition compared to the Swedish one.

Linköping, May 2020

Yvonne Andersson-Sköld	*Mikael Johannesson*
Project Manager	*Editor*

Quality review

Review seminars were carried out on 27 June 2019 and 1 July 2019 where Sondre Meland, NIVA, and Martin Hassellöv, University of Gothenburg, reviewed and commented on different parts of the report. The authors have made alterations to the final manuscript of the report. The research director Mattias Haraldsson examined and approved the report for publication on 16 January 2020. The conclusions and recommendations expressed are the authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Granskningsseminarium har genomförts 27 juni 2019 och 1 juli 2019 där Sondre Meland, NIVA, respektive Martin Hassellöv, Göteborgs universitet, var lektörer för olika delar av rapporten. Rapportförfattarna har genomfört justeringar av slutligt rapportmanus. Forskningschef Mattias Haraldsson har därefter granskat och godkänt publikationen för publicering 16 januari 2020. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

Contents

Definitions and abbreviations

Asphalt consists of a mixture of aggregates, e.g. crushed rock (stone materials), sand, gravel or slag, and a binding agent, usually bitumen. Asphalt may also contain additives. In American English, the words ‘asphalt concrete’ or ‘asphalt pavement’ is used instead, since ‘asphalt’ denotes what in British English is called bitumen.

Bitumen is the binding agent most commonly used for binding aggregates (e.g. stone materials) in asphalt, and is at room temperature a thermoplastic dark brown to black, solid or viscous liquid. Bitumen is a very complex mix of hydrocarbon compounds with a relatively high, but varying, molecular weight, which can be produced through distillation of crude oil, but also occurs in natural deposits. In American English, the word ‘asphalt’ is equivalent to bitumen.

$CaCl_2$ is the chemical formula for calcium chloride. Calcium chloride solutions can be used for sample preparation using density separation.

Density separation is a method used for sample preparation, e.g. to separate plastic particles from components with a different density, such as heavier stone materials, see also section 7.2. Densities of different tyre and road materials are provided in section 2.2.1.

Elastomers are polymers with the properties that they can be stretched significantly without the material breaking, and that the original dimensions are restored when the tension is removed.

FTIR is an abbreviation for Fourier Transform Infrared Spectrometry. It is an advanced form of infrared spectrometry, which is currently the industry standard.

GC-MS is an abbreviation for gas chromatography–mass spectrometry, which is an analytical method. See also section 7.5.

KBr is the chemical formula for potassium bromide. Potassium bromide solutions can be used for sample preparation using density separation.

µ-FTIR is an abbreviation for Micro-Fourier Transform Infrared Spectrometry. This method is developed from FTIR. It is sometimes used to determine the molecular structure of polymers and organic compounds. See also section 7.4.2.

Microplastics are usually defined as plastic particles smaller than 5 mm. Sometimes a lower limit of 0.1 or 1µm is also included. Particles smaller than the lower limit are then known as nanoplastics.

NaCl is the chemical formula for sodium chloride, which can be used for sample preparation by density separation. See also section 7.2.

NaI is the chemical formula for sodium iodide, which can be used for sample preparation by density separation. See also section 7.2

Nanoplastics is a term used to differentiate between larger microplastic particles and very small plastic particles. When this classification is used, nanoplastic particles are defined as particles smaller than 0.1 or 1µm.

PAH is an abbreviation for polycyclic aromatic hydrocarbons, which is a group of chemicals composed of two or more aromatic rings. This is currently the largest known group of carcinogenic substances.

PCB is an abbreviation for polychlorinated biphenyl. PCB is a collective name for a number of substances with similar damaging effects on the environment and human health, containing different amounts of chlorine bound to biphenyl. Biphenyl is a compound composed of two aromatic rings.

PCDD is an abbreviation for polychlorinated dibenzo-p-dioxins. This group contains 75 substances. PCDD and PCDF are often grouped together as ‘dioxins and dioxin-like compounds’. They are formed e.g. during combustion of organic materials combined with materials containing chlorine, such as PVC plastic.

PCDF is an abbreviation for polychlorinated dibenzofurans. The group polychlorinated dibenzofurans include 135 compounds.

PE is an abbreviation for polyethylene, which is a thermoplastic and one of the most commonly used plastics. It is used predominantly in products like kitchen utensils, toys, pipes, cables, plastic bags, cling film, and plastic bottles.

PET is an abbreviation for polyethylene terephthalate, which is a thermoplastic polyester, and one of the most commonly used plastics. It is mainly used as a synthetic textile fibre and in plastic bottles.

Plastic is a material group, which includes a large number of materials with versatile areas of application. In this report plastic covers polymer materials consisting of thermoplastic polymers or thermoset polymers with chemical additives, and thereby includes rubber (tyres), road markings, and polymer modified bitumen. Thermosets are plastics that cannot be melted down or reshaped once produced. Thermoplastics can both be melted down and reshaped after manufacture.

$PM_{2.5}$ and **PM_{10}**, where PM is an abbreviation for particulate matter, are two measurements of inhalable particles. A simplified explanation is that these measurements relate to the concentration in air of particles with a diameter smaller than 2.5 and 10 µm, respectively.

Polymer is a synthetic or natural chemical compound composed of very long chains made up of smaller repeating units, so called monomers. The term ‘unreacted monomer’ is used to describe monomers that have not polymerised.

Polymer modified bitumen is bitumen that contains additives of either thermoplastic polymers, thermoplastic elastomers, thermosetting polymers, or elastomers of thermosetting polymers. The polymers may have been added either to the bitumen product before it was mixed with an aggregate (of e.g. rock), or to heated aggregates before mixing with bitumen, or during the mixing of asphalt (bitumen and aggregate).

POP is an abbreviation for Persistent Organic Pollutants.

PP is an abbreviation for polypropylene (also known as polypropene) which is a thermoplastic and one of the most widely used plastics. It is used in products like food containers, packaging, toys, furniture, and textiles.

PVC is an abbreviation for polyvinyl chloride, which is a thermoplastic and one of the most widely used plastics worldwide. In its basic form, PVC is a rigid (hard) plastic, used in water and sewage piles, hard plastic toys, and vinyl records. Most of the plasticisers used in plastic materials are used in the manufacturing of soft PVC, which is used in for example tubes, flooring, cable casing, soft plastic toys, and in hospital equipment such as blood bags.

Road is used in this report to describe both roads in built-up areas (often called streets) and roads outside urban areas.

Road dust is the collective fraction of all particles found on a road, and may consist of road wear (i.e. road surfacing and road markings) and vehicle wear (e.g. brake pads, tyres, and studs), vehicle emissions, atmospheric deposition, and other particles, including organic materials from nearby vegetation that settle on the road.

Road marking products are used on the roads to regulate, warn, and guide traffic. They consist of plastic polymers, pigments, fillers, and additives; glass beads are also commonly added, to give the material reflective properties.

Road wear particles are particles generated during driving, either in a road simulator (with asphalt or concrete cassettes) or on a road outdoors. The particles consist of particles torn off both from the asphalt or concrete surface of a road, and from road markings, and may be contaminated with other types of particles deposited on the road.

Rubber is an elastic material, which is either produced from latex from the rubber tree (known as natural rubber) or produced synthetically from different chemical substances. During vulcanisation, the rubber transforms from a liquid to a solid, but elastic, state through crosslinking of the polymer chains. The polymers in rubber are elastomers of thermoset type. Apart from polymers, rubber also contains fillers (e.g. carbon black), and chemical additives.

SEM is an abbreviation for scanning electron microscopy, which is an analysis method. See also section 7.4.1.

SEMEDS or **SEMEDX** is scanning electron microscopy with energy-dispersive x-ray spectroscopy (abbreviated EDS or EDX). See also section 7.4.1.

SPT is an abbreviation for sodium polytungstate, a tungsten salt that can be used for sample preparation using density separation.

Street cleaning machine is a machine used to clean streets, also known as a street sweeper. The machine is usually fitted with brushes that help remove and collect dust from the road surface. See also section 8.2.3.

Tyres consist of an outer rubber layer (tread and sidewalls), containing elastomers of thermoset type, several inner layers of different types of textile and steel, and an inner rubber layer.

Tyre and road wear particles are particles generated during driving, either in a road simulator or on a road outdoors. The particles consist of tyre wear particles and road wear particles. These are often referred to as TRWP (abbreviated from Tyre and Road Wear Particles).

Tyre crumb rubber is recycled scrap tyre which has been fragmented into small pieces and is e.g. often used as infill material (cushioning) in artificial turf fields. It consists of the rubber part of the tyre, as reinforcing materials (e.g. steel and textile) and contaminants (e.g. such as rock) from the road have been removed.

Tyre tread is the rubber part of the tyre that provides grip and traction on the road. It is from this part of the tyre that tyre wear particles (i.e. rubber particles) are generated during driving.

Tyre tread particles are particles generated in a laboratory, e.g. using a rotating abrader, a rasp, or a grinder after freezing. The particles consist solely of rubber materials from the tyre tread. These are sometimes referred to as TP (abbreviated from Tread Particles).

Tyre wear particles are particles generated during driving, either in a road simulator (with asphalt or concrete cassettes) or on a road outdoors. The particles consist of rubber from the tyre tread, as well as some road particles attached to the surface of the rubber particles. These are usually referred to as TWP (abbreviated from Tyre Wear Particles), but sometimes also TP (abbreviated from Tyre Particles).

WDS (Wet dust sampler) is a sampling equipment used to collect samples of road dust for analysis. See also section 6.1.

Summary

Microplastics from tyre and road wear: A literature review

by Yvonne Andersson-Sköld (VTI), Mikael Johannesson (VTI), Mats Gustafsson (VTI), Ida Järlskog (VTI), Delilah Lithner (VTI), Maria Polukarova (VTI) and Ann-Margret Strömvall (Chalmers University of Technology)

This literature review concerns microplastics generated by road traffic. Particles are produced as a result of tyre and road surface wear. The vast majority of all microplastic particles from road traffic are tyre wear particles; however, particles are also generated as a result of the wear of road markings (e.g. road paint) and of the road surfacing, which may contain polymer modified bitumen. Based on present knowledge and mapping of microplastic sources in Sweden, it can be assumed that at least half of the Swedish microplastic emissions are tyre wear particles. Other traffic related sources of microplastics which are not related to tyre and road wear, such as crashed vehicles, littering and, wear from certain brake pads, are not included in this report. The report is also published in Swedish (VTI rapport 1028).

As there is limited knowledge about microplastics from road traffic, and tyre wear is assessed as the largest source of microplastic emissions in Sweden, the Swedish Government commissioned the Swedish National Road and Transport Research Institute (VTI) to (during 2018-2020) develop and disseminate knowledge about microplastics from road traffic. The assignment is part of the Government´s work to implement national and international efforts to reduce the problems of plastic in the environment.

Scientific studies have shown that microplastics in general are widespread in the environment. Microplastics have been found in water and sediments from oceans, lakes, and watercourses. They have also been found in sludge from wastewater treatment plants, in stormwater, in soil and vegetation, in indoor and outdoor air, in food and drink, and in many different organisms, including humans. The presence of tyre wear particles has been demonstrated in road dust, air, watercourses, stormwater and different sediments, including on the west coast of Sweden, however, as the number of studies is very small it is not possible to know what represents normal, high, or low levels in different media. There are no studies on the presence of these particles in sewage sludge, terrestrial environments (except in traffic environment), or in organisms in nature.

There is currently insufficient knowledge to evaluate the effects on the environment and human health caused by the exposure to current levels of microplastics in the environment. Despite this, the fact that emissions from tyre and road wear are very high and increasing; that the particles are likely to be persistent in the environment; and that the particles themselves, as well as hazardous substances in particles, or sorbed on the surface of the particles, may cause negative effects on organisms, are deemed sufficient to motivate measures to be taken.

The aim of this report is to provide a basis for reducing the generation and spread of microplastics from road traffic. One aim of the report is to collate and disseminate knowledge about microplastics from tyre and road wear, and to review the current state of knowledge. Another aim is to identify knowledge gaps and research requirements in relation to microplastics from road traffic.

Each chapter in this report summarises existing knowledge about microplastics from tyre and road wear with respect to one or more aspects. Aspects include sources, dispersal and presence; effects on and risk to the environment and human health; characteristics and chemical composition; tyre and road wear; sampling methods; analysis and sample preparation; and measures. The report also includes a chapter with overall conclusions, and finally a chapter about further research and development needs.

Only a small number of the existing studies of microplastics relate to microplastics from road traffic, and the ones that do, almost exclusively consider tyre wear particles. Studies about particles from the wear of road markings and polymer modified bitumen are almost non-existent. The least is known about the very smallest particles, i.e. the nano-sized ones.

This knowledge review shows that there is currently almost no, or very limited, knowledge on microplastic generated by tyre and road wear. Consequently, there is an extensive lack of knowledge regarding the amounts of microplastic particles emitted from tyre, road and road marking wear; the sizes of the generated particles; how they spread and potentially change in the environment; at what levels they are present in different environments; the levels of exposure to humans and the environment; and to what extent the exposure is hazardous to the environment and human health.

There are currently no standards for the collection, preparation, or analysis of microplastic samples. This makes it difficult, and sometimes impossible, to compare different findings. This is a major problem, as the number of available studies is comparatively small, and studies are both time-consuming and expensive to carry out. Having standards in place for the above-mentioned areas would enable us to faster, and at a lower cost, generate the knowledge we need to assess the risks to humans and the environment posed by microplastic particles from road traffic.

There are also considerable gaps in our knowledge about different ways to reduce the generation of microplastics from road traffic, and their effectiveness. When combined with the knowledge gaps described above, this means that we do not possess the knowledge needed to, on objective grounds, make well-informed prioritisations between different policy instruments and measures, or to assess the cost-effectiveness of different measures.

Even though there are major gaps in our knowledge, this literature review also shows that some important insights exist. A few examples are set out below:

- A sizeable proportion of the tyre wear particles consists of relatively large particles, larger than 20 micrometres, and are assumed to be mostly deposited on or near the road. This means that a large part of the dispersal of tyre particles takes place via runoff from the road surface, vehicle movement and wind, snow removal, and street cleaning. A smaller proportion, up to 10 percent, is deemed to consist of airborne particles.
- Of the few toxicity tests (acute and chronic) that have been made, it is mainly the toxicity of leachates from tyre tread particles that has been studied on aquatic organisms. These show that toxic substances are leached, and that the concentrations that cause effects on test organisms vary both between different tyres and different tests. The two studies that are available on ingestion showed that the organisms ingested the tyre tread particles and that they were later excreted with the faeces.
- There is wide variation in the physical characteristics of microplastic particles from tyres, road markings, and polymer modified bitumen, including their form, size, and density. They also have different chemical compositions. All these factors influence their behaviour in the environment and the potential risk they pose to both humans and the environment.
- Several different factors have an impact on tyre wear, apart from the tyres themselves. A few of the most important ones are load, tyre pressure, wheel alignment, vehicle speed, driving behaviour, and the characteristics of the road surface.
- Existing analysis and preparation methods available for tyre and road wear particles are complicated and time-consuming and can only be performed by a small number of experts. This means that they are costly and that it can be difficult to get analyses carried out. Development efforts to automate and simplify both the preparation and analysis of samples are currently underway both in Sweden and internationally.

- Examples of measures to reduce the generation of microplastics from road traffic are those that limit traffic density, reduce speeds, decrease the use of studded tyres, promote calmer driving behaviour, result in a transition to lighter vehicles, lead to optimal tyre pressure and wheel alignment, and reduce the unevenness on the road surface at micro level.
- Some of the measures can at the same time give other benefits such as decreased emissions of air pollutants and greenhouse gases, decreased noise pollution, decreased energy consumption, decreased road wear, less congestion, and fewer serious accidents. They could, therefore, be motivated for more reasons than for decreasing emissions of tyre and road wear.
- Measures that limit the dispersal of microplastics from road traffic include stormwater facilities and various filtration systems. Approximately 80 percent of the road runoff facilities in Sweden are ponds, which have been shown to have the capacity to remove 90–100 percent of microplastic particles larger than 20 µm.
- The efficiency to remove microplastic particles from wastewater, which means they are captured in the sludge, varies between different wastewater treatment plants. At three Swedish wastewater treatment plants, the removal efficiency for particles larger than 20 µm varied between 70 and 90 percent. For particles larger than 300 µm the removal efficiency was above 99 percent. In another Swedish wastewater treatment plant, the removal efficiency was more than 99 percent for particles larger than 10 µm. No studies have been performed on tyre and road wear particles.

Two of the most important questions from a policy perspective are:

- Does the current and potential future exposure to humans and the environment from microplastic particles generated by road traffic pose a significant environmental or health issue? And if this is the case, how big is this problem?
- What measures could be put in place to cost-effectively reduce the impact of microplastics from road traffic on the environment and human health?

To answer the first question will for instance require effect studies under laboratory conditions, to investigate how different organisms in different media are affected by different concentrations of different types of microplastics from road traffic, over shorter and longer time periods. We also need to know at what concentrations different microplastics from road traffic are present in different media in the environment, to enable us to assess the levels of exposure to different organisms. The results of the laboratory studies and data on presence and exposure can then be used in the assessment of the impact on the environment.

To answer the second question, we need to identify and evaluate different measures. We need to generate knowledge about the relative effectiveness of individual measures, i.e. an understanding of the extent to which a particular measure will reduce the emissions or spread of different types of microplastic particles.

This literature review is based on a review of scientific articles and reports, as well as technical literature and some information from experts and industry.

Sammanfattning

Mikroplast från däck- och vägslitage. En kunskapssammanställning

av Yvonne Andersson-Sköld (VTI), Mikael Johannesson (VTI), Mats Gustafsson (VTI), Ida Järlskog (VTI), Delilah Lithner (VTI), Maria Polukarova (VTI) och Ann-Margret Strömvall (Chalmers tekniska högskola)

Denna kunskapssammanställning handlar om mikroplast från vägtrafiken. Partiklarna bildas genom slitage av däck och vägbana. Den helt dominerande delen av mikroplastpartiklar från vägtrafiken utgörs av däckslitagepartiklar. Utifrån nuvarande kunskap, och kartläggning av källor till mikroplast i Sverige, kan det antas att minst hälften av de svenska utsläppen av mikroplast utgörs av däckpartiklar. Mikroplastpartiklar bildas också vid slitage av vägmarkeringar (t.ex. vägfärg) och av vägbeläggning om den innehåller polymermodifierad bitumen. Andra vägtrafikrelaterade källor till mikroplast som inte är kopplade till däck- och vägslitage, såsom krockade fordon, nedskräpning och slitage från vissa typer av bromsbelägg, ingår inte i kunskapssammanställningen.

Eftersom kunskapen om mikroplaster från vägtrafiken är mycket begränsad samtidigt som vägtrafiken är en stor källa, gav regeringen Statens väg- och transportforskningsinstitut (VTI) i uppdrag att under 2018–2020 ta fram och sprida kunskap om mikroplast från vägtrafiken. Uppdraget är ett led i regeringens arbete att nationellt och internationellt genomföra insatser för att minska problemen med plast i miljön.

Forskningsstudier har visat på stor spridning av mikroplast i miljön. Mikroplast har påträffats i vatten och sediment i hav, sjöar och vattendrag. Det har också påträffats i slam från avloppsreningsverk, i dagvatten, i jord, i växter, i inomhus- och utomhusluft, i mat och dryck, och i många olika organismer, även i människor. Förekomst av specifikt däckslitagepartiklar har påvisats i vägdamm, luft, vattendrag, dagvatten och i olika sediment, t.ex. på den svenska västkusten, men studierna är så få att det är omöjligt att veta vad som är normala, höga eller låga halter i olika media. Studier om förekomst i avloppsslam, terrestra miljöer (förutom trafikmiljöer) och i organismer i naturen saknas.

Det finns inte tillräckligt med kunskap för att bedöma vilka miljö- och hälsoeffekter som exponeringen för nuvarande halter av mikroplaster i miljön medför. Det faktum att utsläppen av mikroplast från däck- och vägslitage är mycket stora och ökar i och med att vägtrafiken ökar, att partiklarna sannolikt är svårnedbrytbara i miljön och att partiklarna och miljö- och hälsofarliga ämnen i partiklarna kan påverka organismer negativt bedöms dock vara tillräckligt för att motivera att åtgärder vidtas.

Syftet med rapporten är att den ska utgöra ett underlag för att minska emissioner och spridning av mikroplast från vägtrafiken. Ett mål med rapporten är att sammanställa och sprida kunskap om mikroplast från däck- och vägslitage och att redogöra för nuvarande kunskapsläge. Ytterligare ett mål är att identifiera kunskaps- och forskningsbehov avseende mikroplast från vägtrafiken.

Varje kapitel i denna rapport sammanfattar befintlig kunskap om mikroplast från däck- och vägslitage avseende en eller flera aspekter. Dessa aspekter är: källor, spridning och förekomst; miljö- och hälsoeffekter samt risker; egenskaper och kemisk sammansättning; däck och vägslitage; provtagningsmetoder; analys- och provberedningsmetoder samt åtgärder. Dessutom finns ett kapitel med sammanfattande slutsatser och ett kapitel om forsknings-, utvecklings- och utredningsbehov.

Det finns få studier om mikroplast från vägtrafiken och de som finns handlar nästan uteslutande om slitagepartiklar från däck. Studier om slitagepartiklar från vägmarkeringar och polymermodifierad bitumen saknas i princip helt. Minst är kunskapen om de minsta partiklarna, de i nanostorlek.

Denna kunskapssammanställning visar att kunskap om mikroplast från däck- och vägslitage saknas nästan helt eller är mycket bristfällig inom många områden. Bristen på kunskap är således omfattande

vad gäller vilka mängder av mikroplastartiklar som emitteras genom slitage av däck, vägar och vägmarkering, i vilka storlekar partiklarna genereras, hur de sprids och eventuellt förändras i miljön, i vilka halter de förekommer i olika miljöer, vilken exponering som människor och miljö utsätts för och vilken miljö- och hälsofara som exponeringen kan medföra.

Det saknas standarder för att t.ex. samla in, bereda och analysera prov av mikroplast. Det gör det svårt och ibland omöjligt att jämföra olika resultat. Det är ett stort problem eftersom det finns förhållandevis få studier och de är tidsödande och kostsamma att genomföra. Om det hade funnits standarder på nämnda områden så skulle vi snabbare och till en lägre kostnad kunna få den kunskap vi behöver för att bedöma vilka risker mikroplastpartiklar från vägtrafiken utgör för människors hälsa och för miljön.

Vidare finns det stora kunskapsbrister om olika metoder som kan begränsa uppkomsten och spridningen av mikroplast från vägtrafiken och hur effektiva de är. I kombination med ovan nämnda kunskapsbrister innebär det att vi saknar kunskap för att på sakliga grunder kunna göra väl underbyggda prioriteringar mellan olika styrmedel och åtgärder och bedöma hur kostnadseffektiva olika åtgärder är.

Även om kunskapsbristen är stor visar kunskapssammanställningen också att det finns viktig kunskap varav en del sammanfattas nedan:

- En stor andel av däckslitagepartiklarna utgörs av relativt stora partiklar, större än 20 mikrometer och bedöms därför huvudsakligen deponeras på eller nära vägen. En stor del av spridningen av däckpartiklarna sker därför genom avrinning från vägbanan, fordonsrörelse och vind, snöröjning och vägrenhållning. En mindre del, upp till 10 procent, bedöms utgöras av luftburna partiklar.
- Av de få toxicitetstest (akuta och kroniska) som har genomförts är det främst giftigheten på lakvatten från däckslitbanepartiklar som har studerats med vattenlevande organismer. Dessa visar att giftiga ämnen lakas ut och att halten som ger upphov till effekter på testorganismer varierar mycket både mellan olika däck och olika studier. De två studier som finns om förtäring visar att organismerna äter partiklarna och att partiklarna utsöndras via avföringen.
- Mikroplastpartiklar från däck, vägmarkeringar och polymermodifierad bitumen uppvisar stor variation i fysikaliska egenskaper som exempelvis form, storlek och densitet. Dessutom varierar den kemiska sammansättningen. Detta påverkar hur de beter sig i miljön och den potentiella risk de utgör för människor och miljö.
- Det finns en rad faktorer som påverkar däckslitaget utöver själva däcken. Några av de viktigaste är last, däcktryck, hjulinställningar, fordonshastighet, förarbeteende och vägbanans egenskaper.
- De analys- och provberedningsmetoder som finns för däck- och vägslitagepartiklar är komplicerade och tidskrävande och kan endast utföras av ett fåtal experter. Det innebär att de är kostsamma och att det kan vara svårt att få analyser utförda. Utvecklingsarbete bedrivs såväl i Sverige som internationellt för att automatisera och förenkla såväl beredningen som analyserna av prov.
- Exempel på åtgärder som minskar uppkomsten av mikroplast från vägtrafiken är de som begränsar trafikarbetet, sänker hastigheterna, minskar användningen av dubbdäck, leder till lugnare körbeteende, innebär en övergång till lättare fordon, medför att däcktrycket är optimalt och att hjulinställningen är optimal och minskar vägytans ojämnhet på mikronivå.
- Vissa av åtgärderna kan samtidigt ge andra vinster som t.ex. minskade utsläpp av luftföroreningar och växthusgaser, minskat buller, minskad energiåtgång, minskat vägslitage, mindre trängsel och färre allvarliga olyckor och skulle därför kunna motiveras också av andra skäl än att de bidrar till minskade utsläpp av mikroplast.

- Åtgärder som minskar spridningen av mikroplast från vägtrafiken till vattenmiljöer är t.ex. dagvattenanläggningar och olika filtersystem. Av vägdagvattenanläggningarna i Sverige är cirka 80 procent dammar vilka har visat sig kunna avskilja 90–100 procent av mikroplastpartiklar större än 20 µm.
- Avskiljningsgraden för mikroplastpartiklar varierar mellan olika avloppsreningsverk. I tre svenska avloppsreningsverk var avskiljningsgraden mellan 70 och 90 procent för partiklar större än 20 µm och över 99 procent för partiklar större än 300 µm. I ett annat svenskt avloppsreningsverk var avskiljningsgraden över 99 procent för partiklar större än 10 µm. Inga studier har genomförts specifikt för däck- eller vägslitagepartiklar.

Två av de mest grundläggande frågorna ur ett policyperspektiv är:

- Utgör människors och miljöns nuvarande och eventuella framtida exponering för mikroplastpartiklar från vägtrafiken ett påtagligt miljö- eller hälsoproblem? Om så är fallet hur stort är detta problem?
- Vad finns det för åtgärder som på ett kostnadseffektivt sätt kan minska miljö- eller hälsopåverkan från mikroplast från däck- och vägslitage?

För att besvara den första frågan behöver det bl.a. göras effektstudier i laboratoriemiljö som undersöker hur olika organismer i olika media påverkas av olika halter och olika typer av mikroplast från vägtrafiken. Vi behöver också veta vilka halter som förekommer i olika delar i miljön för att kunna bedöma vilken exponering som olika organismer utsätts för. Utifrån laboratoriestudierna och kunskap om halter och exponering i miljön kan man sedan bedöma miljöpåverkan.

För att besvara den andra frågan behöver vi identifiera och utvärdera olika åtgärder. Kunskap krävs bl.a. om effektsamband för olika åtgärder, d.v.s. kunskap om hur mycket en åtgärd minskar emissionerna eller spridningen av olika mikroplastpartiklar.

Underlaget till denna kunskapssammanställning utgörs av vetenskapliga artiklar och rapporter samt facklitteratur och information från branschen och från experter.

1. Introduction

Microplastics from tyre and road wear caused by road traffic have in several studies been identified as a major source of microplastics in the environment. These microplastics mainly come from tyre rubber, but may also come from road markings (e.g. paint), and sometimes from polymer modified bitumen, where this is included in the asphalt. In a survey of Swedish microplastic emissions by Magnusson et al (2016), microplastics from road traffic were estimated as the largest source of microplastic emissions in Sweden.

During the last 10 years, microplastics and plastic waste have attracted a lot of attention. Awareness of the problems caused by plastic waste, mainly in marine environments, has increased gradually since the 1970s. However, it was not until the early 2000s that we received alarming reports of an 'island' of accumulated floating plastic waste in the middle of the Pacific Ocean ("the Great Pacific Garbage Patch") (Moore et al, 2001), which was later also found in other subtropical gyres (Law et al, 2010; Eriksen et al, 2013). It was also shown that microplastics are a widespread marine pollutant (Thompson et al, 2004). This, in combination with findings from further research studies that demonstrated widespread presence in the environment and effects on organisms, made both the research community and the general public, authorities and organisations all over the world take a greater interest in microplastics and plastic waste.

Microplastics are found (e.g. SAPEA, 2019; Klein & Fisher, 2019; Schwabl et al, 2019; Ebere et al, 2019):

- in oceans, lakes, and watercourses (in water and sediments)
- on land (in soil, plants, sludge from wastewater treatment plants, stormwater, and the built environment)
- in air (indoors and outdoors)
- in food and drink
- in goods and products
- in many different organisms (both aquatic and terrestrial, including humans).

Globally, road traffic is continuously increasing, as is the use of plastics, which leads to higher emissions of both microplastics and macroplastics, that can break down into microplastics. Plastics and microplastics also accumulate in the environment, as most of the plastic being produced is very persistent and can take anything from decades to hundreds of years to break down completely (Ojeda, 2013). The microplastics found in the environment may either have been deliberately produced at this size (e.g. microplastic beads in scrubs and plastic pellets/powder) or been unintentionally generated in this size (e.g. particles from tyre and road marking wear). It may also come from degradation and fragmentation of larger plastic objects (GESAMP, 2016). The effects on the environment and human health from microplastics may be caused either by the plastic particles themselves or by the chemical substances present in, or on, the particles. These substances may be part of the plastic material (e.g. chemical additives, unreacted monomers, and degradation products) or have been sorbed from the environment (e.g. persistent organic compounds). Many laboratory tests have demonstrated effects on organisms, however, there is uncertainty about how the findings from these studies can be translated into effects in the real environment (SAPEA, 2019).

The subject area is very complex, and despite plenty of ongoing research and increasing knowledge about microplastics, there are still big gaps in our knowledge about actual concentrations and effects on the environment (SAPEA, 2019). It is, therefore, not possible to with sufficient certainty determine the current risk, which is here defined as the probability that the current levels of microplastics in the environment are causing effects in the environment at present. Although the current risk cannot be determined, there is enough knowledge and sufficient reasons to take action to reduce emissions of plastics and microplastics (see section 3.2.1). We know that emissions of persistent plastics, and their accumulation in the environment, are increasing, that these emissions spread widely and are found everywhere in the environment, and that microplastics cause effects on organisms. If emissions continue, the effects on the environment may be widespread. There is also a lack of knowledge about nano-sized particles, both in relation to their prevalence in the environment and to how they may affect different organisms, which is a further argument for reducing emissions.

When it comes to microplastics specifically from road traffic, there is very limited knowledge. It is important to improve our knowledge of their presence, spread, effects, and risks, to enable development of effective measures that can reduce the emissions and spread of microplastics from road traffic.

1.1. Aims and purpose

The purpose of this report is to provide a basis for reducing emissions and spread of microplastics from road traffic. One aim of the report is to collate and disseminate knowledge about microplastics from tyre and road wear, and to review the current state of knowledge. Another aim is to identify knowledge gaps and research needs regarding microplastics from road traffic.

1.2. Scope

This literature review concerns microplastics from tyre and road wear, generated by road traffic. This includes tyre wear particles from tyres, road markings from the road, and polymer modified bitumen which may be present in asphalt. The main focus is on tyre wear particles, which make up the greater part of microplastic emissions from road traffic. Road markings are described to a lesser extent, and polymer modified bitumen is only covered briefly. Other road traffic related sources of microplastics than those connected to tyre and road wear, such as vehicle breakdowns/crashes, littering, and wear from certain types of brake pads, are not covered in this report. Very little research has been carried out on microplastics from tyre and road wear, however, there is more research on other microplastics made of materials usually regarded as plastics (see below). As some of the findings from this research are also relevant to microplastics from tyre and road wear, the relevant parts are discussed here.

There is no exact definition of the term ’plastic’. The plastic material group is very big and comprises a large number of materials with versatile properties and uses, which makes it difficult to delimit. For this reason, a number of different delimitations exist. Polymer materials are often divided into the categories: thermoplastics, thermosets, elastomers, and thermoplastic elastomers. Common for all these categories is that the materials consist of thermoplastic polymers and/or thermoset polymers, and sometimes all categories are included in the term ‘plastics’, however, the term more commonly refers only to thermoplastics and thermosets. In this case, elastomers are seen as a separate group, and thermoplastic elastomers are considered a mix of plastics and elastomers. Where this report relates specifically to thermoplastics and thermosets (and not elastomers) this is specified as ‘materials usually regarded as plastics’. In research on microplastics, rubber particles from tyre wear have lately been considered as a category of microplastics. This report uses a broader definition of the term plastics, which includes all manufactured polymer materials consisting of thermoplastic polymers or thermoset polymers with chemical additives, which therefore also includes rubber (tyres), road markings, and polymer modified bitumen. Bitumen is not covered by this definition, but as it is not possible to differentiate between bitumen and polymer modified bitumen in field samples, and as it can also be difficult to tell bitumen and rubber particles apart, bitumen is also mentioned in this literature review.

Microplastics are usually defined as plastic particles smaller than 5 mm (GESAMP, 2016). A growing need to distinguish between larger and smaller microplastic particles has made it increasingly common to refer to the smaller microplastic particles as nanoplastic particles. There is no generally accepted definition of the boundary between microplastics and nanoplastics. However, where this division is used, the term ‘nanoplastics’ usually refers to either particles smaller than 1 µm or smaller than 0.1 µm (SAPEA, 2019), and microplastics are defined as particles in the size range between 0.1 or 1 µm and 5 mm. The studies referred to in this report usually use one of the above-mentioned size limits. When this report, and its underlying documentation, refers only to ‘microplastics’ without a defined size range, it refers to particles smaller than 5 mm. In theory, this includes the nanoplastic fraction, but in practice this is usually not the case, as the nanoplastic fraction may not have been studied e.g. due to limitations in measuring and analysis methods.

1.3. Method

This literature review is based on a review of scientific articles and reports, as well as technical literature and information from industry and experts.

1.4. Contents of the report

The report is divided into ten chapters with the following content:

- Chapter 2 describes the sources of microplastics from road traffic, possible dispersal pathways, and current knowledge about presence and spread of microplastics from tyre and road wear in the environment.
- Chapter 3 describes what is currently known about the effects on, and risks to, human health and the environment of microplastics from tyre and road wear, and from microplastics in general, and also reports on the available effect studies on tyre and road wear particles. An overview of the aquatic effect studies is presented in Appendix A.
- Chapter 4 provides information about physical and chemical characteristics and chemical composition of tyres, road marking products, bitumen, and polymer modified bitumen. In addition, physical and chemical characterisations of tyres and tyre crumb rubber are described.
- Chapter 5 describes factors that influence tyre and road wear and how the wear can be calculated. It also looks at the significance of the use of studded tyres, and of the composition and development of the traffic and the vehicle fleet.
- Chapter 6 describes the various sampling methods and approaches available for sampling tyre and road wear in different media.
- Chapter 7 describes analysis and sample preparation methods that can, or could, be used to analyse microplastic particles from tyre and road wear, and sets out the possibilities and problems of each approach.
- Chapter 8 describes potential measures to reduce the generation and spread of microplastics from tyre and road wear. Measures include both those that prevent particles from being generated and those that stop them from spreading.
- Chapter 9 contains a general discussion and summarises the most important conclusions. Summarised conclusions in bullet form are also included at the end of chapters 2–8.
- Chapter 10 presents further research, development, and investigation needs regarding microplastics from road traffic.

2. Sources, dispersal pathways and presence

This chapter begins by describing the sources of microplastics from road traffic. It then sets out key factors that influence the spread and presence of tyre and road wear particles, and identifies potential pathways for dispersal. It ends by reporting on the presence of tyre and road wear particles in the environment.

2.1. Sources and generation of particles

Microplastics from road traffic mostly originate from the tyre tread, which is the rubber part of a tyre that gives grip and traction on the road surface. Particles are also released from road markings (paint) on the road surface, used to regulate, warn, or guide road users. If the binding agent (bitumen) in the asphalt is polymer modified, this may also be a minor source of microplastics.

Microplastics from tyre and road wear are generated as a result of the contact that takes place between the road surface and a tyre in motion. This contact causes wear on the tyre and produces friction heat within the tyre. The wear leads to emissions of rubber particles from the tyre, while the increase in temperature may cause volatile tyre components to evaporate. In wear tests carried out by Cadle & Williams (1979) in a laboratory, not only tyre particles were released, but also gases containing hydrocarbon and sulphur. These were identified as monomers and dimers (i.e. two monomers joined by bonds) which are the components of rubber polymers, and sulphur compounds that are used in rubber production. According to Cadle & Williams (1979), this suggested that some degradation of the rubber material may take place at local hot spots on the tyre surface as the temperature increases. The contact between the tyre and the road also causes particles to be released from the road, which is made of asphalt or concrete, and from road markings on the road surface. Some of the road particles become attached to the surface of the rubber particles (Kreider et al, 2010).

The amount of tyre wear is influenced by e.g. the characteristics of the tyre, vehicle, and road surface, as well as driving behaviour and driving conditions (Wagner et al, 2018). The wear on the road and road markings is impacted by e.g. the use of studded tyres, type of surfacing, and use of snow ploughs. Tyre and road wear are described in more detail in chapter 5.

Microplastics are often classified as primary or secondary microplastics. The classification relates to the point in time when the particle gained its micro-size. There are, however, different definitions, which means that tyre and road wear particles, and plastic fibres from textiles, are sometimes classified as primary microplastics and sometimes as secondary, depending on the definition used. A core definition is that primary microplastics were originally produced in micro-size (e.g. plastic pellets/powder and microbeads in scrubbing agents), whereas secondary microplastics have gained their size as a result of breakdown (fragmentation and degradation) of larger plastic objects (GESAMP, 2016). According to this definition, tyre and road wear particles are classified as secondary microplastics. An alternative definition of primary microplastics is ‘particles that were micro-sized when released into the environment’. Yet another definition divides primary microplastics into two types, where Type A was produced in a pre-determined microplastic size and Type B was formed and released at a microplastic size during use. According to the latter two, less common, definitions, tyre wear particles are classed as primary microplastics.

Existing studies on tyre and road wear particles use different terms to denote how the particles were generated and what they consist of. These terms are not used in the same way in all studies; this is particularly true for the terms ‘tyre wear particles’, and ‘tyre and road wear particles’. In this report, the terms are used as follows:

- **Tyre tread particles** are particles generated in a laboratory, e.g. using a rotating abrader, a rasp, or a grinder after freezing. The particles consist solely of rubber materials from the tyre tread.

- **Tyre wear particles** are particles generated during driving, either in a road simulator (with asphalt or concrete cassettes) or on a road outdoors. The particles consist of rubber from the tyre tread, as well as some road particles attached to the surface of the rubber particles.
- **Road wear particles** are particles generated during driving, either in a road simulator (with asphalt or concrete cassettes) or on a road outdoors. The particles consist of particles torn off both from the asphalt or concrete surface of a road and from road markings, and may be contaminated with other types of particles deposited on the road.
- **Tyre and road wear particles** are particles generated during driving, either in a road simulator or on a road outdoors. The particles consist of tyre wear particles and road wear particles.
- **Road dust** is all particles found on a road, which may consist of particles from road wear (road surfacing and markings), vehicle wear (e.g. brake pads, tyres, and studs), vehicle emissions, atmospheric deposition, and other particles, including organic materials from nearby vegetation that settle on the road.

Global figures show that:

- 19 million tonnes of tyres were produced in 2019 (Smithers, 2019).
- The demand for road marking products was just over 1.2 million tonnes in 2014 (Grand View Research, 2016a).
- The demand for polymer modified bitumen for road construction was 7.3 million tonnes in 2014 (Grand View Research, 2016b).

Further information about usage, chemical composition, and characteristics for these products and materials is provided in chapter 4.

2.2. Factors influencing presence and spread in the environment

Tyre and road wear particles generated on the road are spread to different parts of the environment. Where in the environment the particles are present, and how they spread, is influenced by many different factors. Key factors include:

- the size, shape and density of the particles
- precipitation
- dispersal pathways.

The final fate of a particle depends, in addition to its physical and chemical properties, also on the environment in which it finally ends up, and e.g. the opportunities for degradation available at this location.

2.2.1. Size, shape, and density

Particle size has a major influence on spread and presence (Wijesiri et al, 2016). The size distribution for tyre and road wear particles depends on factors such as type of road surface, speed, temperature, age and composition of the tyre (Kole et al, 2017), and driving behaviour. The available studies on size distributions and size ranges of road and tyre wear particles show varying results, and have also used different methods to generate, sample, and analyse the particles (Kole et al, 2017). When the findings from four separate studies on tyre wear particles were combined, tyre and road wear particles fell within a size range of approximately 10 nm to several hundred µm (Kole et al, 2017).

Particles smaller than 10 µm (PM_{10}) are interesting from a health perspective, as they can penetrate further into the airways than larger particles. Those smaller than 4 µm can travel deep into the alveoli of the lungs. In addition, the PM_{10} fraction is often airborne. It has been estimated that less than 10 percent of the tyre and road wear materials are emitted in sizes below 10 µm during driving in passenger cars and light duty vehicles (Boulter, 2006). Particles in the size range 1–10 µm can stay suspended in the air for anything from minutes to hours, and travel distances of between 100 m and 50 km (Kole et al, 2017). When tyre wear particles are emitted onto the road, they may form aggregates with other tyre particles or road particles (Kole et al, 2017). This can also occur in stormwater (Wijesiri et al, 2016).

Tyre wear particles generated in a road simulator have been shown by electron microscopes to be elongated with a sausage-like shape, and to include elements of mineral grains from the road attached to the surface of the rubber particles (Kreider et al, 2010). Tyre wear particles from air samples have also been shown to be elongated, with a rubber core fully or partly covered in smaller particles, such as wear particles from the road, brake pads, and other road dust (Sommer et al, 2018). Later studies, using a diamond compression cell for Fourier transform infrared spectroscopy of sediment samples, indicate that also black elastomer fragments which are more angular, may be tyre wear particles (Hassellöv et al, 2018; Karlsson et al, 2019).

The densities of tyre and road wear particles (see Table 1) are also of great importance to their spread and presence. These can be compared to the densities of freshwater or seawater to indicate the likelihood that particles will float or sink.

The table shows that:

- The rubber polymers in natural, butadiene, and styrene butadiene rubber are lighter than water.
- Bitumen, as well as road markings and polymers in bitumen, may be lighter or heavier than water.
- The density of pure tyre tread particles is slightly higher than the mean density of seawater, whereas tyre wear particles with road particles on the surface are heavier than seawater.
- Concrete, asphalt and different rock-forming minerals found in rock materials (e.g. quartz) are significantly heavier than water.

Table 1. Densities for seawater, freshwater, and different materials included in tyre and road wear particles.

Material/medium	**Density**	**Comment/reference**
Seawater	1.025 g/cm^3 mean density by the surface	Increases with decreasing temperature, higher salinity, and increased pressure
Freshwater	1.00 g/cm^3 at 4 °C	Decreases slightly with higher temperatures
Pure tyre tread particles	1.15–1.18 g/cm^3 1.13–1.16 g/cm^3	(Vogelsang et al, 2019) (Rhodes et al, 2012, cited in Wagner et al, 2018)
Tyre wear particles with road particles on the surface	1.7–2.1 g/cm^3	(Vogelsang et al, 2019)
Concrete	2.3–2.4 g/cm^3	(Betongindustri, 2019)
Asphalt (bitumen and aggregates)	e.g. 2.38–2.52 g/cm^3	(Viman & Brons, 2013)
Bitumen	0.925–1.07 at 15 °C	Measured according to EN ISO 12185/EN ISO 3838/EN 15326 (ECHA, 2019a)
Rock-forming minerals for siliceous rocks	2.65 g/cm^3 for quartz to approx. 2.8 g/cm^3 for calcium-rich plagioclase	(SLU, 2019)
Rubber polymers in rubber Natural rubber (polyisoprene) Butadiene rubber Styrene butadiene rubber	 0.906 g/cm^3 0.90 g/cm^3 0.910–0.965 g/cm^3 (depending on the proportion of styrene 5–45%)	 (Scientific Polymer Products, Inc., 2019)
Polymers for road markings Pentaerythritol resin Ethylene vinyl acetate (EVA) Polymethyl methacrylate (PMMA) Epoxy	 1.09 g/cm^3 0.925–1.06 g/cm^3 (depending on the proportion of vinyl acetate 18–70%) 1.20 g/cm^3 1.16–1.19 g/cm^3	 (ECHA, 2019b) (Scientific Polymer Products, Inc., 2019) (Polymerdatabase.com, 2019)
Polymers for bitumen Styrene butadiene styrene Polypropylene (PP) Polyethylene (PE) Polyethylene terephthalate (PET)	 0.910–0.965 (5–45% styrene) 0.866–0.90 g/cm^3 0.92–0.95 g/cm^3 (low and high density PE, respectively) 1.385 g/cm^3	 (Scientific Polymer Products, Inc., 2019)

Apart from forces in the water, and flow conditions, the sedimentation rate for a particle in water also depends on the size, density, and shape of the particle, and on the salinity and temperature of the water (Vogelsang et al, 2019). The sedimentation rate is much lower for small particles than for large ones with the same density. Very small particles may be suspended (Vogelsang et al, 2019) and will only settle if the suspension is left undisturbed. Vogelsang et al (2019) estimate that the main fraction (approx. 85%) of the tyre wear particles are larger than 50 µm and have a relatively high density (≥ 1.7 g/cm^3 with road particles on the rubber surface included), and this fraction is, therefore, expected to settle in water.

The data on size distribution, density, and composition of tyre wear particles are based on samples collected from road simulators and roads, and on calculations. Whether, or how, the densities of the particles change in the environment has not been studied. If road particles present on the surface of the tyre wear particles were to fall off during transportation, or due to turbulence in the water, the density of the tyre wear particles would decrease and approach the density of seawater. At the same time, the size of the particles would decrease. This could affect their ability to spread. The size a particle has when released may also change in the environment as a result of biofilm fouling (e.g. algae and bacteria), degradation, or fragmentation (Unice et al, 2019b). The density of the rubber polymers in the rubber material is, as shown above, lower than the density of water, and if the rubber material breaks down into rubber polymers, these may float.

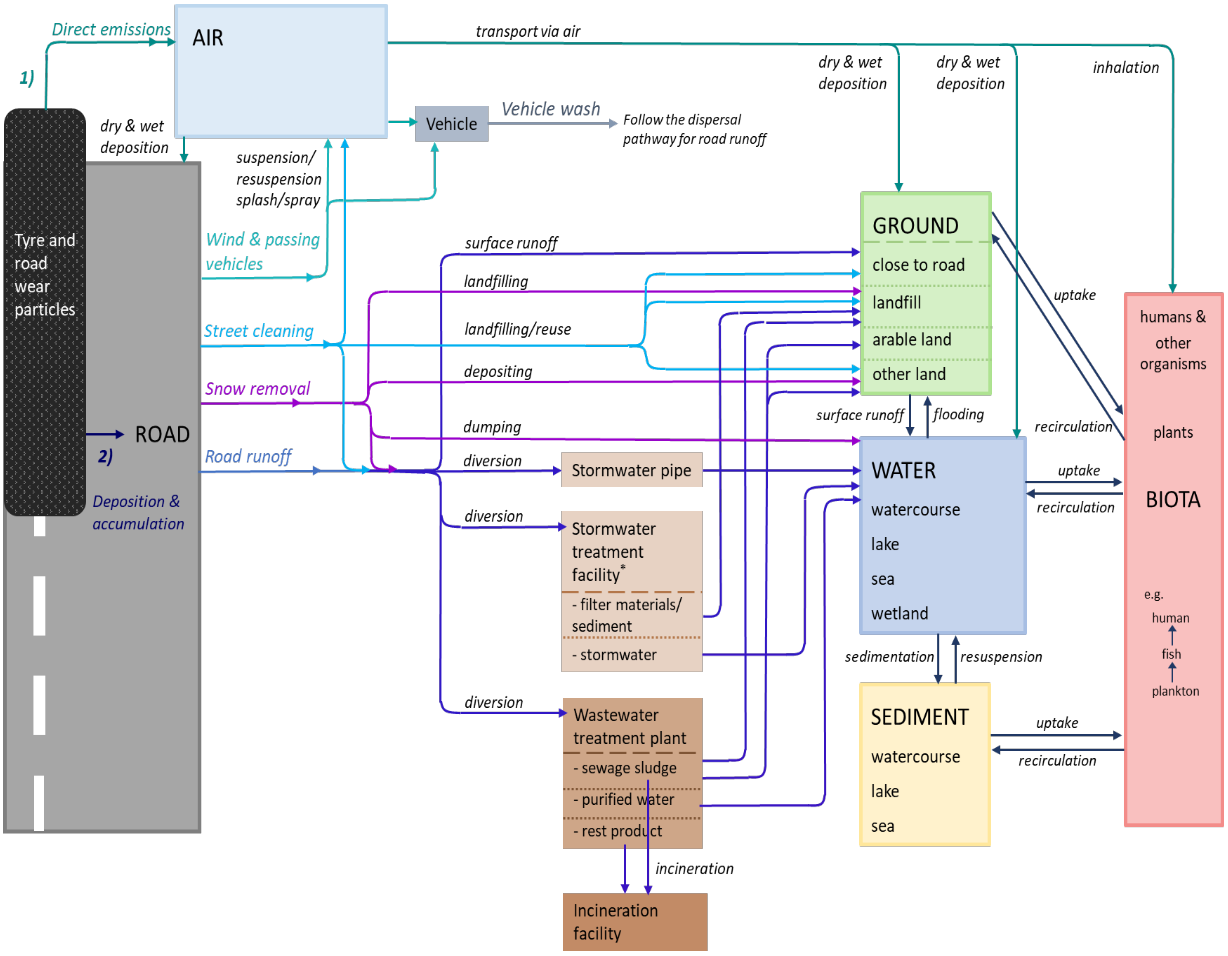
Increased knowledge about the size, density, and sedimentation propensity of tyre and road wear particles, and of the ways in which they change in different environments over time, is important to give a better understanding of the dispersal and presence of tyre and road particles in the environment.

2.2.2. Precipitation

The amount of rain that falls and the intensity of a precipitation event have a significant impact on the extent to which particles can be washed off a road and spread further with the water. Heavy and intense rainfall causes more particles to be washed off the road, which means that more particles can reach ditches or available stormwater systems. Large amounts of precipitation also lead to stronger flows, which allow particles to travel further before they settle. If there is snow by the roadside, fast melting can result in strong water flows with the ability to transport tyre and road wear particles greater distances from the source.

2.2.3. Potential dispersal pathways and transport processes

Tyre and road wear particles are generated during contact between a tyre and the road, and released straight into the air or onto the road. From the air and road, wear particles can then spread to different parts of the environment. Depending on particle mass and meteorological conditions, particles emitted to the air will either be deposited on the road surface, or at different distances from the road via wet or dry deposition. Some of the particles may stick to the vehicle or be inhaled by humans or animals. The particles that end up on the road may either stick permanently to the pores (Kole et al, 2017) and macrotexture of the road surface or remain for a longer or shorter period of time before being transported further away from the road in different ways. The amount of particles that stick depends on the proportion of hollow space in the asphalt (Kole et al, 2017) and the depth of the macrotexture, as well as the meteorological conditions and the speed and composition of traffic. Porous asphalt contains a large proportion of pores, which means that a greater number of particles get captured in it than in regular asphalt with a smaller proportion of pores (Kole et al, 2017). Tyre and road wear particles that fall on the road may interact with other particles on the road, such as wear from brake pads and tyre studs, exhaust fumes from vehicles, and atmospheric deposition (Wagner et al, 2018). Removal of particles from the road takes place for example by wind and passing vehicles, road runoff, snow removal, and street cleaning. *Figure 1* shows potential dispersal pathways and transport processes for tyre and road wear particles. These are also described in sections 2.2.3.1–2.2.3.7.



Tyre and road wear particles are generated during contact between a tyre and the road and released straight into the air (1) or onto the road (2). The particles can then spread to different parts of the environment. Depending on particle mass and meteorological conditions, particles emitted to the air will either be deposited on the road surface or at different distances from the road via wet or dry deposition. Some of the particles may stick to the vehicle or be inhaled by humans or animals. Of the particles that end up on the road some may be trapped permanently in the road surface, while others remain for a longer or shorter period of time before following different dispersal pathways.

Removal of particles from the road takes place for example by wind and passing vehicles, road runoff, snow removal, and street cleaning. Particles in road runoff may drain onto land, be diverted directly to a recipient via storm water pipes, or be diverted via a stormwater facility or waste treatment plant before reaching the recipient. In the recipient, particles may move between land, water, and sediments, and be taken up by biota (flora and fauna) or be recirculated via faeces or decomposition of dead organisms. The dispersal pathway for vehicle washing, and some pathways for street cleaning and snow removal, follow the same dispersal pathway as road runoff.

**Examples of stormwater facilities include stormwater ponds, sedimentation basins, sedimentation tanks, detention storage, constructed wetlands, constructed ditches, flooding surfaces, and floodplains. Water treatment facilities are sometimes available at vehicle washing installations.*

Figure 1. Potential dispersal pathways and transport processes for tyre and road wear particles. Figure: Delilah Lithner, VTI.

There are major knowledge gaps concerning the spread of tyre and road wear particles and the distribution between different dispersal pathways. However, some attempts to estimate and calculate different flows have been made (e.g. Kole et al, 2017; Unice et al, 2019a, 2019b; Vogelsang et al, 2019). A sizeable proportion of the tyre wear is emitted as relatively large particles (> 20 µm) and is therefore believed to be deposited on or near the road (Grigoratos & Martini, 2014). It is mainly the smaller particles (< 10 µm) that spread further through the air (Kole et al, 2017). Attempts to estimate the proportion of particles that become airborne have been made, however, the results vary and are based on an insufficient number of measurements. When comparing different wear factors for tyres with emission factors for PM10 for tyres, presented in Amato (2018), approximately 10 percent of the total tyre wear is PM10. There is, however, wide variation in the data.

2.2.3.1. Wind and passing vehicles

In dry conditions, passing vehicles and wind may result in particles deposited on the road being suspended or resuspended, and moved to the side of the road or transported further afield in the air (Vogelsang et al, 2019). Wheel tracks in particular are efficiently cleared by the air pumping mechanism that occurs when the rubber enters and exits the road surface texture, as the tyre rolls across the surface (Eisenblaetter et al, 2010). Turbulence below and around the vehicle also causes road dust to swirl up. This effect depends on the speed, number of tyres, and size of the vehicle. Even when the road surface is damp, traffic can cause particles to swirl up from the road and be further dispersed due to the splash and spray that occurs when vehicles travel on a wet surface (Vogelsang et al, 2019).

2.2.3.2. Road runoff

An important dispersal pathway for tyre and road wear particles is runoff from roads and traffic areas during precipitation (Kole et al, 2017) and snowmelt. Removal of tyre and road wear particles from the road during precipitation occurs more easily if the road surface is smooth. Small particles can accumulate in the road surfacing (Vogelsang et al, 2019). In areas with no stormwater systems, the tyre and road wear particles will drain off with the rain onto land adjacent to the road, and into any open ditches, from which they may also be carried further to nearby streams and other watercourses (Wagner et al, 2018). Most of the particles will, however, probably end up relatively close to the road, which has also been shown in an older study by Cadle & Williams (1975).

Where stormwater systems are present, which is commonly the case in built-up areas, in particular on and near roads, the dispersal will depend on the design of the stormwater system. Stormwater may be diverted from the road, for example via wells to stormwater sewers taking the water directly to a recipient, which would usually be a watercourse, a lake or an ocean, but could also be a wetland. The stormwater may also be diverted to different types of stormwater facilities (e.g. stormwater ponds, sedimentation basins, sedimentation tanks, detention storage, constructed wetlands, constructed ditches, flooding surfaces, or flood plains), or to a wastewater treatment plant. The way in which particles are spread from stormwater facilities depends on the type of end treatment provided for the sediments, soils or other materials; if and when the facilities are dredged or the materials (e.g. in detention storage) changed; and the amount of particles able to pass through the facility with the stormwater. In wastewater treatment plants, a large proportion of the microplastic particles end up in the sewage sludge, from where they can spread into the terrestrial environment if the sludge is deposited on arable soils or other land. Some waste fractions can be removed in the treatment process (e.g. slurry and matter caught in sludge sieves) and sent for incineration (Ljung et al, 2018). Dried or dewatered sludge is also sometimes incinerated (Statistics Sweden, 2018). The microplastics not caught in the sewage sludge, or rinsed away, are transported with the treated wastewater to a watercourse, a lake or an ocean. See also section 2.3.2.

Where the tyre and road wear particles that reach a stormwater system or a water recipient finally end up is not known. There is neither knowledge about the amounts that settle nor the amounts that are transported further within the recipient or to other recipients by strong flows, turbulence, ocean currents, or waves. The small number of currently available studies indicate that tyre wear particles (identified as black rubber-like particles) are present in stormwater and sediments close to points of discharge for stormwater and wastewater (see section 2.3).

2.2.3.3. Snow removal

When snow is cleared outside built-up areas, it is often left by the side of the road, and the tyre and road wear particles then spread according to the location-specific dispersal pathways that apply for runoff from the road. Within built-up areas, it may be necessary to transport some of the snow away from the road. The tyre and road wear particles are then spread to the locations that receive the snow and will follow the site-specific dispersal pathways at that location. The cleared snow is often placed on a nearby piece of land or designated place, but may in Sweden also be dumped in watercourses, lakes or oceans, in cases where an exemption from the Swedish ban on dumping snow in water areas has been granted.

2.2.3.4. Street cleaning

Street cleaning (sweeping) can lead to significant dust generation and spread of particles to air, depending on the type of road sweeper and technology used. In Sweden, sand collected during street sweeping is classed as waste (Spångberg, 2013) and some of it is landfilled, while some is reused (City of Stockholm, 2019). Sand swept up from roads is in Sweden for instance used for road construction, noise barriers, and cable and piping shafts (City of Stockholm, 2019). Water can be used during sweeping to reduce dust generation (Magnusson et al, 2019), and e.g. for washing of tunnels. The water may be collected in stormwater systems, combined sewer systems, or drain off into the ground, while the road dust and sludge fractions may be deposited in landfills (Vogelsang et al, 2019).

2.2.3.5. Emissions to air

Wear particles emitted directly into the air as part of tyre and road wear, and particles that originally settled on the road but later spread to the air as a result of suspension, resuspension, or splash and spray, are deposited in different land and water environments via dry or wet deposition. Dry deposition means that the particles are deposited on surrounding surfaces (e.g. on a vehicle) or on land and water areas, whereas wet deposition means that the particles are washed out from the air and deposited via precipitation. Dry and wet deposition can occur on the road itself, near the road, in built environments, or on land and water areas further away. Where the particles end up depend on their size, propensity for air transportation, wind conditions and the timing of precipitation events. The particles may also be inhaled by humans and animals who are exposed to them. The greatest risk of exposure via inhalation occurs in the proximity of high-traffic roads and in streetscapes where concentrations are comparatively high.

2.2.3.6. Vehicle washing

Tyre and road wear particles may stick to the surface of vehicles travelling along a road. This seems to apply particularly to smaller-sized airborne particles, why the total volume of particles that stick is deemed to be relatively limited (Vogelsang et al, 2019). When vehicles are washed, these particles may follow the same dispersal pathways as road runoff. Many vehicle washing installations are fitted with a water treatment facility, connected to a stormwater or wastewater sewage system, however, this is commonly not the case for smaller establishments. In addition, some car owners in Sweden wash their cars in the street despite the fact that there is a Swedish Environmental Code banning all intentional pollution of land and water, and that many municipalities have banned this activity.

2.2.3.7. Soil, water, sediments, and biota

Particles found in soil, water, or sediments can be transported between these environments. They may e.g. move from water to sediments via sedimentation, or from sediments to water via resuspension. In terrestrial and aquatic environments, tyre and road wear particles may be taken up by the organisms that live in these environments, from which they may spread to other organisms further up the food chain. Particles can then be recirculated via faeces or the decomposition of dead organisms. Organisms on land may also absorb particles through inhalation (see 2.2.3.5).

2.3. Presence of tyre and road wear particles in the environment

There are few studies on the presence of tyre and road wear particles in the environment, and it is difficult to analyse tyre wear particles in field samples (see chapter 7). A few studies on the presence of tyre wear particles in road dust, water, sediments, and air are described in the following sections.

To be able to assess the spread and presence of tyre and road wear particles in Sweden requires knowledge about the magnitude of the wear under Swedish conditions, as well as sampling of particles at the source and in soil, sewage sludge, stormwater, surface water, sediments, air, and biota.

2.3.1. Estimated proportion of tyre and road wear particles of total microplastics

Many studies describe the presence of microplastics in different parts of the environment and have quantified the number of microplastic particles mainly in oceans, lakes, and watercourses, and before and after wastewater treatment plants. The studies show that microplastics are present everywhere: in many different types of organisms and environments, and in all parts of the world (see e.g. SAPEA, 2019; Klein & Fisher, 2019; Schwabl et al, 2019; Ebere et al, 2019). Many of the studies demonstrate high concentrations of microplastics.

That vehicle tyres may be a significant source of microplastics in marine and other aquatic environments has been highlighted in recent research (Hann et al, 2018). Attempts have been made to estimate the proportion of the microplastics in the environment related to tyre and road wear particles, however, these estimations are very uncertain. One calculation shows that rubber particles from tyre wear may contribute just over 50 percent by weight of the identified primary sources of microplastic emissions in Norway (Sundt et al, 2014). Modelling has indicated that tyre wear may contribute up to 40 percent in weight of the total amount of microplastics in European rivers (Siegfried et al, 2017). Estimations of how much reaches the oceans varies between 1 percent in weight according to Dutch calculations, and 32 percent in weight according to Norwegian calculations (Kole et al, 2017).

2.3.2. Presence on and adjacent to roads

The presence of micro-sized rubber particles in road dust and airborne road dust has been demonstrated in studies in Iran (Abbasi et al, 2017, 2019; Dehghani et al, 2017). One of the studies identified 44 to 782 micro-rubber particles per 10 g sample in road dust, where the highest levels were measured in samples from a highly trafficked road used by heavy vehicles (Abbasi et al, 2017). Similar results were achieved in a later study, which found between 40 and just over 1,000 micro-rubber particles per 15 g road dust sample, and where the highest levels were quantified in samples from an industrial area (Abassi et al, 2019). On average, 1,150 microplastic particles, of which 250 micro-rubber particles, were found per 15 g road dust sample (Abbasi et al, 2019). The road dust samples were collected in urban, industrial, commercial and residential areas. Fluorescence microscopy, polarised light, and scanning electron microscopy (SEM) were used to quantify the microplastic particles, excluding rubber particles, while only a scanning electron microscope and tweezers were used to quantify the micro-rubber particles (Abassi, et al, 2017, 2019). The microplastic particles varied in colour, shape and size, but were dominated by white, transparent, spherical (74%) and film-like (14%) shapes, and mainly found in sizes below 100 µm. The micro-rubber particles were dominated by black fragments (61%) and fibres (36%), and mainly found in the size range 100–250 µm (Abassi et al, 2019). In the airborne dust mainly microplastics (at magnitudes of 1 particle/m^3 air) were identified. Micro-rubber particles (mainly fragments) were also present in the airborne road dust, however, they were very small and difficult to classify (Abassi et al, 2019).

There are currently no published results from measurements of tyre wear particles in terrestrial environments, such as roads, in Sweden. Data on what proportion of the tyre and road wear particles ends up in soil by the roadside is very limited.

2.3.3. Presence in water and sediments

The presence of tyre particles (black, rubber-like particles) has been demonstrated in stormwater, as well as in sediments from watercourses and coastal waters. An extensive American study, carried out over three years, investigated the presence of microplastics in the San Francisco Bay and its tributaries, in several sub-studies looking at stormwater, surface water, sediments, treated wastewater, and fish (Sutton et al, 2019). Black, rubber-like particles constituted a large proportion of the analysed particles, mainly in stormwater and sediments, but were not detected in treated wastewater, surface water, or fish (Sutton et al, 2019).

In the stormwater study by Sutton et al (2019), samples of stormwater were collected during precipitation events in twelve small tributaries to the San Francisco Bay, close to urban and non-urban areas. Microplastic particles were identified in the stormwater, at levels of between 1.3 and 30 microplastic particles per litre (12,352 microplastic particles in total). The greatest number of microplastic particles was found in the smallest filter fraction (125–355 µm). Almost half (48%) of the total number of microplastic particles were black fragments with a distinct rubbery texture, which was confirmed using tweezers (Sutton et al, 2019). The particles were similar to other particles previously identified as rubber using Fourier-transform infrared spectroscopy (FTIR) (Sutton et al, 2019). Such particles were found in all stormwater samples, except one, which came from a rural area.

In the sediment study by Sutton et al (2019), samples of sediments (> 45 µm) were collected from 18 locations in the San Francisco Bay and two locations in the Tomales Bay, close to points of discharge for stormwater and wastewater. The most commonly found microplastic particles were fibres (69%, 3,960 particles), followed by fragments (26%, 1,516 particles). Of the fragments, 29 percent (429 particles) were black fragments with a rubber-like texture, similar to the particles found in the stormwater (Sutton et al, 2019).

Another American study investigated the presence of microplastics (≥ 63 µm) in watercourses that flow into the Charleston Harbour Estuary (Leads & Weinstein, 2019). The study detected between 0 and 652 microplastic particles per m^2 in the top two centimetres of the sediment from the intertidal area, of which tyre particles constituted on average 18 percent, with a peak value of 28.7 percent (Leads & Weinstein, 2019). In sediments outside the intertidal zone, the highest number of tyre particles was 1,833 particles per kg wet weight, and tyre particles constituted on average 12.5 percent of the microplastic particles. The highest number in the surface water (sampled in the upper millimetre) was 8 tyre particles per litre, and tyre particles constituted on average 17.8 percent of the microplastic particles (Leads & Weinstein, 2019). The greatest number of tyre particles was found in the smallest fraction (63–149 µm) (Leads & Weinstein, 2019). Tyre particles were mostly identified using morphological analysis methods.

Studies recently carried out by Gothenburg University show that what in previous Swedish studies has been identified as black elastomer fragments are probably tyre wear particles (Hassellöv et al, 2018; Karlsson et al, 2019). The presence of significant numbers of black elastomer particles has been detected in sediments from the west coast of Sweden, and in the watercourse Kvillebäcken in Gothenburg (Hassellöv et al, 2018; Karlsson et al, 2019). Sediments from three sampling locations in Kvillebäcken were found to contain between 15,490 and 16,798 black, anthropogenic particles (≥ 100 µm) per kg dry weight (Hassellöv et al, 2018). Tweezers were used to determine that approximately 32 percent of these were rubber-like elastomers (Hassellöv et al, 2018). In sediments from Kvillebäcken, black anthropogenic particles constituted the largest proportion of the microparticles, while microplastic particles from materials usually regarded as plastics dominated in sediments from the river of Göta älv, which Kvillebäcken flows into (Hassellöv et al, 2018). The number of black particles (≥ 100 µm) was considerably lower in the sediments from Göta älv (121–436 black anthropogenic particles per kg dry weight) than detected in Kvillebäcken (Hassellöv et al, 2018). These studies show that the proportion of these particles increases significantly with decreasing particle size, and that they often settle close to the source. However, further research is required to confirm occurrence, spread, and related risks (Karlsson et al, 2019).

Further studies from Gothenburg also indicate that large amounts of microplastics in the form of black microparticles may be present in roadside stormwater. Up to approximately 1,000 unidentified black particles per litre (Jannö, 2016) and high levels of micro-rubber particles and low-density bitumen particles (1,000–6,000 particles/l) (Aronsson et al, 2018) have been measured in roadside stormwater.

Tyre wear particles have also been found in 97 percent of 149 sediment samples collected from the Seine River (France), Chesapeake (USA), and Lake Biwa (Japan) (Unice et al, 2013). Measured concentrations in sediment was 62–11,600 µg/g dry weight for Seine, 50–4,400 µg/g for Chesapeake, and 26–4,600 µg/g for Lake Biwa. There are also modelling studies which demonstrate significant deposition of tyre wear particles to sediments in lakes and watercourses (Hann et al, 2018; Unice et al, 2019b).

Mass balance model estimates on transport of tyre and road wear particles (TRWP) in the Seine watershed, by Unice et al (2019b), indicated that 18% of the total released TRWP were transported to fresh water and that 2% could reach the estuary (which corresponds to 11% of the TRWP entering fresh water). Assumptions used were for instance a particle density of 1.8 g/cm^3, a size of 105 µm, and that 49 % by weight would be transported by direct run-off, of which 75% would be directed to wastewater treatment plants with a removal efficiency of 95%. There is, however, variation in e.g. size and density, which, as shown in other estimates by Unice et al (2019a), gives a large variation in the figures. There is also uncertainty relating to the density of tyre wear particles in the environment (see section 2.2.1). Small and low-density particles are less likely to settle, and therefore generally transported greater distances with water, whilst heavier and larger particles settle and are transported shorter distances.

When it comes to microplastics from materials usually regarded as plastics, and microplastics in general, there are plenty of measurements and calculations of concentrations in oceans, lakes, and watercourses. There are large variations between different geographical locations, and between different studies, as illustrated e.g. in a review of data from different studies on microplastics in freshwater environments by Li et al (2019). In addition to the studies that have identified tyre particles in water and sediments, Horton et al (2017a) found particles from road markings during measurements in sediment near a stormwater outlet in a tributary to the River Thames.

2.3.4. Presence near wastewater treatment plants and in sewage sludge

Tyre and road wear particles that reach wastewater treatment plants via stormwater systems may end up in the sewage sludge or pass through the treatment plant to the receiving recipient. Some microplastic particles are included in fractions removed as part of the wastewater treatment process, such as slurry and matter caught in sludge sieves, and sent for incineration (Ljung et al, 2018). The amount of tyre and road wear particles that reach wastewater treatment plants is not known.

There are, however, a few studies on microplastics in general. These studies show that a considerable amount of microplastic particles can pass through some wastewater treatment plants, both due to incomplete treatment and due to large flow volumes (Sun et al, 2019; Conley et al, 2019). This means that high concentrations may be present in the recipients of the wastewater treatment plants. The proportion of the particles that pass through depends on the removal efficiency of the treatment plant. At three Swedish wastewater treatment plants, the removal efficiency for particles larger than 20 µm varied between 70 and 90 percent. For particles larger than 300 µm, the removal efficiency was above 99 percent (Magnusson & Wahlberg, 2014). In a later study of a different wastewater treatment plant in Sweden, the removal efficiency for particles larger than 10 µm was above 99 percent (Ljung et al, 2018). Elevated levels of microplastics have been measured downstream of wastewater treatment plants in for example the Raritan River and the Chicago River (Estahbanati & Fahrenfeld, 2016). As an example, concentrations at the most polluted location downstream of a wastewater treatment plant in the Raritan River was 3 to16 times higher than the background level upstream of the same plant, which indicates that microplastics are emitted from the plant. When microplastic particles are efficiently removed from the water phase, the majority of the particles end up in the sewage sludge (Magnusson & Norén, 2014; Mintenig et al, 2017), and in fractions removed by the wastewater treatment process (Ljung et al, 2018).

The American study in the San Francisco Bay did not detect rubber particles in wastewater that had passed through the wastewater treatment plants, only other microplastic particles (mainly fibres) were found (Sutton et al, 2019). However, rubber-like particles were found in sediments collected close to the discharge points of the treatment plants (Sutton et al, 2019).

Calculations have indicated that large amounts of microplastics may enter the ground via sewage sludge, and that there is a high probability that sewage sludge is a major source of the spread of microplastics to soil (Horton et al, 2017b). In Europe, it is fairly common for sewage sludge to be composted and pasteurised to be used as fertiliser, or that it is deposited on land (Horton et al, 2017b). According to data from 2012 (Eurostat), approximately 38 percent of the sewage sludge produced in the EU was spread on agricultural land, corresponding to around 5 million tonnes in dry weight (Willén et al, 2016). In 2016, the use of sewage sludge in Sweden was divided as follows: arable land 34%, construction soil 27%, landfill cover 22%, incineration 2%, landfill 1.5%, storage 5.5%, and other uses 7% (Statistics Sweden, 2018). There are regulations in place relating to the content of hazardous substances in the sewage sludge, but the content of microplastics is not regulated (Horton et al, 2017b). In order to find out how much of the tyre and road wear particles end up in the sludge, both the dispersal of tyre particles via stormwater systems to wastewater treatment plants and their presence in sewage sludge should be studied.

2.3.5. Presence in air

Tyre and road wear particles become airborne as a result of direct release from tyres and roads, or through resuspension of particles on the road surface (Wijesiri et al, 2016). Tyre wear particles have been identified in air samples collected in road environments.

Panko et al (2018) have compiled the estimated proportions of tyre wear particles within the PM_{10} fraction from a selection of 14 studies performed between 1994 and 2013. According to this compilation, proportions vary between 0.1 and 13 percent. One example not included in this compilation concerns the measurements carried out in Marylebone Road in central London, where it was estimated that tyre wear particles constitute 10.7 ± 2.3 percent of airborne particles (Harrison et al, 2012). Another study by Panko et al (2013) (funded by the tyre industry) analysed air samples from urban and rural roads in France, Japan, and the United States. According to this study, tyre wear particles only constituted a very small proportion (0.14–2.8%) of the total PM_{10} fraction measured in the air samples.

Sommer et al (2018) analysed larger airborne microparticles (> PM_{10}) using scanning electron microscopy in combination with energy-dispersive spectroscopy after passive sampling along three high-traffic roads in Germany: in an industrial area, an agricultural area, and an urban area, respectively. The findings from this study showed that 90 percent of the analysed particles were traffic-related, and mainly composed of a combination of tyre, road, and brake materials. Of the studied particles (508 in total), 34 percent were classified as tyre wear particles (corresponding to more than 50% of the volume), and 38 percent were classified as road wear particles (i.e. mineral particles bound to bitumen).

2.4. Degradation

When it comes to degradation of tyre and road wear particles in the environment, there is almost no knowledge available. There is one older study by Cadle & Williams (1980) on the degradation of tyre tread particles and tyre wear particles in soil, and in glass beads, respectively. In this study, the half-time of styrene butadiene rubber polymers in tyre wear particles in soil was found (by extraction-pyrolytic method GC) to be 16 months (around 490 days). The degradation of tyre wear particles in the glass beads over the same time period was lower (36%), which was assumed to be due to a lack of microorganisms (Cadle & Williams, 1980). The pure tyre tread particles did not degrade at all (Cadle & Williams, 1980).

As the main constituents of the tyre tread are rubber polymers and carbon black, Wagner et al (2018) suggest that tyre wear particles in the aquatic environment can be expected to be persistent, i.e. only degrade slowly. Degradation is also limited in environments with inadequate levels of oxygen and a lack of microorganisms. It is of great importance that the degradation of tyre wear particles in different environments is investigated, to give an understanding of how persistent they are in different environments, which degradation products are formed, and the potential toxicity of the degradation products.

2.5. Conclusions

- Microplastics from tyre and road wear consist mainly of tyre wear particles from the tyre tread. Microplastic particles are also released as a result of road wear, both from road markings and from those asphalt surfaces that contain polymer modified bitumen.
- A significant proportion of the tyre wear is released as relatively large particles (> 20 µm) and is, therefore, expected to be deposited on the road or roadside. The percentage of airborne particles is estimated to around 10 percent. This means that tyre and road wear particles are mainly spread via road runoff during precipitation events, and by moving vehicles and wind, but also as a result of snow removal and street cleaning. Particles may spread to land, surface water, sediments, sewage sludge, and biota.
- There are big knowledge gaps concerning the distribution of tyre and road wear particles between different dispersal pathways, and between different environmental compartments. There is also a lack of knowledge about the fate of these particles in the environment.
- Increased knowledge about the size, density, and sedimentation propensity of tyre and road wear particles, and of how they change (e.g. through degradation and biofilm fouling) in different environments is required to gain a better understanding of the spread and presence of tyre and road wear particles in the environment.
- There is also a need for increased knowledge about the degradation of tyre wear particles in different environments, to enable evaluation of their persistence.
- Data on dispersal, presence, and persistency are also required to access the exposure to microplastics in the environment, and thereby also the risks posed by microplastics in the environment.
- The presence of tyre wear particles in the environment has been demonstrated in studies on road dust, air, stormwater, and sediments, however, the number of studies is small. There are no studies on presence in sludge from wastewater treatment plants, in terrestrial environments (apart from traffic environments), or in organisms in nature.
- There is no data on the presence of wear particles from road markings.

3. Effects and risks

This chapter gives an overview and review of current knowledge of the environmental effects of microplastics, and the knowledge required to enable assessment of the risks posed by microplastics in the environment. The focus is on microplastics from tyre and road wear, and in particular tyre rubber particles. In this chapter this type of microplastic is referred to either as tyre tread particles, or tyre and road wear particles. No effect studies are available for road markings or polymer modified bitumen. There are, however, some data on the chemical composition of road marking products and polymer modified bitumen. This information has been compiled in chapter 4, together with information concerning chemical composition of tyre tread. There is a very limited number of studies on the effects and risks of microplastics from tyre and road wear. There are considerably more studies on microplastics from materials usually regarded as plastics, and on microplastics in general. As some of the knowledge from this research is also relevant to microplastics from tyre and road wear, the relevant parts are addressed here.

3.1. Knowledge about effects and risks

3.1.1. Tyre and road wear particles

There are relatively few studies on toxicity to aquatic and terrestrial organisms exposed to tyre tread particles or tyre and road wear particles. These are described in sections 3.2.1 and 3.2.2 below.

It is currently not possible to assess the risk posed by tyre wear particles in aquatic environments, as there is not enough reliable knowledge about important aspects such as the transportation mechanisms of tyre wear particles in surface water, concentrations in surface water and sediments, how the particles change over time in the environment, degradation time, effects on aquatic organisms (Wagner et al, 2018), and the extent to which toxic substances are released from tyre wear particles. This lack of knowledge also applies to terrestrial environments. When it comes to microplastics from road markings and polymer modified bitumen in asphalt, generated by road wear, there are no effect studies at all.

3.1.2. Microplastics in general

There is much more research available on the environmental effects of microplastics (i.e. plastic particles < 5 mm–0.1 µm or 1 µm) from materials usually regarded as plastics. A large number of ecotoxicological studies have been carried out during the last decade, in particular post 2012 (de Sá et al, 2018), and new studies are continuously being published. There are also a few meta-analyses, where several effect studies have been assessed and reviewed (e.g. Burns & Boxall, 2018; de Sá et al, 2018), as well as review reports where existing knowledge on effects and risks of microplastics have been compiled (Ašmonaté & Carney Almroth, 2019; SAPEA, 2019). A SAPEA report (SAPEA Evidence Review Report 2019), prepared by a large working group with world leading experts in the field of microplastics, offers a comprehensive evaluation of what is currently known about the effects and risks posed by nanoplastics and microplastics in nature and society. SAPEA is the abbreviation for Science Advice for Policy by European Academies and is a part of the European Commission´s advice mechanism. Based on the SAPEA report, the European Commission's Group of Chief Scientific Advisors then published a scientific opinion (”Scientific Opinion 6/2019”) on ”Environmental and Health Risks of Microplastic Pollution”, directed to the highest level of policy making, with recommended measures for reducing microplastic emissions (European Commission, 2019) (see section 8.2.5).

Although there are many studies within the field of microplastics, there are still major knowledge gaps, a lack of standardisation (in relation to measurements and analysis, as well as effect studies), and a lack of realistic impact studies (Buns & Boxall, 2018; de Sá et al, 2018; SAPEA, 2019; Ašmonaté & Carney Almroth, 2019).

The environmental relevance of many of the laboratory-based effect studies is uncertain (SAPEA, 2019). Most effect studies on microplastics have been performed on aquatic (mainly marine) organisms, and usually only cover one species, one type of polymer, one type of particle, and one particle form (Ašmonaté & Carney Almroth, 2019), as well as relatively short-term (acute) exposure (SAPEA, 2019). A majority of the studies use concentrations that are higher, and particle sizes that are smaller, than those measured in the environment (SAPEA, 2019). At the same time, SAPEA (2019) stresses that our understanding of the levels present in the environment is incomplete and limited by the sampling and analysis methods used in the studies, as well as by what can be analysed at present. It is regarded by many that the estimated concentrations are lower than the actual concentrations in the environment, in particular for very small particles, partly because most samples have been collected by trawling using nets with a mesh size greater than 0.3 mm, and partly because analysis methods for identifying plastic fibres and small particles have limitations, or do not exist (SAPEA, 2019).

Compared to the situation a few years ago, there is now, according to Ašmonaté & Carney Almroth (2019), a greater understanding within the microplastics research field of the complexity of the issues concerning microplastics and the underlying mechanisms causing the effects of microplastics.

A number of reports and articles discuss the risks to human health or the environment from microplastics, but only a couple of attempts (Burns & Boxall, 2018; Everaert et al, 2018; Besseling et al, 2019) have been made to quantitatively estimate the risks posed by microplastics in the environment based on available data on measured concentrations and effects. These assessments are, however, associated with major uncertainties, e.g. because:

- The sizes, forms, and polymers used in the experiments are inconsistent with those measured in the environment today (SAPEA, 2019).
- There are knowledge gaps e.g. in terms of actual concentrations in the environment (including nanoplastic particles), what the distribution between different polymers, sizes, and forms looks like (SAPEA, 2019), and the effects on different types of organisms from different types of exposure (Ašmonaté & Carney Almroth, 2019).
- There is little quantitative data of adequate quality (SAPEA, 2019).
- There are no agreed methods for measuring exposure or performing hazard characterisations (SAPEA, 2019).

Altogether, many assumptions and extrapolations need to be made in the risk assessments, which makes them uncertain (SAPEA, 2019).

The SAPEA working group´s statements about risk are based on the ratio between measured or predicted environment concentration (PEC) and predicted no-effect concentration (PNEC), i.e. PEC/PNEC. If the PEC/PNEC ratio is greater than 1, concentrations in the environment are higher than the concentrations believed to be ‘safe’ for the environment. When this is the case, the assessment is that there is a risk, i.e. a likelihood of harmful effects in the environment.

According to the SAPEA working group (2019), current gaps in our knowledge about nanoplastics and microplastics in the environment mean that it is not possible to, with sufficient certainty, draw either the conclusion that there currently is a risk, or that there is not (with risk defined as PEC/PNEC > 1).

Even though the knowledge gaps are too wide to draw certain conclusions about the risk, the SAPEA working group (2019) has, based on the attempted quantitative risk assessments made, formulated three conclusions relating to the ecological risks of microplastics, although they also state that these conclusions are uncertain:

A. **Present local risks**: 'There may at present be at least some locations where the predicted or measured environmental concentration exceeds the predicted no-effect level (PEC/PNEC > 1).'[1]

B. **Present widespread risks:** 'Given the current generally large differences between known measured environmental concentrations (MEC) and predicted no-effect levels (PNEC), it is more likely than not that ecological risks of microplastics are rare (no widespread occurrence of locations where PEC/PNEC > 1).'[1, 2, 3]

C. **Future risks**: 'If microplastic emissions to the environment will remain the same, the ecological risks of microplastics may be widespread within a century (widespread occurrence of locations where PEC/PNEC > 1).' [1, 3]

By this they mean that based on the data we currently have on measured environmental concentrations and effects on organisms, it is likely that widespread ecological risks are currently rare, but that there may be some locations where ecological risks already occur today, and that the ecological risks may be widespread within a century if the emissions remain the same or increase (SAPEA, 2019). There is even less knowledge about the risks to human health; however, the conclusion by the SAPEA working group is that we have no evidence of widespread risks to human health from microplastics at present (SAPEA, 2019).

The SAPEA working group still feels that the currently available evidence is sufficient to support the position that action is needed to prevent and reduce emissions and spread of nanoplastics and microplastics (SAPEA, 2019). What we do know about microplastics at present includes that they are:

- present everywhere in the environment (in high concentrations at some locations)
- continuously added to and accumulating in the environment because of increasing emissions and slow degradation
- shown in tests to cause adverse effects in organisms.

Our lack of knowledge regarding concentrations and effects of nanoplastics further supports the view that action is required. The need to take action has also been expressed by the European Commission's Group of Chief Scientific Advisors, in their Scientific Opinion 6/2019 (European Commission, 2019), in which they also specify and suggest measures to be taken (see section 8.2.5).

3.2. Effects on organisms

Microplastics have been found in many different organisms, in a large number of habitats, and at different trophic levels, including in everything from small planktonic animals to large top predators (such as large fish, mammals, and birds) (Ašmonaté & Carney Almroth, 2019; SAPEA, 2019). The main part of the microplastics found in organisms, as well as in water and sediments, consists of fibres and fragments (i.e. particles with an irregular shape), while only a small proportion are round particles (Burns & Boxall, 2018).

Effects on organisms of exposure to microplastics can be caused by the physical particles themselves, which may affect the organism by ingestion, inhalation or entanglement (e.g. fibres). Effects may also be caused by chemical substances released from the plastic particles. Ingestion is considered the most common form of interaction between microplastics and biota (SAPEA, 2019).

There are several important differences between microplastics from materials usually regarded as plastic and microplastics from tyre wear, which may have an impact on the results of effect studies.

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[1] Quote: SAPEA (2019).

[2] MEC = Measured Environmental Concentration

[3] EC50 = Effective concentration 50.

Important differences may also exist among materials usually regarded as plastics. Examples of differences include material characteristics (plastics vs elastomers), chemical composition, shape, size, and degradation (see chapter 4). There are also similarities, which in some cases permits the use of knowledge from studies of one category of microplastics to draw conclusions about another category of microplastics. This must, however, be done with great caution.

Below is an overview of the toxicity studies carried out on microplastics, firstly tyre wear particles, and secondly particles from materials usually regarded as plastics.

3.2.1. The toxicity of tyre particles to aquatic organisms

There are relatively few laboratory studies on the toxicity of tyre tread particles, and tyre and road wear particles to aquatic organisms. Table A in Appendix A provides an overview of tyre-related studies of aquatic toxicity carried out since 2005. These include testing of tyre particles from new and used tyres. The particles have been generated in laboratories, either by abrasion, using e.g. a rasp, file, rotating abrader or steel brush, or in a road simulator with asphalt or concrete cassettes. The test organisms have mainly been small crustaceans, but some algae, fish, and tadpoles have also been tested. The studied effects include acute toxicity (e.g. immobility and mortality) and chronic toxicity (e.g. impact on growth, development, reproduction, and survival).

Most of the studies focus on the toxicity of leachate from tyre tread particles, i.e. the toxicity resulting from the release of chemicals from tyre tread particles into water under different leaching conditions (Wik & Dave 2005, 2006, 2009; Wik, 2007; Khan et al, 2019; Turner & Rice, 2010; Camponelli et al, 2009; Gaultieri et al, 2005a; Villena et al, 2017). These toxicity tests have been carried out either with or without tyre tread particles being present. Three studies focused on the toxicity of sediments to which tyre tread particles or tyre and road wear particles had been added (so called spiking), and on the toxicity of elutriates of the spiked sediments (i.e. the water phase obtained after mixing the sediment with water) (Marwood et al, 2011; Panko et al, 2013; Redondo-Hasselerharm et al, 2018). Ingestion of tyre wear particles has only been studied on two small species of crustaceans, in two studies (Khan et al, 2019; Redondo-Hasselerharm et al, 2018).

The toxicity studies on tyre tread particles and tyre and road wear particles presented in Table A in Appendix A show very varying results. Several studies demonstrate toxic effects (e.g. Wik & Dave, 2005, 2006, 2009; Wik, 2007; Khan et al, 2019; Turner & Rice, 2010; Camponelli et al, 2009; Gaultieri et al, 2005; Villena et al, 2017), whereas two studies do not (Redondo-Hasselerharm et al, 2018; Panko et al, 2013). One study only demonstrates effects in some of the tests (Marwood et al, 2011).

In the acute toxicity tests carried out on leachates of tyre tread particles, the acute toxicity, measured as immobility or mortality in small crustaceans, varied between different tyres and different studies. The concentration that caused effect in 50 percent of the organisms after exposure for 48 h (i.e. 48 h-EC50[4]) varied between 0.063 and 7 g particles per litre for toxicity tests carried out with particles present (Wik & Dave, 2005; Wik, 2007; Khan et al, 2019) and between 0.5 and 26.8 g particles per litre for tests with no particles present (Gualtieri et al, 2005a; Wik & Dave, 2006, 2009).

In the chronic toxicity tests, the following effects were found:

- reduced growth or growth inhibition (Gualtieri et al, 2005a; Khan et al, 2019; Wik & Dave, 2009)
- reduced number of offspring (Khan et al, 2019; Wik & Dave, 2009; Villena et al, 2017)
- delayed development (Camponelli et al, 2009)

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[4] EC50 = Effective concentration 50.

- deformity (Gualtieri et al, 2005a)
- death (Khan et al, 2019; Guatltieri et al, 2005a; Villena et al, 2017).

Accumulation of zinc in wood frog and sea lettuce has also been reported (Camponelli et al, 2009; Turner & Rice, 2010). The acute and chronic toxicity tests on organisms in sediments to which tyre tread particles or tyre and road wear particles had been added, and on elutriates of these sediments, demonstrated no, or minor, effects at the highest concentrations tested, which were 10 and 100 g/kg dry weight, respectively (Marwood et al, 2011; Redondo-Hasselerharm et al, 2018; Panko et al, 2013).

In one of two studies on ingestion of tyre tread particles, the crustacean *Hyalella azteca* indiscriminately ingested tyre tread particles (< 500 µm) that had been added to a freshwater medium. Particles could already be observed in the gastrointestinal tract after an hour, and filled the entire gastrointestinal tract after 24 hours (Khan et al, 2019). After transferral to clean water, the crustacean excreted the particles within 48 hours (Khan et al, 2019). This suggests a residence time in the gastrointestinal tract of 24–48 hours (Khan et al, 2019). The second study found only a smaller amount of tyre tread particles in the bodies (2.5 particles on average) and faeces (4 particles on average) in another crustacean species, *Gammarus pulex,* which had been exposed to 10 percent tyre tread particles (10–586 µm) in sediment for 28 days (Redondo-Hasselerharm et al, 2018).

The variations in the results from the studies in Table A, Appendix A, may be explained by differences both in the toxicity of different tyres and in the experimental design. The toxicity of different tyres has in studies by Wik & Dave (2005, 2006) been shown to vary by a magnitude of up to 100. This finding is supported by further tests carried out by Wik (2007) on a number of tyre samples, produced by a rubber manufacturer specifically for that test and designed to represent a typical summer tyre, with each sample containing different, but known, additives. The toxicity varied more than 22-fold between the different variations of the summer tyre samples. The five samples with the highest toxicity contained phenylenediamine (anti-degradant) and benzothiazoles (accelerator).

Examples of experimental design features that may affect the results of a test include choice of sample preparation method; particle size; particle shape; conditions during leaching or extraction (hardness of the water, pH, time, temperature); conditions during exposure (sediment, elutriate, filtered or unfiltered leachate, time); test concentrations; type of organisms tested; and type of toxicity test used. As the experimental design and conditions varied significantly between the studies, and as the number of studies is small, it is difficult to compare the results and draw conclusions from them.

Based on aggregated results from four studies, the size of tyre and road wear particles varies from approximately 10 nm to several 100 µm (Kole et al, 2017). This size range includes smaller particles than the tyre wear particles tested in many of the toxicity studies in Table A, Appendix A. The shape of the tyre particles is influenced by the way in which they are generated. Tyre particles generated on roads can e.g. be more elongated than tyre materials exposed to cryogenic freezing and grinding (Wagner et al, 2018). The toxicity of microplastics is suspected to be higher when particles are smaller and have a more irregular shape (SAPEA, 2019). Smaller microplastic particles and nanoplastic particles have also, in several studies reviewed by Triebskorn et al (2019), been reported to be able to enter tissue.

Below are a few findings from the toxicity studies described in Table A, Appendix A, that illustrate how the experimental design and conditions of an experiment can affect the results:

- Leaching of zinc from tyre tread particles increased with lower pH (in the pH range of 7 to 3) (Gualtieri et al, 2005a).
- The toxicity increased with longer exposure times for all types of tyres (from 24 hours to 48 hours) (Wik & Dave, 2005).

- Aggregation of tyre tread particles during leaching reduced the release of zinc from tyre tread particles and also generated less toxic leachate, probably because the surface available for leaching decreased as a result of the aggregation (Gualtieri et al, 2005a).
- The toxicity of tyre tread particles decreased as sequential leachings were carried out and the leachates were tested for toxicity, which showed that the substances causing the toxicity were easily released (Wik & Dave, 2009).
- When stored (at 4 °C for 6 days) the toxicity disappeared in some elutriate samples of sediments from road runoff detention ponds (Wik et al, 2008).

Other findings reported by the studies compiled in Table A are for instance the following:

- Toxicity Identification Evaluation carried out by Wik & Dave (2006), Wik (2007) and Wik et al (2008) indicated that the toxicity of leachates from tyre tread particles was mainly caused by zinc and organic compounds. The same conclusion was drawn from tests by Gualtieri et al (2005a).
- There was a concentration-dependent relation between toxicity and measured zinc concentrations in the leachate of tyre tread particles (Wik & Dave, 2009).
- When leachates with *D. magna* was exposed to UV light, the toxicity increased 1–39-fold, which suggests that some of the tyres contained substances with phototoxic properties (i.e. they change and become more toxic when exposed to UV radiation), such as PAH (Wik & Dave, 2005).

In addition to the studies of tyre tread particles and tyre and road wear particles produced in laboratories, two studies on field samples have been carried out, in which attempts were made to relate measured concentrations of chemical substances in the field samples to tyre wear particles (Wik et al, 2008; Peter et al, 2018). One of these studies, by Wik et al (2008), tested acute and chronic toxicity of sediments, and elutriates of sediments, from 13 detention ponds, 3 stormwater wells on roads, and 2 basins that receive washwater from road tunnels. As tyre wear was not measured, extractable organic zinc (0.13%) was used as a tyre wear marker to calculate tyre content based on measured zinc concentrations. The calculated content in the samples varied from less than 0.15 to 10.8 g tyre wear particles per kg dry weight. Four of the studied sampling points showed some toxicity.

The second study, by Peter et al (2018), used high-resolution mass spectrometry to trace the sources of pollutants in stormwater-affected watercourses where spawning salmon displayed a mortality syndrome. Water samples from the affected watercourses were compared both to stormwater samples from a high-traffic road, and to leachates from different vehicle-related sources (such as tyre tread, windshield washer fluid, power steering fluid, motor oil, antifreeze, and gear oil). Hierarchical cluster analysis indicated that leachate from tyre wear particles had more chemical similarities with the samples from watercourses where toxicity in salmon had been observed than with samples from the rest of the analysed vehicle-related sources. The prominent road pollutants in the water samples from watercourses with affected salmon included 1,3-diphenylguanidine (DPG) (a vulcanisation activator) and hexa(methoxymethyl)melamine (a crosslinking agent and adhesion promoter), which both originate from tyre wear particles, as well as polyethylene glycol, octylphenol ethoxylate, and propylene glycol (Peter et al, 2018).

In studies focusing on the toxicity of sediments with tyre and road wear particles, where no or small effects were demonstrated, relatively far-reaching conclusions were drawn about the risks posed by tyre wear particles (Marwood et al, 2011; Redondo-Hasselerharm et al, 2018; Panko et al, 2013). These were expressed as conclusions either that the results indicate that tyre and road wear particles should be considered of low concern when it comes to acute toxicity of aquatic ecosystems (Marwood et al, 2010), or of minor importance with respect to aquatic toxicity (Panko et al, 2013), or that tyre wear particles pose a low risk to benthic freshwater-living invertebrates given the predicted environmental concentrations in sediments (Redondo-Hasselerharm et al, 2018). However, our judgement is that these three studies are too limited for such general conclusions to be drawn. The studies by Marwood et al (2010) and Panko et al (2013) were funded by the tyre industry.

3.2.2. Toxicity of tyre and road wear particles to terrestrial organisms

There is only a small number of available studies focusing specifically on the exposure of terrestrial organisms to tyre and road wear particles (e.g. Kreider et al, 2012; Gualtieri et al, 2005b, 2008; Beretta et al, 2007; Mantecca et al, 2009, 2010; Gustafsson et al, 2008). The available studies look at the effects that may arise as a result of exposure to tyre tread particles, or tyre and road wear particles, in air. The most problematic particles from a health perspective are those with a diameter of less than 10 µm, as they can penetrate further into the airways. This is particularly true for particles smaller than 4 µm, as they can travel deep into the alveoli of the lungs and remain there.

In a study by Kreider et al (2012), funded by the tyre industry, rats were exposed to tyre and road wear particles in concentrations of up to 100 µg/m^3 for 6 hours a day for 28 days. The particles had been generated in a road simulator with asphalt cassettes, and the exposure took place through nasal inhalation. Apart from a few focal areas where minimal inflammatory cell infiltration of the lung was observed, the tyre and road wear particles had no effect on the rest of the studied endpoints, i.e. general toxicity, cytotoxicity, and inflammation in the airways, or on the cardiovascular endpoints (mainly haematological parameters, and blood coagulation). The NOAEL value (No-Observed-Adverse-Effect Level, i.e. the highest dose that does not cause adverse effects), for rats was therefore set to 112 µg tyre and road wear particles per m^3.

Other studies have looked at cells exposed to organic extracts from tyre tread particles, where the organic extracts contained substances released from the particles by extraction in dichloromethane, and once the solvent had evaporated, were dissolved in dimethyl sulfoxide (DMSO), which was then added to a cell culture medium. The tyre tread extracts caused increased mortality, DNA damage, and changes in cells from human lungs A549 (Gualtieri et al, 2005b, 2008; Beretta et al, 2007). Tests on mice using tyre tread particles (10 µm and 2.5 µm, respectively) in a solution that was injected into the trachea (intratracheal instillation) caused inflammation and cytotoxicity in the lungs (Mantecca et al, 2009; Mantecca et al, 2010). Tests in which leukocytes from human blood were exposed to tyre and road wear particles from a road simulator induced release of cytokines, indicating that these particles can induce inflammation in the airways (Gustafsson et al, 2008). The response varied for the different aggregates used as road materials in the simulator test, where granite induced a higher response than quartzite (Gustafsson et al, 2008).

In relation to road dust and its effects on human health, several different types of studies are available, as described in a review article by Khan & Strand (2018). These studies do not describe road wear particles or road markings specifically, but instead look at road dust and particles more generally. For this reason, it is difficult to assess the relevance of microplastics from tyre and road wear. The reported health effects relate mainly to effects on the respiratory organs and the cardiovascular system (Khan & Strand, 2018). There is one additional study, funded by the tyre industry, in which Kreider et al (2019) tried to carry out a risk assessment relating to tyre and road wear particles in air, based on the available literature. Like the previously mentioned studies funded by the tyre industry, this study draws far-reaching conclusions from a comparatively small amount of data. The authors write that despite uncertainties in both hazard assessments and exposure analyses, current weight of evidence suggests that tyre and road wear particles pose a low risk to human health. (Kreider et al, 2019). Our judgement is again that there is not enough data to draw this conclusion.

In addition to studies relating to exposure by air, the effects of tyre crumb rubber for artificial turf have been studied in soil, on earthworms (*Eisenia fetida*), and by microbial respiration in two studies (Pochron et al, 2017, 2018). The exposure took place during 30–33 days, in a mix of 50 percent soil and 50 percent new or aged tyre crumb rubber, respectively. The results showed that exposure to new tyre crumb rubber lead to decreased bodyweight (Pochron et al, 2017) and that exposure to aged tyre crumb rubber increased sensitivity to stress (light and heat) (Pochron et al, 2018) in earthworms. However, neither the survival of the earthworms nor their microbial respiration rate was affected in either of the studies (Pochron et al, 2017, 2018).

3.2.3. Effects of microplastics usually regarded as plastics

Laboratory studies have shown that exposure to high concentrations of microplastics from materials traditionally regarded as plastics under certain conditions may induce both physical toxicity (i.e. effects caused by the physical particles) and chemical toxicity (i.e. effects caused by the chemicals released from the particles) (SAPEA, 2019). It is currently not known how these conditions translate to effects in the real environment, as most studies use concentrations higher than those currently reported in the environment, or smaller particles than there is exposure data for, or spherical particles, which are less common, or relatively short exposure times (SAPEA, 2019).

In a review article about the effects of microplastics on aquatic organisms by Sá et al, (2018) a total of 130 studies reported ecotoxicological effects on aquatic organisms caused by microplastics. The most studied taxonomic groups were crustaceans (45%), followed by fish (21%), molluscs (18%), annelid worms (7%), echinoderms (7%), and rotifers (2%).

Reported effects included:

- reduced feeding activity
- increased energy consumption
- oxidative stress
- genotoxicity
- neurotoxicity
- decreased growth rate
- delayed growth
- depletion of fat reserves
- inflammatory response (inflammation)
- reduced reproductive capacity
- death (de Sá et al, 2018).

The review article by de Sá et al (2018) concludes that it is undeniable that many organisms are exposed to microplastics and that this exposure may cause a number of effects both on individual organisms of different species, and on the ecosystems in which they live. The organisms considered most susceptible to ingesting microplastics are filter feeders, deposit feeders, and pelagic planktons, due to the relatively unselective nature of their feeding strategies (SAPEA, 2019). There are few effect studies on biota in soil, and most of these relate to earthworms (SAPEA, 2019). Some of these studies demonstrate increased mortality rates, whereas others do not (SAPEA, 2019).

Microplastics have also in several studies been shown to adsorb organic compounds from surrounding waters, including persistent organic compounds, which increases the number of harmful chemicals that may be associated with a plastic particle. Sorption of organic compounds is, however, not unique to plastic materials, it also occurs to other organic materials (Koelmans et al, 2016). A study by Beckingham & Ghosh (2017) compared adsorption of PCB on microplastic of polypropylene with adsorption on microparticles of other organic materials (driftwood, coal, and biochar). The release of PCB from these materials to artificial gastric fluid was also studied. The release of PCB varied between different organic materials, and was lowest in coal, followed by polypropylene, then biochar, and highest in driftwood. Bioaccumulation of PCB in annelid worms (*L. variegatus*) that had been exposed to sediment, which either contained only PCB, or microplastics and PCB, or biochar and PCB were also studied. The results showed that the biological uptake of PCB was lower after exposure to sediment with microplastics and PCB, than for sediment containing only PCB, and slightly lower again for sediment with biochar and PCB (Beckingham & Gosh, 2017). It was deemed that the transfer of adsorbed organic compounds from microplastics in the diet to the organism, is probably only a small contribution compared to other natural routes of exposure, such as ingestion of other organic materials and biota (Beckingham & Gosh, 2017) A similar conclusion was drawn in a study by Koelmans et al (2016).

The transfer of additives from plastics present in higher concentrations may, however, be a bigger issue (Hermabessiere et al, 2017). It is well known that additives from plastics can leach into the environment. Evidence of this are for instance available from environmental monitoring, where typical chemicals in plastics (e.g. phthalates, brominated flame retardants, bisphenol A, and nonylphenols) have been measured in organisms and the environment (Hermabessiere et al, 2017), and from leaching and toxicity studies (Lithner et al, 2009, 2012; Bejgarn et al, 2015; Hamlin et al, 2015; Li et al, 2016). Knowledge about the magnitude and effects of chemicals leaching from plastic products is currently limited. One difficulty is that the chemical composition is often unknown and may vary significantly between different products.

Effects on human health relates to effects that may arise from exposure to nanoplastics and microplastics as a result of ingestion of microplastics from food and drink, or through inhalation. Very little data is available in this area. As neither the extent of the exposure nor the daily intake is known, and there is also a lack of data on nano-sized particles, it is not possible to assess the risks (SAPEA, 2019). In a review by WHO (2019) on microplastics in drinking water it was noted that there is not enough data to draw reliable conclusions about the risks to human health. However, according to WHO (2019), the limited data available indicate that when considering chemicals and pathogens on microplastic particles in drinking-water, they have little impact on human health. As regards the effect of the physical particles present in drinking-water, there is according to WHO (2019) currently no reliable information that suggest evident health concerns. It has, however, not been possible to assess the effects of nanoplastics (WHO, 2019).

Since the effects of microplastics of materials usually regarded as plastics are not the main focus of this report, no further information about available effect studies will be presented. Further summarised information about the effects of such microplastics, and of microplastics in general, is available in e.g. the following recent review articles by Ašmonaté & Carney Almroth (2019), de Sá et al, (2018), Burns & Boxall, (2018), and in SAPEA's Evidence Review Report (2019).

3.3. Properties and chemical compositions associated with toxicity

To analyse and understand the toxicity of microplastics requires a certain level of knowledge about the composition and properties of the materials in question, in this case tyres, road marking products, and polymer modified bitumen. The composition relates to components and chemical constituents, and their relative proportions. Chemical properties (e.g. chemical stability, and flammability) are characteristics that describe the material's ability to undergo a certain chemical change. Physical properties include characteristics such as mass, volume, shape, density, hardness, and elasticity of the material. The physical and chemical properties are important for understanding which substances, and amounts of substances, may be released from the particles under different conditions, as well as the physical effects the particles can potentially cause.

Chemical analyses of leachates from tyre particles have for example shown the presence of zinc and polyaromatic hydrocarbons (PAH), however, these only reflect the occurrence of the small number of substances selected for analysis. In addition, the chemical composition of tyres is complex and varies greatly between different tyres. Although the basic composition of a typical tyre is known, there are wide variations when it comes to included additives, and amounts of additives, which makes it difficult, if not impossible, to know what different tyres contain.

In the case of rubber and other plastic particles, the chemical toxicity is generally not caused by the plastic polymer molecules themselves, but by the non-polymeric substances that are either weakly bound to the polymers, or not bound at all. This relates to e.g. additives, unreacted monomers, and reaction and degradation products (Sheftel, 2000).

What can be released from a material to a surrounding medium depends on many factors in addition to its content of non-polymeric substances.

In general, migration of a non-polymeric substance (molecule or atom) from a polymer is more likely if:

- the polymer structure is permeable
- the size of the voids between the molecules in the polymer is greater than the size of the non-polymeric substance
- the substance is small, has a similar solubility parameter to the polymer and is volatile
- the temperature is high
- the surrounding medium is water for water-soluble substances, fat for fat-soluble substances, and acidic for many metals (Brydson, 1999; Sheftel, 2000).

Knowledge about the chemical composition, physical and chemical properties, release of chemical substances, and exposure are all important parts of the toxicological analysis and understanding of the effects caused by microplastics, and these should be considered together.

Chapter 4 describes some physical and chemical characteristics, as well as the chemical composition of tyres, road marking products, and polymer modified bitumen.

3.4. Knowledge required to assess the risks of microplastics

To be able to assess the risks posed by microplastics, it is necessary to carry out both a hazard analysis of the intrinsic properties of the microplastics and the substances they contain, and an exposure analysis to assess at what concentrations, and for how long, humans and the environment are exposed to the microplastics and the substances they contain. The largest knowledge gap usually concerns the exposure. To increase our knowledge and understanding of exposure, we need more information about e.g. the presence, spread, potential degradation in the environment, and actual environmental concentrations of microplastics. But we also need more information about composition and characteristics such as sizes, and shapes of microplastics, and the effects caused by exposure to these microplastics.

The SAPEA working group (2019) concluded that there is a significant need to improve the quality of the methods used within the microplastics area, and to develop standardised and internationally harmonised methods. This applies to methods for sampling, physical and chemical characterisation, concentration assessments, exposure and effect studies, as well as new methods for risk assessments of nanoplastics and microplastics.

Examples of what future effect studies should include, to more accurately assess the risks of microplastics to aquatic organisms are available in e.g. the review articles about effect studies by de Sá et al (2018) and Burns & Boxall (2018). These include:

- environmentally relevant concentrations
- effects of the types of plastics most commonly found in organisms

- effects of the most common shapes (fibres and fragments) and sizes
- effects on other types of organisms than those studied so far (e.g. echinoderms, cnidaria, and porifera)
- effects on freshwater organisms
- effects in multi-species systems and mesocosm studies (i.e. studies covering many parts of the food web).

There is also a need for further effect studies on longer-term exposure, as well as effect studies on nanoplastics (SAPEA, 2019).

The need to standardise and harmonise methods for sampling, analysis, and effect studies, as described above, is also highly relevant for microplastics from tyre and road wear. As there are so few effect studies on tyre and road wear particles, and no effect studies at all on road markings or polymer modified bitumen, the research needs are significant. The complexity also increases considerably in studies looking at the effects of tyre and road particles generated on real roads, as these, apart from rubber from the tyre tread, also include road markings, road materials (bitumen or polymer modified bitumen and aggregate), as well as other pollutants from the road surface (e.g. brake wear, stud wear, atmospheric deposition, and exhaust fumes).

3.5. Conclusions

- There are few studies on the effects on organisms of microplastics from tyre and road wear. Most of the available studies relate to aquatic organisms.
- It is mainly the toxicity of leachate from tyre tread particles that has been studied. These studies show that toxic substances are leached, and that the concentrations causing effects vary significantly both between different tyres, and between different studies.
- The two available studies on ingestion show that the tested organisms ingest the particles, then excrete them with their faeces.
- No effect studies have been carried out on road markings or polymer modified bitumen.
- There is a strong need for research on presence, exposure, effects, and risks of microplastics in general, and on tyre and road wear particles and road markings in particular.
- There are many more effect studies on microplastics of materials usually regarded as plastics, and on microplastics in general, than on microplastics from tyre and road wear. Effects have been demonstrated in several of these laboratory studies, however, the environmental relevance of these studies is uncertain.
- Although knowledge is growing within the area of microplastics, the knowledge gaps are too big to with any certainty assess the risks to humans and the environment posed by current levels of exposure to microplastics. There is e.g. a lack of standardised, internationally harmonised, and agreed methods for sampling, analysis, and studies on exposure and effects. There is also a lack of reliable data on presence of, and exposure to, microplastics in the environment. The knowledge about nanoplastic particles is even more limited.

4. Characteristics and chemical composition

This chapter describes the differences and similarities between typical plastic materials and elastomers and provides information about the characteristics and chemical composition of tyre tread, different types of road marking products, bitumen, and polymer modified bitumen. It also presents studies on physical and chemical characterisation of tyre and road wear particles, and of tyre crumb rubber for artificial turf fields.

4.1. Plastic, elastomer or both?

Microplastics from tyre and road wear consist of rubber, materials usually regarded as plastics (thermoplastics and thermosets), or a mix of these. They have different physical characteristics that may influence the way they behave in the environment.

The term ‘plastic’ is used to describe an extremely diverse group of materials, which covers many different types of polymers, properties, and applications. A polymer is a chemical compound (molecule) made up of one or more types of repeating monomers (smaller molecules), bonded to each other in a sequence, to form chains (OECD, 2019). The name ‘plastic’ comes from the Greek word ‘plastikos’, which means ‘suitable for shaping’ and refers to the plasticity of the material during manufacture, meaning that it can be moulded, pressed, or extruded into many different shapes (PlasticsEurope, 2019).

An elastomer is a polymer material that can be stretched and deforms under tension, but soon returns to its original shape and size when the tension is removed (Harper & Petrie, 2003). The name elastomer means ‘elastic polymer’.

The development of new polymers (e.g. thermoplastic elastomers) and new applications has blurred previous, more evident distinctions between e.g. rubber (elastomers) and plastic. As there is no single definition of plastic that covers the large variations within this material group today, both broad and narrow definitions are used (see section 1.2). A narrow definition may include materials usually regarded as plastic, whereas a broad definition may include all materials consisting of thermoplastic polymers or thermoset polymers, with chemical additives. The broader definition, which is used in this report, includes for example elastomers (e.g. tyre rubber), road marking products, and polymer modified bitumen. Although there are different ways to characterise polymers, most can be divided into two main groups: thermoplastic materials and thermoset materials (Harper & Petrie, 2003).

4.1.1. Importance of the polymer structure

In thermosetting materials, the polymer chains are held together by covalent bonds in a network of crosslinks, and the material cannot be re-melted by heating (Harper & Petrie, 2003). The number of crosslinks is higher thermoset plastics, and the material is harder and more rigid than in elastomers (Sastri, 2010; Brydson, 1999). Elastomers, i.e. elastic polymers, are instead loosely crosslinked and randomly coiled, which make them elastic (Sastri, 2014). The rubber material in car tyres consists of this type of crosslinked elastomers, which are thermosetting polymers. Elastomers can also be thermoplastic (Harper & Petrie, 2003).

In thermoplastic materials, the polymer chains are instead held together by weaker van der Waals forces, and the material can be re-melted by heating. The thermoplastic polymer molecules (polymer chains) can be:

- ***Amorphous, i.e. randomly arranged, twisted, coiled and bundled.*** The polymers are more elastic and can give materials with good impact resistance, but low resistance to wear (Sastri, 2010) and loading. There is more space between the polymer chains (free volume) than in semi-crystalline polymers (Teegarden, 2004). This leads to a lower chemical resistance, as the polymer structure is more permeable to chemicals and solvents (Sastri, 2010). Examples of amorphous polymers include polystyrene, PVC, polycarbonate, acrylic, ABS, and low-density polyethylene (Sastri, 2010). Most thermosetting polymers, including elastomers, are amorphous.

- ***Semi-crystalline, i.e. more organised and tightly packed***. The polymers are less elastic and can give a strong, material with good resistance to loading and wear. The polymer chains contain both crystalline and amorphous parts. As there are fewer amorphous parts, which are permeable to chemicals and solvents, and the crystalline parts are more tightly packed, the chemical resistance is higher than for amorphous polymers (Sastri, 2010). Examples of semi-crystalline polymers include high-density polyethylene, polypropene, and polyesters (Sastri, 2010).

4.2. Material types in microplastics from road traffic

The different sources of microplastics from road traffic contain the following materials, which may be included in the plastic material group:

- Tyre tread – contains elastomers (rubber) of thermoset polymer type.
- Road markings – contain either thermoplastics or thermosets, and may contain some elastomers.
- Polymer modified bitumen – contains either thermoplastic, thermoplastic elastomers, or thermoset polymers.

The shape and elasticity of the tyre wear and road marking particles vary significantly. Kreider et al, (2010) have shown that tyre wear particles have an elongated shape and contain elements of small mineral particles from the road. Other studies (e.g. Hassellöv et al, 2018; Karlsson et al, 2019) have indicated that particles also may be angular fragments of irregular shape. They are also more elastic than the road marking particles, which are harder and may have jagged and sharper edges. Road marking particles with glass beads and broken edges have been identified in sediments from tributaries to the River Thames (Horton et al, 2017a). The differences in shape and elasticity could potentially result in different types of effects on organisms ingesting the particles. There are also differences in the densities of individual plastic and rubber materials. These influence e.g. where in the environment different microplastic particles end up, and therefore also the types of organisms that may be exposed to them. See also section 2.2.1.

4.3. Physical and chemical characterisation of tyre and road wear particles and tyre crumb rubber

Physical and chemical characterisation of different tyre and road wear particles has been performed by Kreider et al, (2010) on:

- tyre and road wear particles collected during outdoor driving, using a suction system with a collecting device mounted on the wheel hub close to the tyre (field-generated)
- tyre and road wear particles collected from a road simulator (i.e. a simulated roadway in a laboratory) (laboratory-generated), see section 6.2
- tyre tread particles from unused tyres that were frozen (cryogenically) and ground.

The results indicate that the tyre and road wear particles generated in the field and by the road simulator have a higher content of metals and other elements that are associated with the road surface and other traffic-related sources (e.g. fuel, brakes, road and atmospheric deposition) than the tyre tread particles (Kreider et al, 2010). The concentrations of PAH in the field-generated tyre and road wear particles were 19 times higher than in the tyre tread particles, and 24 times higher than in the laboratory-generated tyre and road wear particles (Kreider et al, 2010). This illustrates the importance of taking into account the way in which the tested particles were generated when conclusions are drawn from laboratory tests.

In the last few years, the number of studies on tyre crumb rubber used in artificial turf fields has increased, due to concerns about both their health effects and their contribution to the spread of microplastics in the environment. These will not be reviewed here, however, short descriptions of a couple of the studies particularly relevant to the studies of microplastics from tyre and road wear have been included.

The United States Environmental Protection Agency (US EPA) has as part of 'the Federal Research Action Plan on Recycled Tire Crumb Used on Playing Fields and Playgrounds' published a final report (part 1) on tyre crumb rubber characterisation (US EPA, 2019). The second part of the research action plan (not yet published) will look at potential exposure to humans to chemicals included in tyre crumb rubber when using artificial turf fields (US EPA, 2019).

Part 1 includes a comprehensive characterisation of tyre crumb rubber from nine tyre recycling facilities, as well as tyre crumb rubber infill from 25 outdoor and 15 indoor artificial turf fields in the United States. The findings provide information on the types of chemicals associated with recycled tyre crumb rubber (content and type), concentrations and variations, and the release of selected chemicals to air and to artificial, simulated biological fluids.

A large number of chemicals were found to be present in the tyre crumb rubber, including several metals (chromium, cobalt, lead, zinc, barium, copper, iron, molybdenum, rubidium, and strontium), PAHs (pyrene was the most common), phthalates (e.g. DEHP and dibutyl phthalate), and many other tyre-related chemicals (including benzothiazoles, 4-tert-octylphenol, and cyclohexylamine compounds) (US EPA, 2019). In total, 355 chemical substances were identified as potentially associated with recycled tyre crumb rubber. Based on data from previous studies of tyre crumb rubber, information on potential ingredients in tyre manufacturing, and analysis possibilities, 95 of these substances where selected for chemical characterisation and concentration assessments. The analysis results showed that the majority of the 95 substances selected for chemical analysis were present at levels above the detection limit in most of the tyre crumb rubber samples. The analyses also identified the presence of many additional chemicals, whose chemical identity was determined, although very tentatively. In general, concentrations of many organic substances seemed to decrease with increasing age of the artificial turf field. In line with this, the highest concentrations were found in samples from recycling facilities, and the lowest were found in samples from outdoor artificial turf fields (US EPA, 2019). These results indicate that organic substances from tyre crumb rubber are released into the environment through evaporation and leaching (including leaching due to rainfall or irrigation) (US EPA, 2019).

The bioavailability tests covered only release of metals from tyre crumb rubber to artificial biological fluids. The average migration rate for all metals into the tested fluids was approximately 3 percent for gastric fluid, and less than 1 percent for saliva and sweat plus sebum, respectively (US EPA, 2019).

The Dutch National Institute for Public Health and the Environment (RIVM) has also carried out a comprehensive study on chemicals in tyre crumb rubber infill materials, from a health perspective, looking at 100 artificial turf fields (RIVM, 2017). This study included both analyses of the targeted harmful substances (PAHs, phthalates, bisphenol A, benzothiazole, phenols, PCB, and metals) in infill materials from tyres, and migration studies on artificial sweat (pH 4.5), saliva, and gastric fluid (pH 6.5; 3.0; 1.8), as well as an evaporation test (60 °C). These analyses were used to assess the extent to which these chemicals are able to enter the human body through the skin, gastrointestinal tract, and lungs. The chemical analyses showed that tyre crumb rubber contains several PAHs, metals, phthalates, benzothiazoles, and phenols, and some samples also contained low concentrations of PCB.

Metal analyses on leachates from tyre crumb rubber infill materials in water (pH 7) showed that zinc was released in all samples, but also that copper and cobalt were released in most samples.

The migration tests showed that the substances were released in very low concentrations. Based on exposure calculations, it was concluded that the health effects of exposure during sporting activities are practically negligible (RIVM, 2017). Effects on, or risks to, the environment were not studied.

4.4. Toxicological data on chemicals in tyres

To increase our understanding of potentially problematic substances in tyre wear particles, toxicological information can be compiled for chemical substances that are known or suspected to be present in tyres. Of the total of 355 chemicals identified in the study from the US EPA (2019), approximately half (167) had one or more guideline or limit values for toxicity (i.e. values put in place to protect human health or the environment). Of the 95 substances selected for chemical characterisation (see section 4.3) 82 percent had guideline or limit values. It should be noted that guideline and limit values are lacking for many substances due to insufficient data.

Perkins et al (2019) identified a similar number (306) of potential chemicals in infill materials from tyres used in artificial turf. Of these, 52 were classified as known, probable, or suspected carcinogenic substances by the European Chemicals Agency (ECHA) or US EPA.

4.5. Chemical composition of the tyre tread

A tyre is made up of several layers. A tyre for a passenger car contains on average up to 25 components (mostly different types of reinforcement components, e.g. steel cords and different textiles), and the rubber part may contain 12 different types of rubber and chemical additives (Continental, 2019). There are many chemical additives to choose from.

According to Continental (2019), their most popular summer tyre has the following composition (in weight percent):

- rubber (natural and synthetic) 41%
- fillers (carbon black, silicon dioxide, carbon, chalk, etc.) 30%
- reinforcement materials (steel, polyester, rayon, nylon) for the casing and cord 15%
- plasticisers (oils and resins) 6%
- chemicals for vulcanisation (sulphur, zinc oxide, etc.) 6%
- anti-aging agents and other chemicals 2%.

The tyre tread is the rubber portion of the tyre that provides grip and traction on the road. It is from this part of the tyre that tyre wear particles (i.e. rubber particles) are generated during driving. The chemical composition of the tyre tread varies both between different tyres and between different types of tyres. As an example, the proportion of synthetic rubber is higher than the proportion of natural rubber in tyres for passenger cars, while the opposite is true for truck tyres, which also require less amounts of additives (U.S. Tire Manufacturer Association, 2019).

The tyre tread consists of a mix of natural rubber and synthetic rubber polymers, fillers, and different chemical additives, such as vulcanisation agents, activators, vulcanisation inhibitors, anti-degradation and anti-aging agents (antioxidants and antiozonants), peptizers, plasticisers, and processing aids, see Table 2 below. Several of the chemical additives are hazardous for human health and the environment.

Table 2. Examples of tyre tread constituents and their function, and of chemicals they contain. (Sources: Banerjee, 2019; Fisher, 2010; U.S. Tire Manufacturer Association, 2019; Continental, 2019; Hexion, 2019; Novotrade Invest AS, 2019; Akrochem, 2019; Princi, 2019. These sources do not specify the type of tyre that the information relates to, as e.g. tyres for passenger cars or heavy vehicles.)

Constituent	Function	Examples of chemicals
Natural rubber	Main components providing elastic properties, which give comfort, traction and friction	Polyisoprene
Synthetic rubber polymers		Butadiene rubber and styrene butadiene rubber are the most common.
Fillers	Strengthen the rubber, i.e. improve tensile strength and prevent tear and abrasion	Carbon black and silicon dioxide, precipitated calcium carbonate (PCC), calcium and aluminium silicates, clays, resins
Vulcanisation agents	Transform the rubber into a solid product through vulcanisation (i.e. curing of the rubber) by crosslinking the polymer chains	Sulphur
Activators	Activate the curing during vulcanisation	Zinc oxide and stearic acid, resins
Accelerators	Speed up the vulcanisation	E.g. sulfenamides (N-cyclohexyl-2-benzothiazolesulfenamide, CBS)
Inhibitors (pre-vulcanisation inhibitors)	Inhibit premature vulcanisation	E.g. nitrosodiphenylamine, salicylic acid, benzoic acids.
Antioxidants	Prevent the rubber from degrading due to temperature or oxygen	E.g. trimethylquinoline (TMQ), amines, phenols, quinoline, phosphites
Antiozonants	Prevent degradation caused by ozone exposure	Mono-crystalline waxes and chemical antiozonants, e.g. P-phenylenediamines (DPPD), alkyl-aryl-p- phenylenediamines (PPDA)
Peptizers	Accelerate the mastication process (i.e. when the viscosity is reduced to aid mixing)	E.g. zinc salt of pentachlorophenol
Plasticisers	Function as softening agents and processing aids by reducing the viscosity during processing	E.g. aromatic petroleum process oils (containing PAH), MES oil (Mild Extracted Solvate Oil), rape seed oil, resins
Other processing aids	Aid mixing and processing (e.g. dispersing agents)	E.g. rosin (resin from coniferous trees), synthetic resins, process oils, pine tar and plasticisers, fatty acids, esters of fatty acids, fatty acid metal soap, resins with low molecular weight

Many chemical additives tend to migrate through the rubber material (Anthoine et al, 2005) and may therefore be released into the environment. The migration rate depends on factors such as the type of additive, its solubility and ability to react with other ingredients in the rubber, as well as ambient conditions (Anthoine et al, 2005).

In addition to intentionally added chemicals (polymers, monomers and additives), other substances may also be present in rubber tyres. These include impurities that may be present in the rubber polymers and additives, as well as substances that may form during the manufacture or degradation of tyres.

Since 1 January 2010, the PAH concentration in extender oils (e.g. HA oils) used in the manufacturing of new car tyres and tread for new and re-treaded tyres, has been restricted by EU directive 2005/69/EU, which was later slightly amended in the European Commission Regulation (EU) No. 1272/2013. The limit values for tyres and tyre tread are 1 mg/kg for Benzo[a]pyrene (BaP) and 10 mg/kg for the sum of eight listed PAHs.

4.6. Chemical composition of road marking products

Road marking products are used on the roads to regulate, warn, and guide traffic. They consist of plastic polymers, pigments, fillers, and additives. Glass beads are also commonly added to give the material reflective properties. There are several different types of road marking products:

- thermoplastic systems (hot applied or prefabricated)
- water-based paints
- solvent-based paints
- 2-component systems
- road marking tape.

Table 3 shows the chemical compositions of different road marking products, which are also described in more detail in the following sections.

Table 3. Chemical compositions of different types of road marking products. (Sources: Babić et al, 2015; 3M, 2019; the Scandinavian Road Marking Association, personal communication, autumn 2019; BEC Materials, 2019.)

Type of road marking product	**Composition** [1)]
Thermoplastic systems	Binding agents: e.g. pentaerythritol rosin ester, C5-hydrocarbon resin, or a mix of these. Some markets also use a proportion of EVA (ethylene vinyl acetate copolymer), or styrene block copolymers
Water-based paints	Binding agent: thermoplastic acrylic resins
Solvent-based paints	Binding agent: mainly thermoplastic acrylic reins, but styrene acrylic mixes are also used Solvents: e.g. esters or ketones, aromatic solvents are still permitted in some countries
2-component systems	*Acrylic systems:* Binding agent: thermosetting acrylic resins (e.g. methyl methacrylate, MMA) Curing agents: e.g. dibenzoyl peroxide (BPO) Solvents *Epoxy systems:* Binding agent: Epoxy resins (a reaction product of bisphenol A and epichlorohydrin is the most commonly used resin) Curing agents: e.g. amines Solvents
Road marking tape	Binding agents: polyurethane and flexible polymer Adhesive To add reflective properties, either glass beads or micro-crystalline ceramic beads are used

[1)] Pigments, fillers, and additives are present in all road marking products. Glass beads are included to provide reflective properties.

4.6.1. Thermoplastic systems

Thermoplastic systems consist of a binding agent of thermoplastic polymers, which is mixed with pigment, filler, glass beads, and additives (Babić et al, 2015; Chu, 2019). The thermoplastic polymers can be either hydrocarbon resins (usually C5 aliphatic hydrocarbon resin) or alkyd resins (such as pentaerythritol rosin ester or maleic acid-modified rosin esters) (Babić et al, 2015) or a mix of these. In some countries (e.g. colder climates) ethylene vinyl acetate copolymer (EVA) is also included as one part of the thermoplastic binding agent (the Scandinavian Road Marking Association, personal communication, autumn 2019) or, alternatively, styrene block copolymers (BEC Materials, 2019), to make the material more elastic.

Hot-applied thermoplastic road marking compound is a solid product (powder mixture) that melts when heated (Geveko Markings, 2019a). Before application on the road, the compound is heated to 200 °C, then applied at a thickness of between 2 and 4 mm (Vägmarkeringar AB, 2019) or sprayed onto the road in thinner layers (Swedish Transport Administration, 2005). Preformed or prefabricated thermoplastic road markings are pre-cut signs and symbols (thickness ca 3 mm) applied with a brush and heat torch (Geveko Markings, 2019b; Vägmarkeringar AB, 2019).

Below are some examples of a typical thermoplastic ‘road marking recipe’ (Chu, 2019):

- 16.5% binding agent (pentaerythritol rosin ester, C5-hydrocarbon resin, or a mixture of these)
- 10% pigment (titanium dioxide)
- 49.5% filler (e.g. 22% calcium carbonate and 27.5% quartz sand)
- 4% additives (2% phthalate plasticisers (DOP), 1% PE wax, 1% hydrogenated castor oil)
- 20% glass beads

In Sweden, the binding agents in thermoplastic road markings usually consist of a mixture of EVA and either pentaerythritol rosin ester or C5-hydrocarbon resin. EVA makes up 1–5 percent of the total road marking compound, and is added to improve wear resistance and prevent crack formation, which can be caused by cold climate, studded tyres, and snow clearing. The proportion of glass beads in thermoplastic road marking compounds used in Sweden is approximately 40 percent, which is higher than in the example recipe above. The difference in glass content replaces the corresponding amount of filler. In addition to the glass beads included in the compound, glass beads are also applied on the surface of the paint, after painting. Titanium dioxide is used as pigment for white markings. For yellow markings, an organic pigment is used, and not lead chromate which is used in some countries. Phthalates are not used as plasticisers in road markings in Sweden, instead, mineral oils or plant-based plasticisers are used. The above information about the content of thermoplastic road marking compounds used in Sweden was obtained by personal communication with the Scandinavian Road Marking Association (autumn 2019). Figure 2 shows a close-up and cross-section of a thermoplastic road marking.

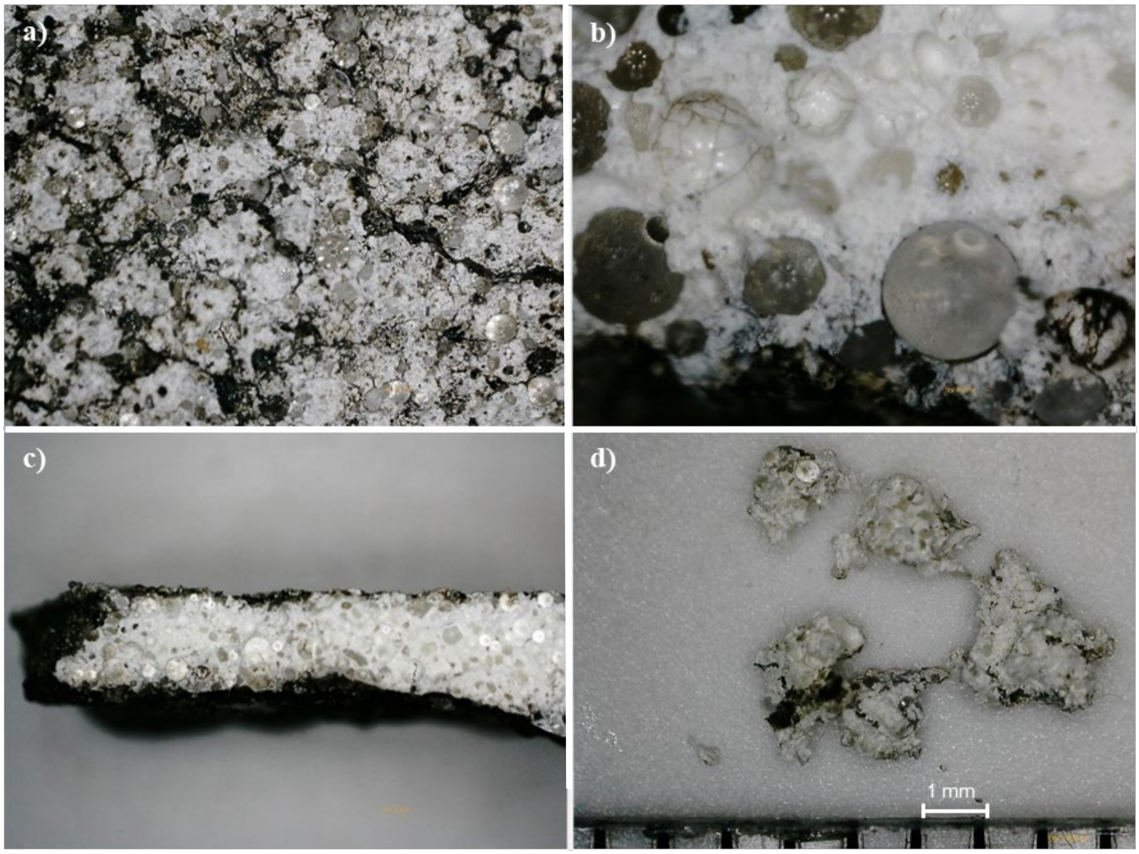

Figure 2. Thermoplastic road marking. a) top; b) top, zoomed in on glass beads; c) cross-section of an approximately 2 mm thick road marking fragment; d) 1–2 mm road marking fragments from above. Photo: Algot Lithner, 2019.

4.6.2. Water-based paints

The resin used in water-based road marking paints is typically a thermoplastic acrylic resin in a water-based emulsion (Babić et al, 2015). The content of volatile organic compounds is usually less than two percent and come from the necessary chemical additives (Babić et al, 2015). Pigments and fillers are also included (Babić et al, 2015). The paint is applied at a thickness of between 0.4 and 0.6 mm, using a high-pressure machine (Vägmarkeringar AB, 2019).

4.6.3. Solvent-based paints

In solvent-based road marking paints, the resin (binding agent) is dissolved in an organic solvent (e.g. esters or ketones; in some countries aromatic solvents are still permitted) (Babić et al, 2015). The binding agent is usually a thermoplastic acrylic resin (Babić et al, 2015), although e.g. styrene-acrylic resins are also used.

4.6.4. 2-component systems – cold plastic

Two-component systems consist of two or more components (a thermosetting resin and a curing agent), which when mixed form a thermoset. There are different types of 2-component systems, also called cold plastic or cold-applied plastic. They are usually either acrylic-based or epoxy-based.

Acrylic-based systems use different acrylates, e.g. mono and multifunctional esters of methyl methacrylate resin (MMA resin) (Babić et al, 2015; Chu, 2019). The acrylates are mixed with filler, pigment and anti-skid material, and to activate polymerisation a curing agent, e.g. dibenzoyl peroxide (BPO), in a solvent or compound is added (Babić et al, 2015; Chu, 2019).

In epoxy-based systems, one component contains the dissolved epoxy resin, solvent, pigment, and additives, and the other contains the curing agent (Babić et al, 2015), e.g. an amine. Newer systems with multifunctional modified epoxy resins are also available (Babić et al, 2015).

4.6.5. Road marking tape

Road marking tape is available either as a permanent tape with a pressure-sensitive adhesive system, or in the form of a temporary, removable tape (Grand View Research, 2019a). Permanent, prefabricated tape has glass beads or microcrystalline ceramic beads embedded in the surface (Lopez, 2004; 3M, 2019). Common binding agents in permanent road marking tape include polyurethane in combination with a flexible polymer (e.g. rubber) (Lopez, 2004; 3M, 2019).

Temporary road marking tapes are used for short-term applications, e.g. during road works. They are thin and consist of a metal foil backing, coated with a self-bonding adhesive on the underside and a pigmented binding agent with glass beads on the upper surface (Lopez, 2004).

4.6.6. Use of road marking products in Sweden and globally

Globally, road marking paints constitute the largest product category, with prefabricated road marking tape and thermoplastic systems in joint second place (Grand View Research, 2019b). Thermoplastic systems are the fastest growing product segment globally (Grand View Research, 2019b). Epoxy-based two-component systems also account for a fairly large proportion globally, around 15% (Grand View Research, 2019b), but are less common in Europe (Babić et al, 2015).

The use of road marking products in Sweden differs from the global use. The data presented below on the use of different road marking products in Sweden has been obtained through personal contact with the Scandinavian Road Marking Association (autumn 2019).

In Sweden, the use of road marking products is dominated by thermoplastic road marking compounds, in particular hot-applied thermoplastic. The second most used product type is water-based road marking paint. There is also very limited use of 2-component systems, for example used for bus and cycle lanes with coloured surfaces (in some locations in the larger cities). Solvent-based road marking paints are hardly used at all, only in exceptional cases when for example weather conditions prevent the paint from drying. Prefabricated tape markings are also rarely used. Prefabricated thermoplastic products, i.e. pre-cut signs and symbols such as symbols for cyclists and pedestrians, are used in cases where signs or symbols on the road surface are required.

The global demand for road marking products exceeded 1.2 million tonnes in 2014 and is expected to reach 1.8 million tonnes by 2022 according to Grand View Research (2016a). A rough estimate of the annual consumption of road marking products in Sweden is approximately 15,000 tonnes for national roads, i.e. excluding roads that belong to municipalities or are private (the Scandinavian Road Marking Association, personal communication, autumn 2019). The national roads constitute approximately two thirds of all public roads where road markings are used, however, as national roads often have multiple lanes, and therefore require more road markings per kilometre, it is not possible to use these figures to estimate the total use of road marking products on all roads in Sweden. Data shows that over 750 tonnes of road marking products are used in the Stockholm municipality each year (City of Stockholm, 2019) and the annual use of road marking products in the Gothenburg municipality has been estimated to 150 tonnes (NCC, personal communication, 2019-09-19).

Around 10–20 percent of all national roads are repainted every year (the Scandinavian Road Marking Association, personal communication, autumn 2019). The lifespan (durability) of road markings depend on many factors, such as road marking product, type of road, annual average daily traffic, studded tyre-usage, snow clearing, and climate. In a comparison of different types of road markings by Babić et al, (2015), the average durability was ranked as follows:

- Road marking tape – superior durability.
- Two-component systems – high durability (up to 5 years on major roads).
- Water-based paints – high durability. Other sources instead claim that the durability is low. According to e.g. Chu et al, (2018) water-based paints have a short lifespan of around 6–12 months, except in the case of newer acrylic paints which may have longer lifespans.
- Thermoplastic systems – average durability, but relatively constant retro-reflectivity (2–4 years on heavily used motorways).
- Solvent-based paints – low to very low durability (6–12 months).

Very hard materials are less durable in cold climates due to the use of studded tyres and snowploughs (the Scandinavian Road Marking Association, personal communication, autumn 2019). Particularly hard road marking materials include epoxy (which is a 2-component system). According to the Scandinavian Road Marking Association, neither road marking tape nor water-based paints are particularly durable in Sweden, because of studded tyres and snow ploughing.

4.6.7. Some hazardous substances in road marking products

Some of the binding agents, additives, pigments, and solvents used in road marking products have inherent properties that make them hazardous to human health and the environment. The binding agents posing the greatest danger to health and the environment include polyurethane and epoxy resins, and their curing agents. Historically, lead chromate was used as the pigment for yellow road markings, and it is still used in several countries. On 7 February 2019, the European Court of Justice decided that the decision by the European Commission to allow a company to sell pigment containing lead chromate for use in paints within the EU was unlawful (Swedish Chemicals Agency, 2019). The most commonly used pigment for white road markings is titanium dioxide, and sometimes zinc oxide or sulphide, and barium sulphate are used. Some particularly dangerous aromatic solvents are still used in solvent-based paint in certain countries. Glass beads (usually made from waste glass) can contain elevated levels of lead, arsenic, and antimony, as shown in analyses by dos Santos et al (2013).

The fillers, which usually consist of calcium magnesium carbonate (dolomite) or calcium carbonate (calcite) and sand (e.g. quartz sand) (Chu, 2019) are not chemically hazardous.

4.7. Chemical composition of bitumen, polymer modified bitumen, and plastic roads

In asphalt, bitumen is the binding agent most commonly used to bind the aggregate, e.g. crushed rock (stone material), sand, gravel, or slag (EAPA, 2019). The amount of bitumen typically used in asphalt in Europe is approximately 5% by weight (EAPA, 2019). This is in line with Swedish data, according to which the proportion is around 5–6% by weight, which corresponds to around 10% by volume (VTI, 2019).

4.7.1. Bitumen

Bitumen is a thermoplastic dark brown to black, solid or viscous liquid at room temperature, which is produced by distillation of crude oil, but which also occurs in natural deposits (WHO, 2005; Asphalt Institute & Eurobitume, 2015). Bitumen is a very complex mixture of hydrocarbons and contains a large number of chemical compounds with a high, but varying, molecular weight (Asphalt Institute & Eurobitume, 2015). The molecules in bitumen are different combinations of alkanes, cycloalkanes, aromatics, and heteronuclear molecules containing sulphur, oxygen, nitrogen, and metals (including e.g. nickel, vanadium, and iron) (Asphalt Institute & Eurobitume, 2015). As the chemical composition of bitumen depends on both the composition of the crude oil and the manufacturing process, no bitumen[5] has identical chemical composition (WHO, 2005; Porto et al, 2019; Honarmand et al, 2019).

The hydrocarbon compounds in bitumen are usually divided into the following categories:

- Asphaltenes (5–25%) – hard, solid, black to brown compounds that are often highly polar, highly aromatic, and complex (tar-like materials with high molecular weight).
- Polar aromatics (resins) – solid to semi-solid dark brown compounds which provide adhesive properties (molecular mass 500–50,000 g/mol).
- Aromatic oils (40–60%) – viscous, dark brown liquid (molecular mass 300–2,000 g/mol).
- Saturated hydrocarbons (paraffins) (5–20%) – often non-polar, colour-less, viscous oils of aliphatic hydrocarbons with alkylnaphtalenes and aromatic alkyls (Honarmand et al, 2019).

Bitumen is insoluble in water at 20 °C (WHO, 2005) and a viscoelastic material, for which pressure or temperature influence the viscosity and elasticity of the material (Honarmand et al, 2019). At a high temperature or when subjected to high pressure (e.g. slow-moving or stationary traffic), bitumen becomes more viscous, whereas it becomes more elastic at lower temperatures, or lower pressure (e.g. faster moving traffic) (Honarmand et al, 2019). At low temperatures, cracks may form (Honarmand et al, 2019). Curing of bitumen in asphalt takes place both during heating, as the bitumen is mixed with aggregate (e.g. rock), and slowly throughout the lifetime of the asphalt (Honarmand et al, 2019).

Bitumen is not classified as an environmental or health hazard according to the EU classification and labelling system. However, according to the European Chemical Agency's (ECHA's) registration dossier, the toxicological and ecotoxicological endpoints were only estimated using a computer model (PETROTOX). Other agencies, including the IARC (2013), WHO (2005) and the Japanese Ministry of Health, Labour and Welfare (MHLW)/Ministry of the Environment (MOE) (2014) have deemed that health effects probably occur as a result of occupational exposure during asphalting. The IARC (2013) has classified bitumen as potentially carcinogenic to humans (group 2B) after occupational exposure

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[5] The CAS number for bitumen is 8052-42-4, but 'Residues (petroleum) vacuum' (CAS no 64741-56-6) and 'Asphalt, oxidised' (CAS no 64742-93-4) are also used for bitumen production (Asphalt Institute & Eurobitume, 2015).

during mastic asphalt work and paving , and the Japanese MHLW/MOE (2014) has given bitumen the following health hazard classifications according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS):

- Causes serious eye irritation (H319[6])
- Suspected of causing genetic defects (H341).
- Suspected of causing cancer (H351)
- May cause respiratory irritation (H335)
- Causes damage to organs through prolonged or repeated exposure (H372).

4.7.2. Polymer modified bitumen

Since the late 1980s, some of the bitumen used in asphalt has been modified with polymers (Zhu et al, 2014) to increase the durability of the asphalt (Honarmand et al, 2019). The polymer content in polymer modified bitumen constitutes between 3 and 10 percent of the weight of the bitumen (Porto et al, 2019). Styrene butadiene styrene polymer (SBS) typically makes up around 3.5% by weight in the final bitumen product (Zhu et al, 2014). The most commonly used polymers in polymer modified bitumen are shown in Table 4.

Table 4. The most commonly used polymers in polymer modified bitumen (Porto et al, 2019).

Polymer type	**Polymer category**
Polyethylene (PE) Polypropene (PP) Ethylene vinyl acetate (EVA) Polyvinyl chloride (PVC) Ethylene butyl acrylate (EBA) Recycled thermoplastic (PE, PP, PVC)[1)]	Thermoplastics
Styrene butadiene styrene block copolymer (SBS) Styrene isoprene styrene block copolymer (SIS)	Thermoplastic elastomers
Epoxy resin Polyurethane resin Acrylic resin Phenolic resin	Thermosets
Styrene butadiene rubber (SBR) Natural rubber Polydiolefins Recycled tyre rubber	Elastomers (e.g. natural and synthetic rubber) of thermosetting type

1) Sasidharan et al, 2019.

Polymers can be added at different stages before or during the production of asphalt. When polymers are added to a bitumen product, the result is a polymer modified bitumen product which can later be

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[6] Hazard code used in the Globally Harmonized System for Classification and Labelling of Chemicals (GHS).

mixed with the aggregates (of e.g. stone) when making asphalt. Polymers can also be added to heated aggregates before the bitumen is added (Sasidharan et al, 2019), or directly into the mixer with the warm asphalt containing stone materials and bitumen, and the products are then known as polymer modified asphalt (PEAB, 2019). In each case, the bitumen part of the asphalt is modified, and in this report all cases are covered by the term ‘polymer modified bitumen’. During tyre and road wear, polymer modified bitumen becomes a source of microplastics.

4.7.3. Use of polymer modified bitumen

The global demand for polymer modified bitumen products was 9.89 million tonnes in 2014, of which 73.5 percent (i.e. 7.27 million tonnes) was used for road construction (Grand View Research, 2016b). In Sweden, polymer modified bitumen has been used since the mid-1990s, mainly on high-traffic roads (Björn Kalman, VTI, 2019-09-03, personal communication).

The most commonly used polymer in polymer modified bitumen in Sweden is styrene butadiene styrene (SBS) (Björn Kalman, VTI, 2019-09-03, personal communication). Globally, thermoplastic elastomers, and SBS in particular, also dominate (Pyshyev et al, 2016), although there are some differences between different countries. Its use is limited, however, mainly due to the high costs involved (Pyshyev et al, 2016).

India instead uses waste plastic (recycled plastic) mixed with bitumen and stone aggregates. This is seen as a way to both utilise waste plastic and reduce construction costs. The first road with recycled plastic was built in 2002, in Chennai in India, and more than 2,500 km of roads containing waste plastic has since been constructed in India (Sasidharan et al, 2019). Shredded waste plastic is usually mixed with the hot aggregates of stone first, after which bitumen is mixed in (Sasidharan et al, 2019). There are also instances where powdered recycled plastic is first mixed with hot bitumen, and then mixed with the aggregates (Sasidharan et al, 2019). According to news media (e.g. The Guardian 2019), the Indian government, in 2015, made it mandatory for all road developers in the country to use plastic waste for road construction in urban areas with more than 500,000 people. Other countries that have used recycled plastic in asphalt at a smaller scale include Great Britain, the United States, Australia, and South Africa (Sasidharan et al, 2019).

4.7.4. Plastic roads – a future source or sink for microplastics?

In the Netherlands, two pilot projects are currently evaluating plastic cycleways made from recycled polypropylene (PlasticRoad, 2019). The PlasticRoad concept consists of a prefabricated road structure based on hollow modules made of recycled plastic, and is designed to replace traditional cycle lane materials. If this is scaled up to roads for cars and trucks, which is a future aim, it could become a new source of microplastics. However, according to the PlasticRoad website the road has a coating that prevents contact between the plastic and vehicle tyres, blocking the release of microplastics from the road material.

4.8. Conclusions

- Tyres and road markings consist of polymers, different chemical additives, and fillers.
- The polymers in tyres are elastomers, which are thermoset polymers. The polymers in road markings and polymer modified bitumen can be thermoplastics, thermosets, thermoplastic elastomers, or elastomers.
- There are many different types of road marking products, and different types of polymers are used to modify bitumen. Sweden uses mainly thermoplastic compounds for road markings, and the thermoplastic elastomer styrene butadiene styrene (SBS) for polymer modified bitumen.

- The above means that the physical and chemical properties, as well as the chemical composition of microplastics from tyres, road markings, and bitumen may vary greatly, which may in turn affect their behaviour in the environment.
- Some of the chemicals used in the manufacture of tyres, road marking products, and polymer modified bitumen are hazardous to human health and the environment, however, there is currently very limited, or in some cases no, knowledge about the extent to which these substances are released from microplastics.

5. Tyre and road wear

This chapter describes the factors that influence the wear of tyres and the road surface, and how the wear can be calculated.

5.1. Factors that affect tyre wear

Different types of tyres wear at different rates and cause different amounts of wear on the road surface. Parameters that affect tyre wear include the chemical composition and pattern of the tyre tread, which vary depending on whether the tyre is intended for use in winter or summer conditions. Tyre manufacturers also use customised compositions to optimise the characteristics of tyres within each category. Winter tyres are made of a softer rubber mixture than summer tyres, to ensure they remain sufficiently soft at low temperatures. Summer tyres are made of a harder mixture, to prevent them from becoming too soft at higher temperatures. In addition to the composition and temperature, factors such as tyre dimension, load, tyre pressure, wheel alignment (toe-in/toe-out, camber), vehicle speed, driving behaviour, and the characteristics of the road surface also impact the wear. If the tyre pressure is too low, internal heat generation occurs, which increases the wear (Li et al, 2011). Higher pressure gives lower wear in modelling (e.g. Salminen, 2014 and Mohammadi & Ngeno, 2015) and it is generally accepted that the wrong pressure reduces the lifespan of a tyre, although the reason for this is that the tyre tread wears unevenly (Figure 3), which means that the tread faster reaches depths below the permitted threshold. No actual measurements of the effects of tyre pressure on the overall wear have been found in the literature.

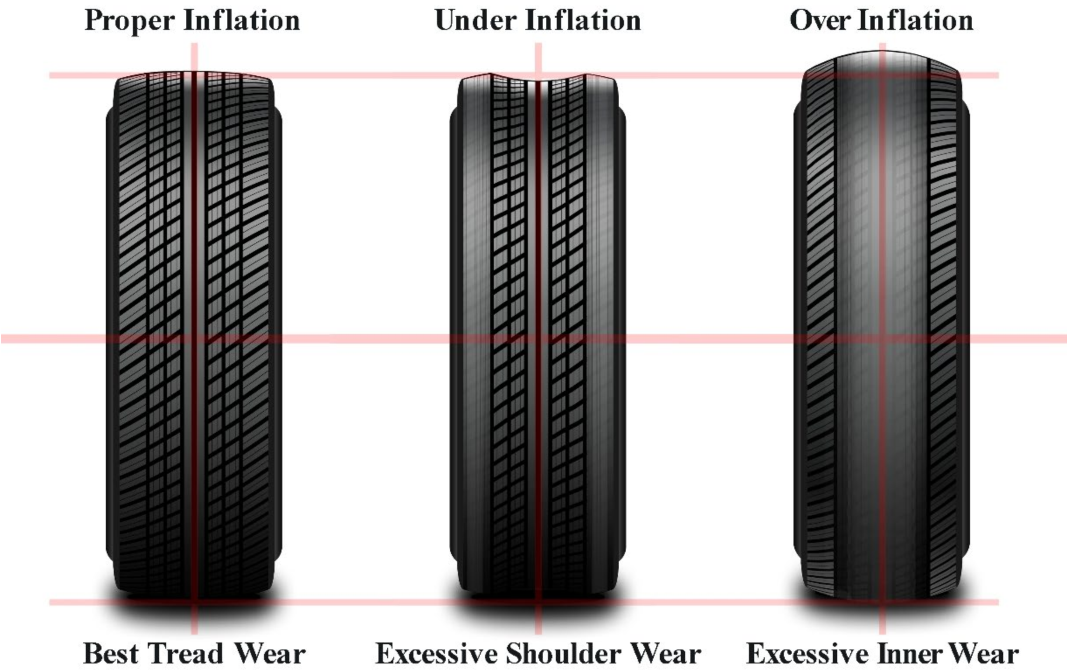

Figure 3. Impact on the wear across the tyre tread from different tyre pressures. Source: Jaco Superior Products[7].

Chen & Prathaban (2013) show in a modelling study how the wear is impacted by the load on the tyre, speed, tyre pressure, and tyre dimension. Whereas higher loads and speeds lead to increased wear, the

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[7] https://jacosuperiorproducts.com/pages/faqs-tire-pressure-gauges-inflators (accessed 2019-11-19)

wear decreases with higher air pressure, diameter, and tread width. The tread depth does not influence the wear (Figure 4).

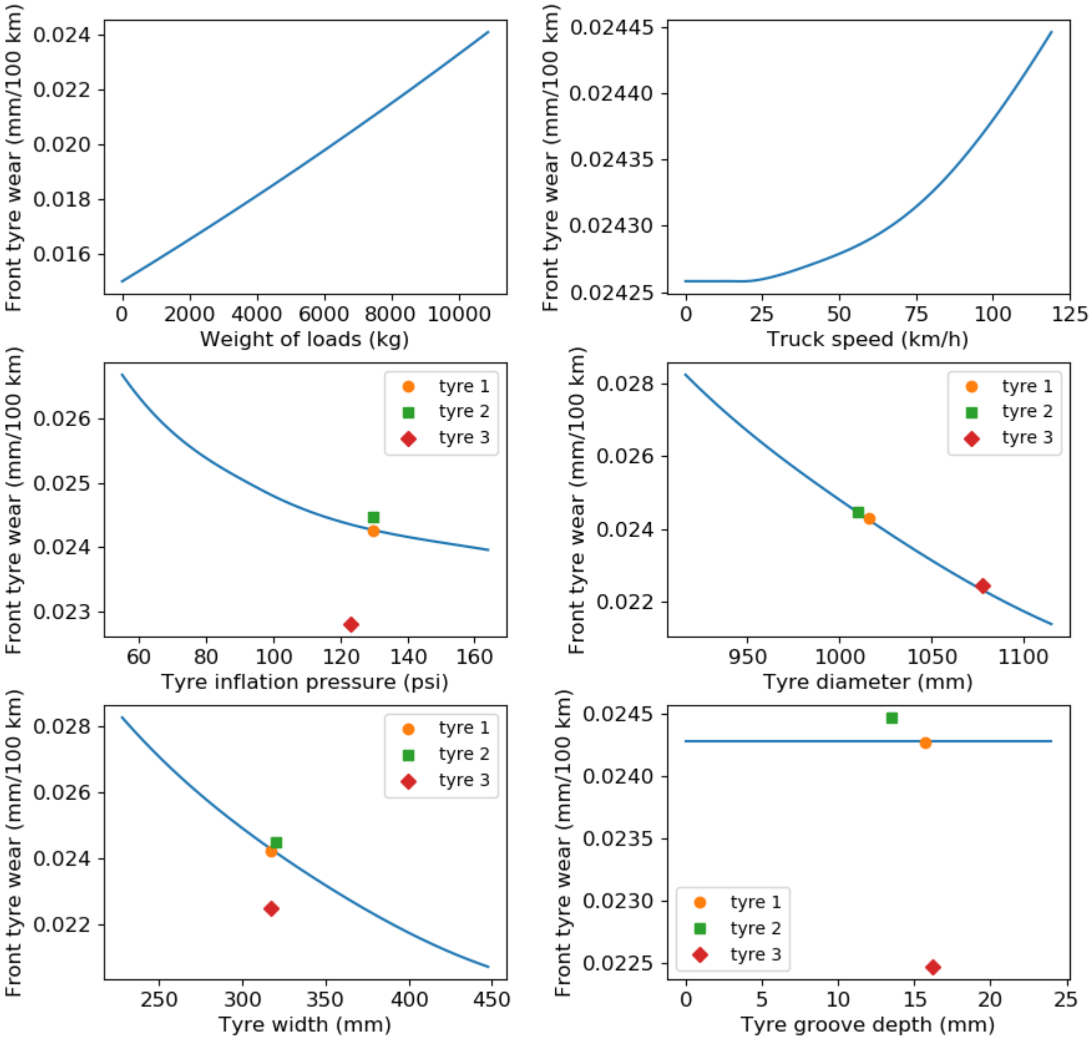

Figure 4. Examples of the impact of different parameters on modelled tyre wear for a truck (modified from Chen & Prathaban, 2013).

Drivers can influence the tyre wear by their behaviour. High speeds, fast acceleration and retardation, and high cornering speeds lead to increased tyre wear (Pohrt, 2019). This means that the design of the infrastructure and the traffic composition influence the wear by providing the conditions in which vehicles are driven. Large numbers of traffic lights and congestion can cause frequent acceleration and retardation, and a winding road requires a lot of cornering, etc.

The road surface influences the tyre wear mainly through its micro- and macrotexture[8]. Deeper microtexture leads to more tyre wear, but the microtexture is also important to the frictional resistance of the road surface, which means that the aims are conflicted. If the road surface is adapted to reduce tyre wear, this may lead to reduced friction, and thereby decreased road safety. To what extent the macrotexture affects the tyre wear is uncertain.

With regard to trends within the car fleet, the increased proportion of electric cars may have an effect on tyre wear. Electric cars are generally heavier than equivalent fossil fuel-driven cars, due to the high

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[8] Microtexture relates to the surface of the aggregate particles and binder. Macrotexture relates mainly to the shape and size of the aggregate, which can vary from 0.5 to 50 mm.

weight of the batteries (Timmers & Achten, 2016). Electric cars also have a higher torque (rotational force), which may lead to increased tyre wear. See also section 5.5.

5.2. Factors that influence the wear of bitumen and road markings

The wear of road surfaces and road markings is caused both by vehicle movements and by management measures. The wear is influenced by the characteristics of the road surface, the characteristics of the surface material, how the surface material is applied, the volume and composition of traffic, and climate (Atkins Limited, 2015). In countries where studded tyres are used, the wear of both road surfaces and road markings is higher than in countries where these tyres are not used (Laurinavičius et al, 2009). In countries with studded tyres, the proportion of vehicles using these is an important factor. In Sweden this varies from approximately 20 percent in the far south to more than 90 percent in the north. The weather also influences the wear in that many of the roads in the northern parts of the country are covered in snow and/or ice during the winter, which protects them from wear. On the other hand, frost weathering can cause them to deteriorate faster. In countries with snow and ice during the winter, roads are also ploughed to remove snow, which impacts the wear, particularly of road markings which can be severely affected by this winter management measure.

5.3. Different ways to calculate tyre wear

According to Hann et al (2018), studies carried out to calculate emissions of microplastics from tyres generally follow one of two approaches. With one approach, the calculations are based on different factors that influence tyre wear, i.e. an emission approach, in which the factors that affect the wear are combined with traffic statistics for different vehicle classes travelling on different types of roads. The other approach calculates the wear by studying qualities and quantities of sold and recycled tyres, i.e. a sales and recycling approach. This data is then complemented by weighing, to calculate the weight loss of the tyres during their entire usage period.

The wear factors for passenger cars, according to the most recent studies on tyre wear, vary between 0.85 and 0.132 g/vehicle kilometre (Kole et al, 2017; Vogelsang et al, 2019). The large variation is due to a number of factors, including the ways in which parameters and variables are managed in the models used to perform the calculations (Sherrington et al, 2016)

The weight loss of a tyre, caused by wear during its usage period, has been estimated to 10–20 percent (Atech Group, 2001; Sundt et al, 2014; Lassen et al, 2015; Magnusson et al, 2016). Tyre wear amounts calculated based on measured weight loss (Sundt et al 2014; Lassen et al 2015) show smaller variations than when the wear is estimated using wear factors. Irrespective of method used, there are still major uncertainties (Hann et al, 2018).

One example of a weight-based calculation method was used by Sundt et al (2014). In this case, a Norwegian tyre collecting and recycling company (Norsk Dekkretur) collected 52,000 tyres during 2013. Of these, around 10,000 tonnes were truck tyres. All non-truck tyres, i.e. a total of 42,000 tonnes of the collected tyres, were estimated, according to available statistical data, to have a life span of 2–4 years, and to lose 12.5 percent of their weight due to wear. According to these calculations, the original weight of the non-truck tyres amounted to 48,000 tonnes, where the difference between the calculated original weight and the collected weight, i.e. 6,000 tonnes, corresponded to the wear. For heavy vehicles, it was assumed that the tyres had been retreaded on average 2.5 times, and assuming the same weight loss percentage as for car tyres, (12.5%), the wear during the usage period of a tyre was calculated as 3,571 tonnes. Based on this, the total tyre wear in Norway was calculated to 9,571 tonnes.

5.4. The importance of the use of studded tyres

Studded tyres are used in Scandinavia, as well as in a number of other countries in northern Eurasia and North America. These tyres cause a significant increase in the wear of both asphalt and road markings. Swedish asphalt typically contains around 95 percent stone materials and 5 percent binding agent (bitumen) (Kalman et al, 2005); it is assumed that similar proportions are present in materials that have been worn away. In Sweden, just over 100,000 tonnes of asphalt are torn off by studded tyres each year, which means that approximately 5,000 tonnes of bitumen are released from the roads. Around 4 percent of all Swedish roads have a wearing course that contains polymer modified bitumen (Björn Kalman, VTI, 2019-08-25, personal communication), which means that the equivalent of around 200 tonnes of polymer-based bitumen are torn off every year. Studded tyres roughen the road surface, why non-studded tyres can be expected to wear slightly faster than would otherwise be the case. Naturally, the road surface would wear even if no studded tyres were used, however, the wear would be significantly less. In countries where studded tyres are not used, the demands on the wear resistance of the surface materials are not as high, which leads to a higher wear rate than that caused by driving on non-studded tyres in Sweden. It seems no data is available on whether studded tyres wear faster or more slowly than other tyres (Sköldén, The Scandinavian Tyre & Rim Organisation, personal communication, autumn 2019).

5.5. The importance of composition and changes to traffic and car fleet

It is obvious that traffic density affects tyre and road wear, as increased density leads to increased wear. According to the latest baseline projection from the Swedish Transport Administration, the number of passenger-kilometres in Sweden is expected to increase by around one percent per annum between 2014 and 2040, i.e. a total increase for the period of around 30 percent. The number of tonne-kilometres for goods by road is expected to increase by 1.9 percent per annum between 2012 and 2040, i.e. a total increase of 67 percent over the period (Swedish Transport Administration, 2018).

Changes to the composition of the vehicle fleet may also affect tyre wear. If vehicles become heavier, increased tyre wear is expected as a result, but also higher fuel consumption and increased emissions of different pollutants (Timmers & Achten, 2016). The trend is currently towards a passenger car fleet with a higher proportion of larger and heavier vehicles, in which e.g. the number of sport utility vehicles (SUVs) is increasing. Sales of SUVs have doubled in the last decade, and SUVs now makes up approximately 40 percent of all new cars sold on the global market (IEA, 2019). Additionally, electric cars are generally heavier than cars that run on liquid fuels or gas, as the weight of the batteries is considerable. Meanwhile, this is mitigated by the fact that electric cars do not contain heavy components like combustion engines, gear boxes or fuel tanks. Electric cars can accelerate faster than many traditional vehicles, which may lead to increased tyre wear if it means that drivers of electric cars drive less smoothly than would have been the case in a non-electric vehicle.

5.6. Conclusions

- A number of factors influence the size of the tyre wear. Some of the most important are the chemical composition of the tyre tread, the tyre dimension, load, tyre pressure, wheel alignment, vehicle speed, driving behaviour, and the characteristics of the road surface.
- The wear of road markings is influenced by traffic characteristics (e.g. type of traffic, traffic volumes, driving behaviour, use of studded tyres), maintenance and management measures (e.g. snow clearing, sanding, and sweeping), and weather conditions.
- Two approaches are available for calculating tyre wear. In one approach, the wear calculations are based on measured or estimated wear factors (g/vehicle-kilometre) in combination with data on traffic flows for different vehicles on different roads. With the second approach, calculations are based on studies of qualities and quantities of sold and

recycled tyres, combined with data on the weight loss of a tyre throughout its usage period.

- The use of studded tyres has a significant effect on the road surface wear. Studded tyres may also influence the wear of other types of tyres, as the studs roughen the road surface. We have not been able to find any data on whether studded tyres wear faster or more slowly than non-studded tyres.
- The ongoing change in the composition of the vehicle fleet (with e.g. increasing numbers of SUVs and electric cars) may contribute to an increase in tyre wear.

6. Sampling methods

This chapter provides an overview of the sampling methods used for tyre particles, and tyre and road wear particles, in different media, and of aspects that should be taken into account when this type of sampling is performed. The chapter contains information about sampling methods used throughout the chain, from the source at the interface between the vehicle and road surface, via air and water as dispersal pathways, and into different recipients. The general description of sampling methods is predominantly based on methods used for microplastics in general, and for materials usually regarded as plastics.

6.1. Three types of sampling strategies

According to Hidalgo-Ruz et al (2012), there are three types of sampling strategies used for identification and quantification of microplastic particles in the aquatic environment: selective sampling, bulk sampling, and volume-reduced sampling. Selective sampling is used for sampling of particles or materials that are visible to the eye. This method is often used in sediment studies investigating e.g. plastic pellets that are easy to identify. However, this method only provides very limited information about the total microplastic content, and whether other types of plastics are present in addition to the sought particles. It also requires the particles to be easy to identify. Bulk sampling involves sampling the entire volume collected, without reducing the sample in any way during the sampling process. This method is mainly suitable in cases where the plastic particles are too small to be visually identified, where concentrations are low, or where the particles to be analysed are hidden by other particles. Volume-reduced sampling means that the volume of the sample is reduced during the sampling process, by filtration of large water volumes, usually using a net or pump with a filter, so that only the particle fraction that is of interest for further analysis remains in the sample. This category includes for example trawling with nets in water or sieving of sediments at the time of sampling.

The concentration of tyre and road wear particles, as well as other particles in the sample, may determine the volume to be collected. A sample containing high particle concentrations does not require the same volume to be collected as for example efficiently treated wastewater. Which sampling method that is the most appropriate also depends on the medium from which the sample is to be collected. If for example volume-reduced sampling of surface water is to be carried out, flow-proportional samplers should be used. A number of different aspects need to be considered during sampling, including e.g. the depth at which the samples should be collected, where particles accumulate, the wind direction, recent precipitation, and the most appropriate time of the year for sample collection. All these different aspects must be considered to ensure the samples collected are as relevant as possible.

The selection of analytical method also influences the sample volume required, and the way in which the sampling should be carried out. For this reason, it is important to, as far as possible, decide what will be analysed before the sample is collected, as this will influence the choice of analytical method, see Figure 5. Different analytical methods are described in chapter 7. Some analytical methods result in destruction of the sample, which must also be taken into account on the sampling occasion, as multiple tests on the same sample may be desirable.

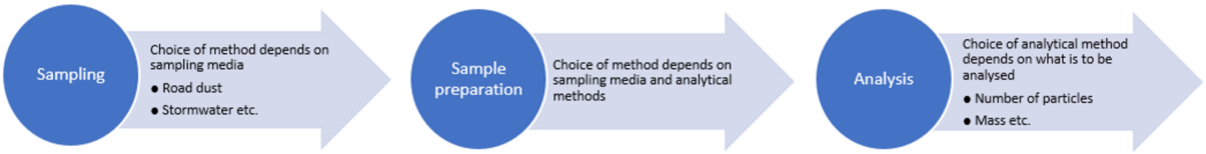

Figure 5. Examples of factors influencing the choice of methods for sampling, sample preparation, and analysis.

To avoid contamination, or at least keep it under control, blank samples are important. Blank samples may be distilled water, water that has passed a sampling system, or water stored in an open container in a laboratory. The blank samples offer an opportunity to explain why some plastics that are not expected to be present in the samples may still be found. Calibrations can be carried out by performing analysis on so called standard samples, i.e. samples containing a known amount of tyre particles or other plastic particle of interest, in parallel with analysis of samples with unknown contents.

Many sampling types lack standardised methods, and there are no standardised methods available specifically for microplastics. There is a need for standards and criteria for this to be developed.

Many assessments of concentrations and recipient loads of microplastics are based on assumptions relating to the strength of the source, and on modelling of how source specific particles, such as tyre and road wear particles, behave in different media (see chapters 2 and 4). To validate the results of the modelling, samples must be collected from different media (air, surface and stormwater, soil, sediments) at different distances from the source. In addition, sampling of microplastic particles from road traffic in different media and at different distances from the source are important to increase our knowledge about *where*, *when* and *how* microplastics from the transport sector are transported and deposited, which is vital to our ability to perform relevant toxicity studies, carry out risk assessments, and understand which measures are appropriate to reduce dissemination.

6.2. Tyres and tyre particles

A simple method for sampling materials from tyre tread is to cut pieces using a knife (Camatini et al, 2001; Sadiktsis et al, 2012). Another commonly used method is to use a file to remove material, which gives coarse tyre filings rather than whole pieces (Redondo-Hasselerharm et al, 2018). Samples are also often frozen using liquid nitrogen, after which they are ground into finer materials to be analysed for chemical composition. A common denominator for all these methods is that they do not reflect real tyre wear, i.e. they do not tell us anything about the physical characteristics of the wear particles, such as shape or size, but provide information about their chemical composition. Naturally, the metal in knives and files can contaminate the samples, but as long as the focus of the analyses is microplastics or other organic compounds, this is a minor problem.

To be able to sample more realistically, generated tyre wear particles requires sampling of wear dust either from a laboratory environment, where tyres are worn against a road surface from a real road, or under similar conditions. As an example, Korea Institute of Machinery and Materials in the Republic of Korea has a test rig where a tyre is worn against a drum covered in sandpaper. The drum is enclosed in a chamber through which purified air flows (Figure 6). Samples are collected from the air, downstream from the contact point between the tyre and the sandpaper-covered drum. At this facility, the main focus is on PM_{10} and smaller particles (Park et al, 2018).

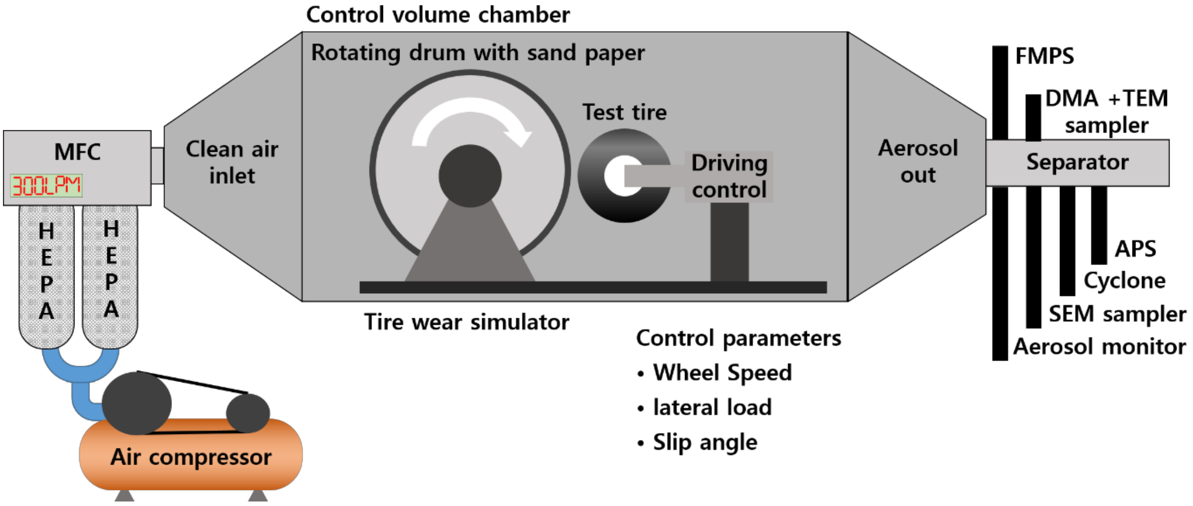

Figure 6. Schematic illustration of a simulator for tyre wear and associated equipment for emission analysis. MFC = mass flow controller, HEPA = high-efficiency particulate air filter, FMPS = fast mobility particle sizer, DMA = differential mobility analyser, TEM = transmission electron microscope, SEM = scanning electron microscope, APS = aerodynamic particle sizer (Park et al, 2018).

There are at least two different types of large-scale test facilities, where real road surfacing materials are used. These can be used to study both tyre wear and road surface wear. BASt (Bundesanstalt für Straßenwesen) and the Karlsruhe Institute of Technology (KIT), both in Germany, have standing drums with road surfacing on the inside, and equipped with an internal wheel rig (Figure 7). This equipment has been used to study wear particles from tyres, e.g. as part of studies funded by the Tyre Industry Project (TIP) in Kreider et al (2010), who used cyclone vacuum cleaners to collect dust behind wheels at the BASt facility. The collection efficiency was low, and the study focused on the inhalable fraction of the dust (PM_{10}). As only small amounts of this fraction were collected, coarser particles (up to 150 µm) were also collected for analysis. At the present time, no methods specifically designed for microplastics from tyre wear have been published for these facilities.

Figure 7. Vertical drums for testing of tyres in contact with road surfaces. BASt (Bundesanstalt für Straßenwesen) Germany. Photo: Re-tyre project, EU.

The other type of facility used for studies of road surface and tyre wear is the circular road simulator (CRS) of the Swedish National Road and Transport Research Institute (VTI). The CRS consists of a

16-metre long circular track that can be covered in any road surface material (Figure 8). The machine rotates around a central vertical axle, on which six wheel axles are mounted. Four of the axles are operational and powered by electric motors. Different types of personal car tyres can be mounted on the wheel axles. During testing, the wheels are lowered onto the track until the desired axle load is reached, and the wheels then drive the rotation of the machine. The speed can be varied continuously to up to 70 km/h. At speeds above 30 km/h, an eccentric movement can be activated, to cause the wheels to move almost across the entire width of the track, rather than follow the same line.

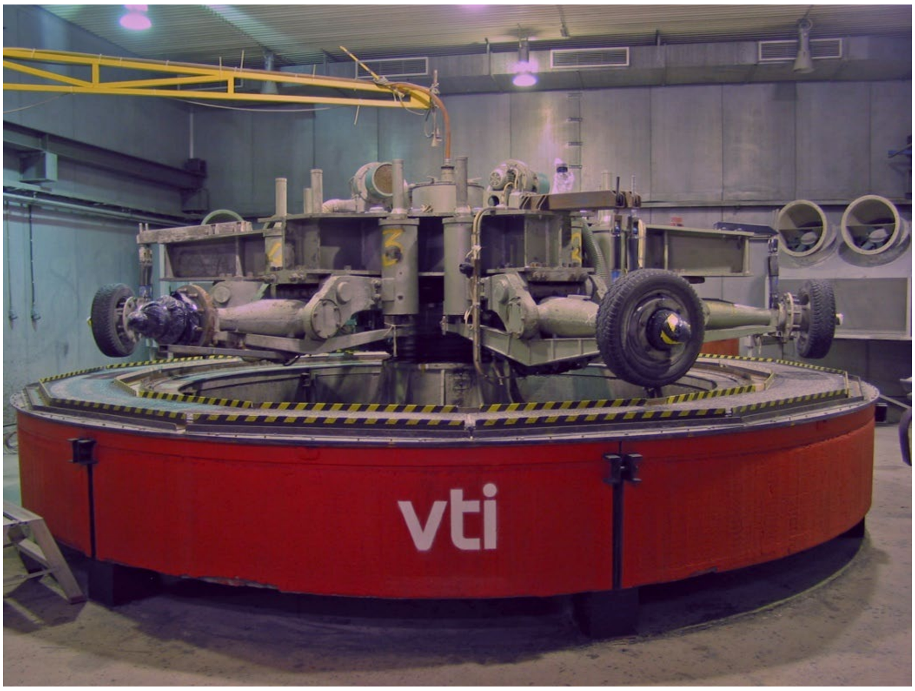

Figure 8. VTI's road simulator. Photo: Mats Gustafsson, VTI.

During tests using the CRS, the tyres follow a fairly tight circular track, which means that the inner edge of each tyre travels slightly more slowly over the surface than the outer edge. This results in a slight rotational slip of the contact surface, why the tyre wear in the PVM is greater than in real driving. Since the early 2000s, the CRS, apart from being used for wear tests of road surfaces has also been used for generation and sampling of wear particles, with focus on the inhalable fraction (PM_{10}). The majority of the studies have focused on the wear caused by studded tyres on different types of road surfacing materials. Some studies on tyre wear have also been carried out (Gustafsson et al, 2009; Grigoratos et al, 2018), although without all the wear materials being collected for analysis. Particles larger than PM_{10} have been collected by the CRS using wet vacuum cleaners connected to a device behind one of the tyres (Figure 9). This method may not be optimal for the collection of samples of microplastics from tyre wear, as both the hose between the device and the vacuum cleaner, and the vacuum cleaner container, are made of plastic which may contaminate the samples (Snilsberg, 2008).

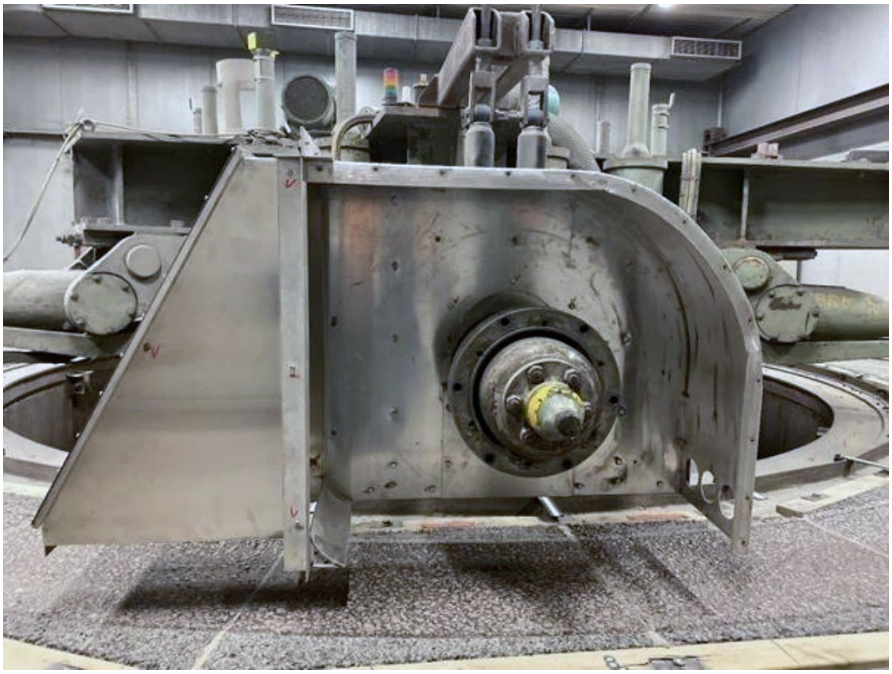

Figure 9. Collection device for VTI's road simulator, used to collect particles from tyre and road surface wear. Photo: Mats Gustafsson, VTI.

A number of vehicle-based systems have been developed to sample emissions from the contact between tyres and the road surface. All have, like most laboratory methods, been designed to study emissions and characteristics of PM_{10}. Studies by the Tyre Industry Project (TIP) used cyclone vacuum cleaners with specially designed mouthpieces mounted behind the tyres (Kreider et al, 2010). Examples of systems include the Finish Sniffer (Pirjola et al, 2009), which measures behind the left back wheel on a van, and TRAKER (Etyemezian et al, 2003), which measures particle concentrations behind both front wheels. This method has been copied by a number of researchers. However, particles have generally not been collected for further analysis of particle sources (Hussein et al, 2008; Mathissen et al, 2012). A similar measuring vehicle has been used in the Republic of Korea (Figure 10) to collect particles for elementary analysis and electron microscopy. Only PM_{10} has been collected, which means that a large proportion of the tyre wear has probably been missed, as studies by Kwak et al (2013) and Lee et al (2013) suggest that larger particles make up the main part. Without exception, the collection methods used are designed to mainly collect inhalable particles.

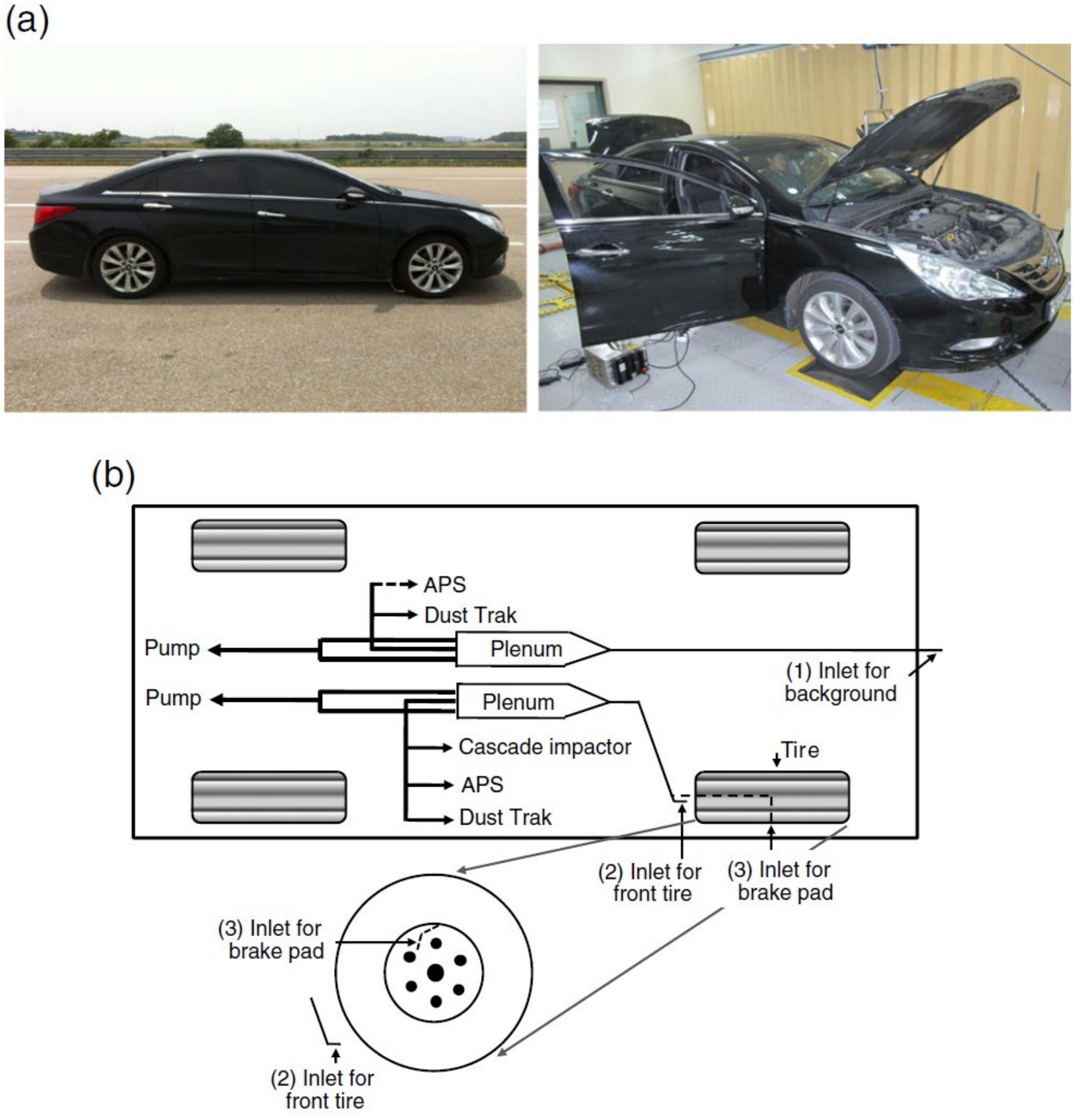

Figure 10. Measuring vehicle (a) and schematic figure of its measurement system (b) designed to collect particles generated during interaction between road and tyre, although exclusively PM_{10} (Kwak et al, 2013). APS = aerodynamic particle sampler, DustTrak = optical particle counter, Plenum = pressure equaliser for isokinetic sampling.

6.3. Road markings

There are multiple studies on resistance and wear of road markings, designed to assess whether they meet set requirements (Johansen & Fors, 2018) and to evaluate the wear of new road markings (Koucheki, 2003). No studies where road marking wear had been sampled specifically for environmental purposes were found during the preparation of this report. The test facilities described in section 6.2 could also be used to test the wear of road markings by tyres.

In the field, samples can be collected in a similar way as soil samples (see 6.5), to then be sieved and separated from other types of particles. On the road surface, fragments can be swept up or sampled using one of the methods described in section 6.4.

6.4. Road dust on the road surface

Studies where the main aim is to collect and analyse the contents of road dust usually simply use a dustpan and brush (Abbasi et al, 2019) or a basic vacuum cleaner (Vaze & Chiew, 2002). In some cases, pre-determined areas are sampled to determine the amount of material per m^2, in other cases the sampling focuses on collecting a particular sample volume, i.e. to collect X grams of material, without any relation to the size of the sampled area.

There are a number of different methods for collecting road dust from a road surface. VTI uses a proprietary sampling machine for road dust, called the Wet Dust Sampler (WDS). The sampler washes a known area of the road using a known amount of pressurised water, which after washing is transferred into a sample bottle using air pressure (Figure 10). A prototype was used from 2011 until 2014, and an improved version, the WDSII, has been used subsequently. Two copies of a slightly modified and further improved version, the WDSIII, have been built and sold to Finland and Norway. The WDS can be used to study the amount of road dust on a road surface. The collected dust samples can also be analysed for physical and chemical characteristics. For many years, the focus of the analyses was on the amount of dust, size distribution, and proportion of organic materials, and aimed at evaluating different methods for decreasing particle concentrations in the road environment (Gustafsson et al, 2010, 2011b, 2016, 2018). Since 2017, samples have also been collected to determine the microplastic content of road dust (Aronsson et al, 2018; Järlskog, 2018). In Norway, the WDS has also been used in studies of organic compounds associated with tyre rubber (Asheim et al, 2019).

Figure 11. Wet Dust Sampler (WDSII), Left: sampling device. Right: field sampling. Photo: Mats Gustafsson, VTI and Sami Kulovuori, Metropolia.

One of the samplers for road surfaces most commonly mentioned in the literature has been developed by Amato (Amato et al, 2009). It is based on a vacuum pump which sucks air through a deposition chamber, a PM_{10} separator, and a filter for PM_{10} with 25 lpm (Figure 12). Samples are collected over an area of one square metre using a hose nozzle.

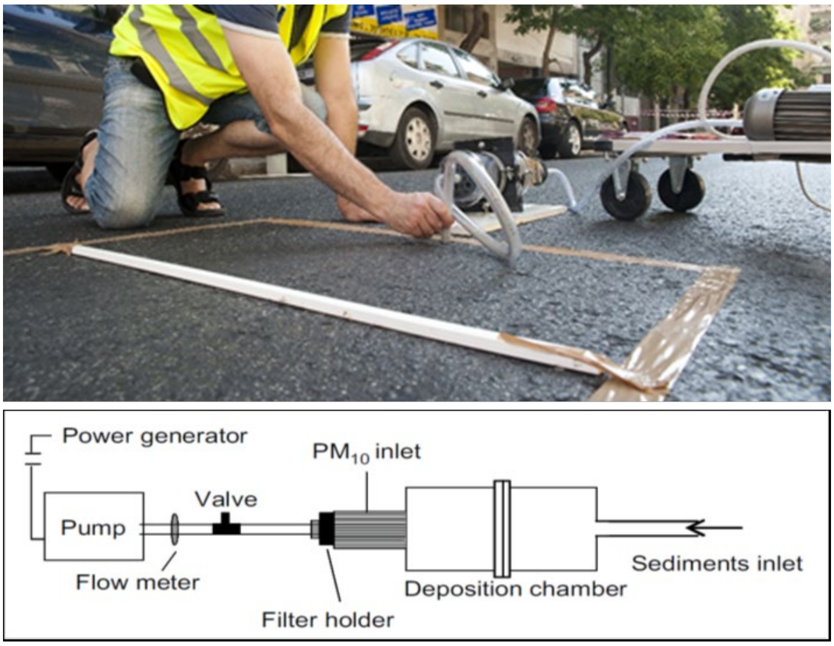

Figure 12. Amato's sampler for dust on road surfaces. Photo: Airuse[9]*. Illustration from Amato et al (2009).*

Another road dust sampler is described by Jancsek-Turóczi et al (2013). This sampler uses a leaf-blower to blow air onto a section of the road surface, covered by a hood. A particle sampler is connected to the hood by a pipe and collects PM_{10} on a filter for analysis (Figure 13). Samples have been collected for elementary analysis and microscopy, however, as far as we are aware, not yet for analysis of microplastics or organic compounds.

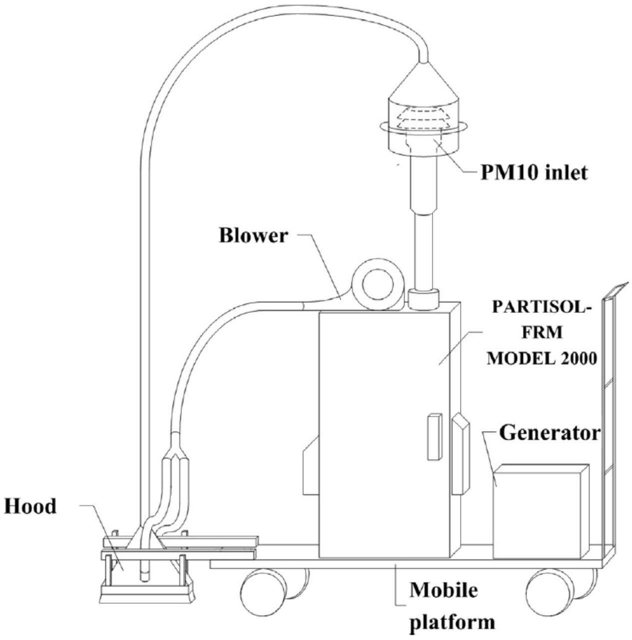

Figure 13. Sampler for road dust based on vacuum cleaner technology (Jancsek-Turóczi et al, 2013).

In relation to sampling approaches for road surfaces, a number of aspects should be taken into account, relating to variations in time and space. Variations in both the size and composition of the dust deposits over the year are likely, depending e.g. on the use of summer and winter tyres, as well as

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[9] www.airuse.eu (accessed 2020-02-11)

meteorological variations (e.g. wind, temperature and rainfall), which may influence the accumulation of road dust on the surface, as well as the emissions of microplastics. It may be of interest to study shorter time periods (hours, days, weeks) to see how e.g. wind and precipitation events or sudden changes in traffic volume, composition, or characteristics affect the dust deposits on the road surface. Variations between different traffic environments, with different road surfaces, traffic volume and composition, speeds etc. also make interesting study objects. Variations in how dust and microplastics are distributed across and along a road may help us understand where deposits of microplastics are found, and how they are affected by differences in the macrotexture and condition of the road, and by the traffic characteristics.

Coarser particles (above 10 µm) can be collected using a dustpan and brush, as was done in the project 'Tire Abrasion in the Environment' (Technische Universität Berlin, 2019) (Figure 14), and analysed for microplastics. A number of studies have used this method. Dehghani et al (2017) used an antistatic brush with durra (*Sorghum bicolor*) bristles and a steel dustpan, to avoid contaminating the samples with any form of plastic.

Figure 14. Road dust collection using dustpan and brush. Photo: Technische Universität Berlin, 2019.

6.5. Soil

There are standardised methods for sampling of soil, e.g. ISO 10381. These methods are not designed specifically for sampling of tyre wear or other types of microplastics, but are recommended due to a lack of specially designed methods. As soil characteristics can vary significantly even over short distances, and with depth, these types of variables must be considered when soil samples are collected (Braun et al, 2018). For this reason, it is important to carefully consider how many soil samples should be taken, and the exact locations where they should be collected, to achieve a fair representation of the spatial variations in the studied area. Strategies for how sampling should be performed have been developed for e.g. polluted areas (Norrman et al, 2009).

6.6. Deposition

Few studies on deposition, where the focus is on microplastics in general and traffic related microplastics specifically, were found in the literature search. Allen et al (2019) is one exception. They investigated atmospheric wet and dry deposition of microplastics in general in a remote area in the Pyrenees, however, specifically microplastics from tyre and road wear were not studied. Samples were collected using rain and deposition collectors of the types Palmex Rain Sampler[10] and NILU Particulate Fallout and Precipitation Collector (Innovation nilu, 2019), respectively. Deposition samplers usually consist of an open container, which is positioned at a certain height above the ground in an open location, sometimes with a collar. Containers made of glass or metal are suitable for sampling of microplastics. Cai et al (2017) used an open deposition container. There is comprehensive literature on deposition in general. In a review of sampling techniques (based on over 200 articles), Amodio et al (2014) identified a number of sampler types considered suitable for collection of the

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[10] www.rainsampler.com (accessed 2020-02-11)

organic pollutants PAH and PCB, and of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD and PCDF, respectively) (Table 5). It can be assumed that these are also suitable for tyre and road wear particles.

Table 5. Examples of deposition samplers suitable for collection of the organic pollutants PAH, PCB, and PCDD/PCDF. The samplers considered suitable for each pollutant is marked with an X. From Amodio et al, (2014).

Collection device	***PAH***	***PCB***	***PCDD/PCDF***
Glass funnel – bottle, bulk collection	X		X
Stainless steel bucket	X	X	X
Stainless steel plate	X		
Device with stainless steel funnel and glass filter	X		
Funnel connected to absorbent cassette (Amberlite IRA-743)	X	X	X
Funnel connected to an adsorbent cassette (XAD-2)		X	X
Automatic wet deposition collector	X		
Two containers with a rain sensor	X		

6.7. Particles in air

There are many different types of filter samplers for sampling of particles of different sizes in air. The most commonly sampled fractions are TSP (total suspended particles), PM_{10} and $PM_{2.5}$. The latter two are regulated via legislation in the EU, as well as in many countries outside the EU, due to their well-documented adverse effects on human health. Any sampler can be used in studies of microplastics in these fractions, although samplers made of plastic should be avoided wherever possible. Passive samplers for airborne particles are available in a wide range of designs. They are often intended for exposure measurements. However, few seem to have been used to study microplastics. One exception is studies using the sampler Sigma-2 (Figure 15), where tyre particles from road environments in particular have been studied (Dietze et al, 2006; Tian et al, 2017; Sommer et al, 2018). Particles are collected on a transparent, adhesive surface inside the sampler over a 7-day period. An appropriate size range for sampled particles is 2.5–80 µm.

When the aim is not to collect particles according to standardised metrics, other types of samplers can also be used, designed e.g. for collection of bioaerosols, allergens, or for other medical purposes. A wide range of both passive and active samplers is available, including impactors and cyclones, used for instance for biomonitoring (Haig et al, 2016). One example is collection in specially designed samplers where particles are deposited in tiny glass bottles, so called vials, with water (Cho et al, 2019).

To avoid contamination of the samples and impact on the chemical analyses, the filter medium should be carefully selected. As an example, both Panko et al (2012) and Miguel et al (1996) used quartz filters to enable analysis of tyre particles in PM_{10} samples. The method used for the final analysis also influences the choice of filter medium. One commonly used filter for samples for electron microscopy analysis are so called Nuclepore filters. These consist of polycarbonate, i.e. a type of plastic; a fact that must be considered during elementary analysis, which is often done using energy dispersive X-ray analysis (see chapter 7). Quartz filters are not suitable for this type of analysis, as they are made of fibres. To solve this problem, the company Particle Vision has developed a substrate for its passive sampler, Sigma-2, on which the particles can be deposited. The substrate is made of polished boron crystal, which was used by Rausch et al (2019) to identify tyre particles using electron microscopy with X-ray detection (see chapter 7).


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Figure 15. Sigma-2 passive sampler for airborne particles. Photo: Particle Vision.

6.8. Runoff from roads

Samples of runoff water from roads have been analysed for different types of pollutants. It has not been possible, in the literature, to find a sampler specifically designed for collecting microplastic samples. For the same reason previously described for samplers used for microplastics in air, any plastic content in the sampling system should be avoided wherever possible. The sampler may need to be adapted for plastics to avoid contamination. Unless sampling during real precipitation events is required, tunnels can be used, as in e.g. Snilsberg & Gryteselv (2017). Samples of runoff water from the road can be collected after washing of the tunnel using flushing equipment. The advantage of using a tunnel is that it provides a more controlled environment with minimal impact from e.g. wind or precipitation. There are also fewer particle sources. This means that the particles are more closely associated with the traffic-related sources.

Samples of runoff water from road surfaces can be collected from e.g. gully pots, or specific facilities for runoff collection. As runoff only takes place during precipitation, it is often difficult to plan and carry out manual sampling, why automatic samplers are frequently used. There are both active and passive automatic samplers. Active samplers are available in a wide range of designs and can usually be programmed to collect samples at certain time intervals or for flow-proportional sampling. An example of this type of sampler is shown in Figure 16. This sampler can be used with different types of containers, either for bulk sampling or for sampling at pre-set time intervals.

Figure 16. Example of programmable runoff sampler. Photo: Hach[11].

One type of passive sampler is shown in Figure 17. This particular type can be placed in gully pots or similar before a rain event and will then fill sample bottles to a pre-defined volume during the rainfall. A cover prevents leaves and other larger objects from obstructing the bottles. Once it is full, it closes automatically, using a floating ball, and no more water is collected. For this reason, this type of sampler is known as a 'first flush sampler', but it is also used to sample during a whole rain event. It is usually made of plastic, meaning that there is a risk of contamination if used for microplastic sampling.

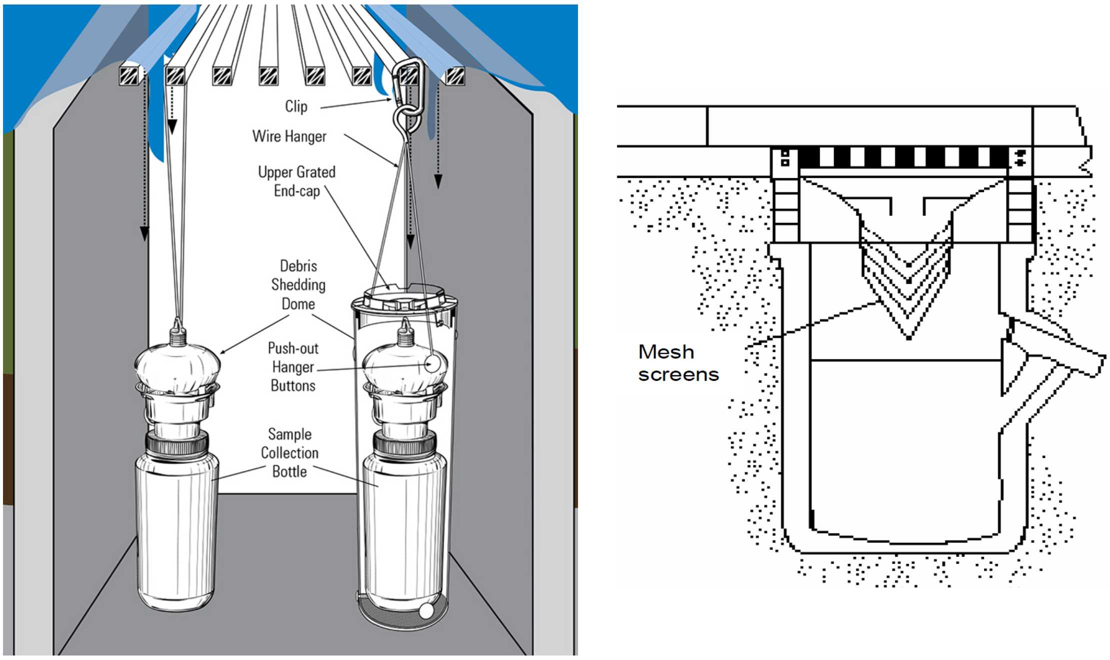

Figure 17. On the left: passive samplers for stormwater. Image from Thermo Fisher Scientific. On the right: passive sampler for sediments in stormwater (Brodie & Porter, 2004).

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[11] www.hach.com (accessed 2020-02-11)

Klein (2013) has produced a report which provides an overview of a few different types of passive samplers, designed for bulk sampling of runoff water and sediments contained therein. The report mentions e.g. a direct sieve sampler, specially designed to sample sediments in runoff water using a series of filter cloths with gradually decreasing pore size. A type of sampler known as gravity flow sampler may also be useful for collecting stormwater samples for microplastic analysis. This is also a type of first-flush sampler, which closes automatically once it is full. A number of different versions are available, including one that can be mounted on the carriageway, and one that can be combined with pipes used to collect runoff water directly by the roadside.

The Swedish road research facility Test Site E18 (Figure 18) has a structure designed to collect runoff water. The facility consists of curbs along a 100-metre long stretch of road, along which water can be collected and transported to a drain. The outlet of the drain is equipped with a flowmeter.

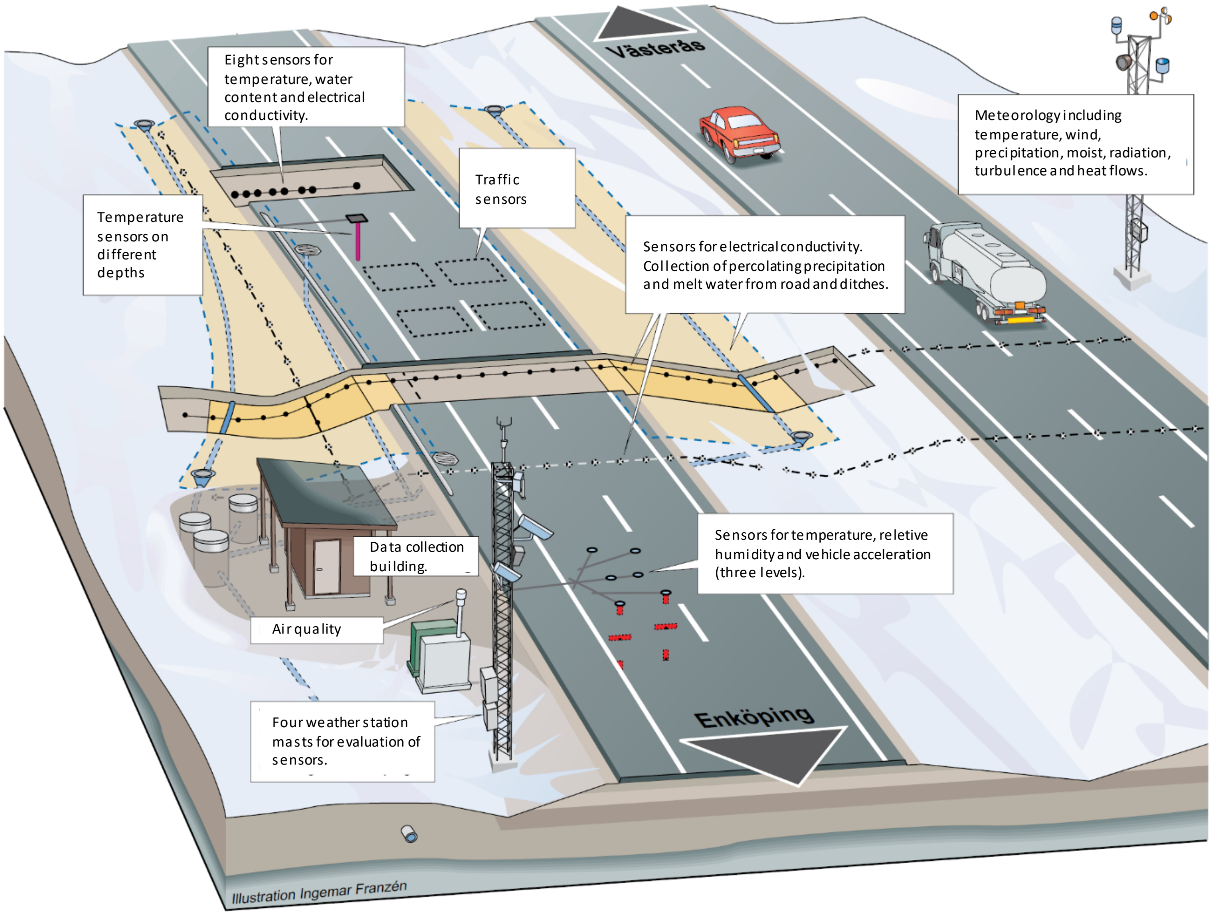

Figure 18. Test Site E18, including a structure for collection of runoff water from the road. Image from the Swedish Transport Administration[12]*.*

6.9. Drainage installations and stormwater ponds

Samples from stormwater ponds can be collected in the same way as samples of other types of surface water. If the pond is comparatively small, representative samples can be collected from the shore. One example is provided in Liu et al (2019), where a suction intake is held at a depth of approximately 20 cm, using a flotation device (Figure 19). The water is sucked in using a pump and filtered through a coarse mesh (mesh size 2 cm) to remove large debris, and subsequently through a filter with a pore size of 10 µm. The flow is measured using a flow sensor.

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[12] www.trafikverket.se (accessed 2020-02-11).

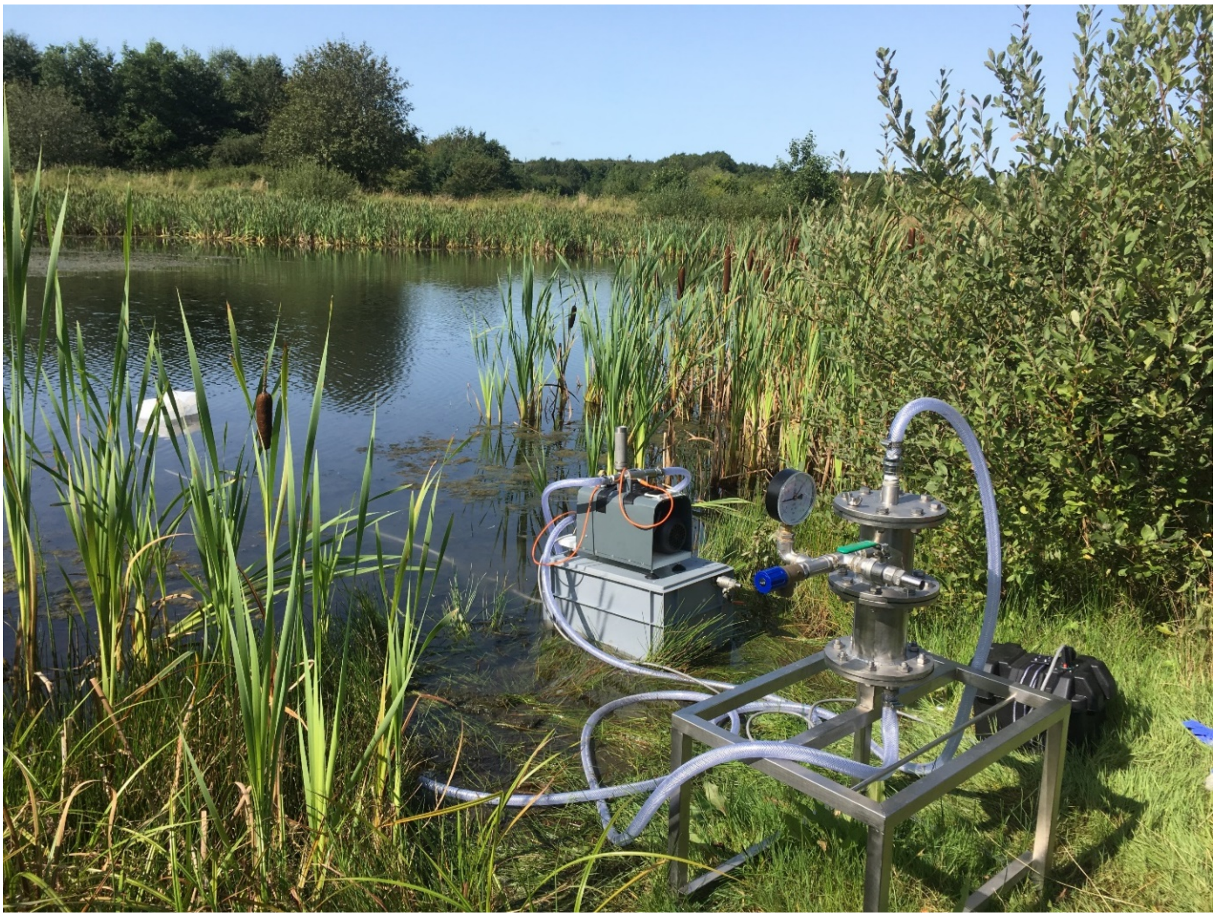

Figure 19. Equipment for sampling of water in a stormwater pond. Photo from Liu et al (2019).

6.10. Bottom sediment

Sediment samples are often collected using core samplers, e.g. Willner or Limnos, alternatively, if the sediment is denser and requires more weight, a Niemistö, VanVeen grabber, or Box-corer can be used (Swedish Environmental Protection Agency, 2012). Further examples of sediment samplers are shown in Figure 20.

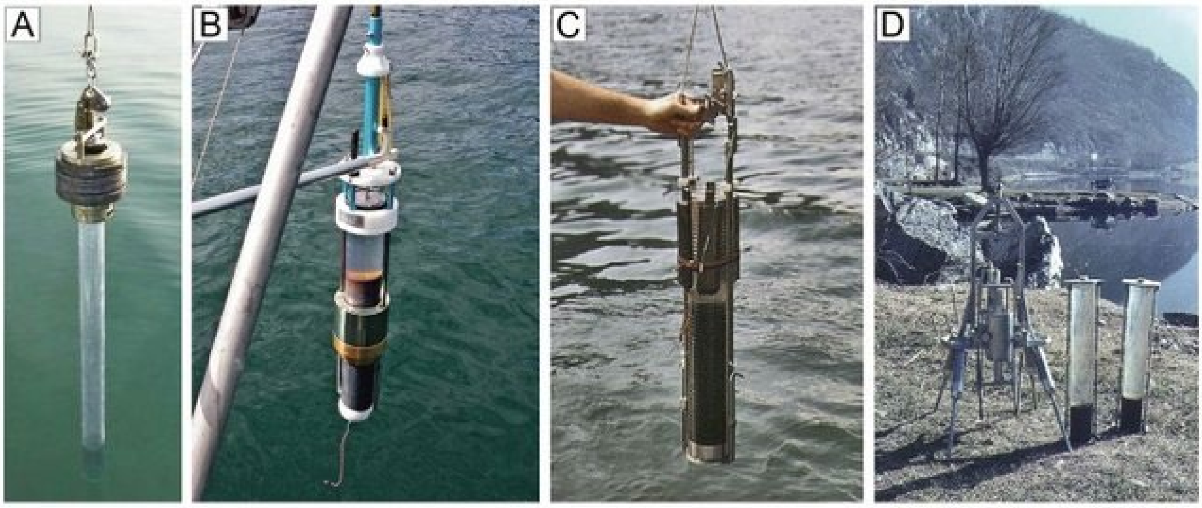

Figure 20. Core samplers for sediment sampling: Gravity collectors (A, B), Limnos (C), and Jenkin (D). Photo from Guilizzoni (2012).

An alternative to bottom samples is to collect samples near the shore of oceans, lakes, or watercourses. According to a review by Hidalgo-Ruz et al (2012), most sediment samples that have been analysed for microplastics were collected by the high-water mark on sandy beaches. Samples have been collected from areas of sizes ranging from 5 x 5 cm to 1 x 1 m, at depths of between 1 and 20 cm (Braun et al, 2018). One example of this type of sampling was carried out by Horton et al (2017a), who collected samples of bottom sediments in the Thames River using a stainless-steel scoop. Samples were taken at a depth of up to 10 cm, at a distance from the edge of 1 m, along a 3-metre length, which gave four replicates. Each sample filled a 1-litre jar.

6.11. Surface water

Many microplastics have a low density and can float in masses of water, but they can also be distributed between different water depths in marine environments (Mai et al, 2018). There is no standard for the areal size, or depth, at which water samples should be collected. There are examples of samples being collected anywhere from in the micro surface layer at a very small scale, to samples being collected using trawling of surface water (0–0.5 m depth) over larger areas. Trawlers usually have a mesh size of 100–500 µm. The mesh size 300 µm is considered the optimal mesh size, as finer mesh sizes lead to other particles clogging the holes, and coarser mesh sizes cause too many microplastic particles to be lost. A proposed protocol for sampling and analysis is offered by Kovač Viršek et al (2016), which describes the stages of sampling, separation of microplastics from other particles, and chemical identification.

Another method is to pump water through filters. This method is usually used for water sampling at greater depths than with the trawlers and may therefore miss microplastics accumulated in the surface layer (Mai et al, 2018). A new filtration method, targeted at particularly small microplastic particles (< 10 µm) in water, has been developed by Lenz & Labrenz (2018). In their system, which is housed in a smaller, moveable container, the water is pumped through a filtration system. The actual sampling is carried out using a normal hose, or in the case of surface water, with an aluminium funnel (see Figure 21).

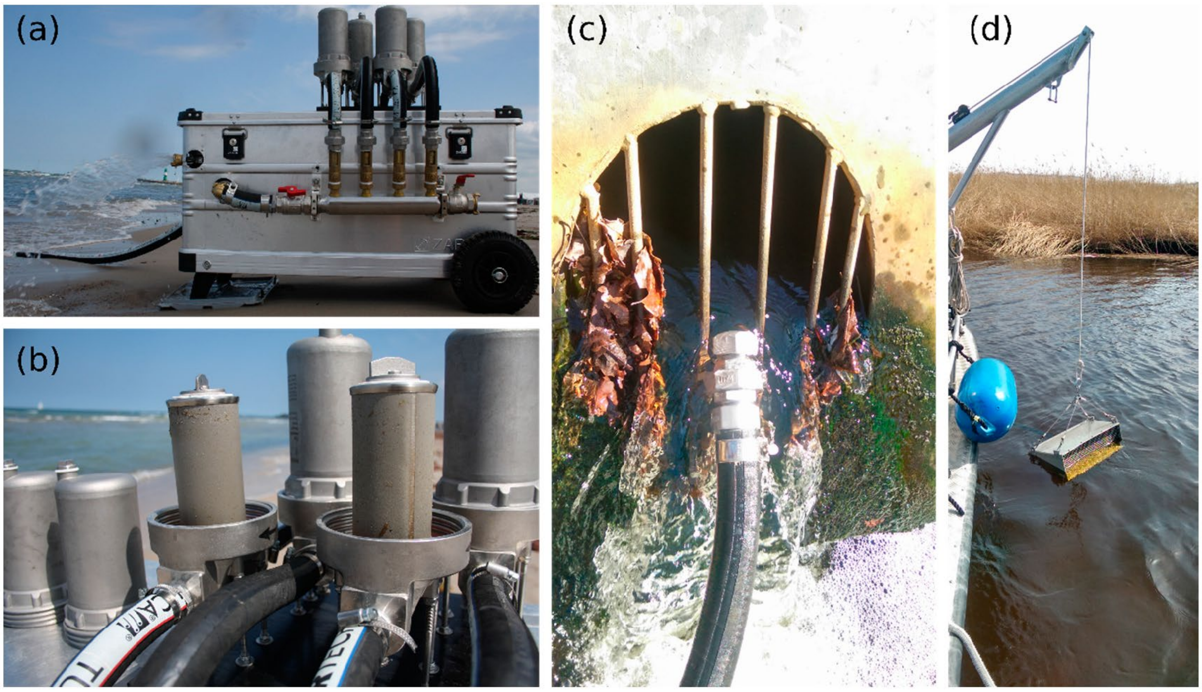

Figure 21. Sampling system for small microplastic particles in water: a) container with equipment, b) filter holders, c) intake, and d) sampling funnel for surface water. Photos from Lenz & Labrenz (2018).

Braun et al (2018) have compiled sampling methods for microplastics in surface water. An important factor is sufficient sample volume, which is determined by the size distribution of the target particles. If very small particles are of interest, the sample volume can be limited to the order of magnitude of millilitres to litres. The particle count can still be assumed to be sufficiently high to give a statistically valid result. However, if the aim is to study the occurrence of larger particles, hundreds of litres of water may be required to achieve a statistically sufficient amount (Table 6). If the aim is to study the occurrence of different types of plastic particles, and their ratios, larger volumes are obviously required than for studies of local occurrence of microplastic particles.

Table 6. Recommended sampling volumes for water for analysis of microplastics, based on literature review by Braun et al (2018).

	Very high particle content	**High particle content**	**Low particle content**	**Almost free from particles**
Expected content of filterable substance in the water	More than 500 mg/l	100–500 mg/l	1–100 mg/l	< 100 mg/l
Example	Intake to treatment plant	Road runoff	Outlet from treatment plant, surface water	Groundwater, mineral water, drinking water
Recommended sample volume for particle analysis	5 ml	500 ml	1 l	500 l

6.12. Conclusions

- Standardised methods for sampling are often not available, and there are no standardised methods specifically designed for microplastics.
- There are three types of sampling strategies for the aquatic environment: selective sampling, bulk sampling, and reduced-volume sampling.
- The choice of sampling method depends on the medium to be sampled.
- The subject of the analysis determines e.g. the sample volume required, how samples should be prepared before analysis, and which analytical methods to consider.
- Multiple aspects must be taken into account to ensure the collected samples are relevant and representative. The different densities of microplastics mean that they spread by different dispersal pathways and accumulate in different environments. Some microplastics accumulate in surface water and along beaches, while others, such as tyre rubber, accumulate in bottom sediment. This must be taken into account when sampling locations and media are selected.
- There are two types of large-scale testing facilities for laboratory studies of tyre and road surface wear: standing drums and road simulators.
- There are a number of vehicle-based systems for sampling of emissions from interactions between tyres and road surfaces in the field. One example is the use of cyclone vacuum cleaners with specially designed nozzles, mounted behind tyres.
- There are a few different types of sampling equipment for road dust. One sampler uses a leaf-blower, equipped with a hood covering the sampling surface. Another sampler is based on vacuum cleaner technology, and a third is the so-called wet dust sampler, which rinses off a known area of the road using a known amount of water, and then collects the water containing the road dust.

- Sampling in soil and sediment is normally made using standard sampling equipment, such as pipe collectors or grabbers.
- Sampling of microplastics in surface waters is normally made using trawls or by pumping water through filters.

7. Methods for preparation and analysis of samples

This chapter describes the methods most commonly used for microplastic analysis. Potential use of these methods to analyse and quantify tyre and road wear particles in the field is also discussed. Section 7.1 provides an overview of the most commonly used analytic methods. Comprehensive preparation is usually required before analysis can be carried out. Preparation often involves density separation, which is described in section 7.2. The remaining sections describe individual analytic methods in more detail.

The methods described in this chapter are generally time-consuming, and only a small number of laboratories are currently able to perform analyses on microplastics from tyres. Even fewer are able to perform quantitative calculations of particle numbers or mass. It is expected that the existing analytic methods will be improved, i.e. become more automated and faster to carry out, within the near future, so that they can be used with more certainty and higher quality for analysis of tyre and road wear particles in field samples.

7.1. General on analytical methods

Several studies have investigated the chemical contents of laboratory-generated materials from rubber and tyres (see e.g. references in Allan et al (2016); Li et al (2017); Wagner et al (2018); Lloyd et al (2019) and section 4.5 in this report). However, only a small number of studies have quantified tyre and road wear particles in field samples, such as stormwater from roads (Eisentraut et al, 2018) and road dust (Unice et al, 2013; Sommer et al, 2018). Table 7 provides an overview of currently available methods for analysis of microplastics, and the data each method can provide. The table also show the required sample volumes, the preparation method associated with each analytic method, the detection limits of the methods, and the range of particle sizes they can be used for. Methods for analysis of nanoparticles, i.e. particles smaller than 1 µm, are not covered in this report; however, this is an emerging and challenging field for the development of new methods for the analysis of field samples (Renner et al, 2018; Nguyen et al, 2019; Oliveira & Almeida, 2019).

Table 7. Analytic methods used to analyse tyre and road wear particles, based on (Braun et al, 2018), supplemented by Järlskog (2019).

	Microscopy methods	**Micro-spectroscopy methods**			**Gas chromatography-mass spectrometry methods (GC/MS)**	
	Light microscopy	Scanning electron microscopy with X-ray detection (SEM-EDX)	µ-Fourier transform infrared spectroscopy (µ-FTIR)	Raman	Pyrolysis GC/MS	TED-GC/MS (Thermal extraction and desorption GC/MS)
Detectable quantities in samples	–	–	ng–µg	ng–µg	µg	µg
Maximum number of measurable particles per sample or sample amount	–	–	10^3–10^5	10^3–10^5	< 20 mg	< 100 mg
Time to perform analysis incl. sample preparation	Hours – days	Hours	Days – weeks	Hours – days	Days – weeks	Hours
Detection limit	20–100 µm	10 µm	20 µm	1–10 µm	< 1 µg*	0,5–2,5 µg
Sample preparation	Filter	Filter	Special filter	Filter	Isolated particles (vial)	Filtrate or material in crucibles
Polymer type	No	No	Yes (difficult)	Yes (difficult)	Yes	Yes
Appearance of particle surface	Yes	Yes	No	Yes	No	No
Degree of degradation	No	No	No	Surface oxidation	Oxidation	No
Particle quantity, size, shape, morphology	Yes, through visual assessment	Yes, quantity	Yes	Yes	No	No
Mass balance	No	No	No	No	Yes?	Yes
Can be used for tyre and road wear particles	Yes, manual identification but uncertain	Tyre and road wear particles can be identified, and development is underway	Yes, and development is underway	Development underway	Yes, with reference spectrum/ library	Yes, with reference spectrum/ library

*Development efforts to reduce the detection limit are underway.

The analytic methods presented in Table 7 can be divided into microscopy, micro-spectroscopy, and gas chromatography mass spectrometry methods. Micro-spectroscopy methods, such as µ-FTIR (micro-Fourier Transform Infrared Spectroscopy), Raman spectroscopy, and SEM (scanning electron microscopy) use the polymers' specific absorption and reflection patterns when exposed to infrared radiation (µ-Fourier Transform Infrared Spectroscopy), laser light (Raman), or electrons (scanning electron microscopy). These can efficiently provide data on particle quantities, sizes, and shapes, but currently require extensive sample preparation before analysis. One challenge when using spectroscopy technology to analyse tyre and road particles in road dust is the presence of the filler carbon black in tyre particles (Kole et al, 2017), which cause disruptive fluorescence phenomena when exposed to laser lights, and absorbs infrared light almost completely (Eisentraut et al, 2018). Analysis with microscopy and scanning electron microscopy (unless combined with x-ray detection) only allows visual differentiation of different polymer materials, and these methods currently require extensive sample preparation. They are also very time-consuming where the aim is to determine the number of particles in a sample (Wang et al, 2017).

Thermal gas chromatography (GC) methods with mass spectrometry (MS) used to analyse microplastics include pyrolysis, so-called pyrolysis-GC/MS, also known as Pyr-GC/MS (Unice et al, 2012, 2013). Analyses can also be performed in two steps, i.e. thermal extraction and thermal desorption, so-called TED-GC/MS (Eisentraut et al, 2018; Dümichen et al, 2019). These methods can be used to identify specific degradation products, which act as markers for different polymers, and the amounts of each polymer can then be quantified. Analyses using Pyr-GC/MS involve the sample being quickly heated to a temperature where the organic compound (including polymers) degrade into single molecules, which are separated using gas chromatography and detected with mass spectrometry. In thermal extraction and desorption GC/MS, the sample is first gradually heated in a separate unit, where the organic compounds in the sample form gases with degradation products, which are concentrated on a sorbent. This is then injected into the gas chromatography system using thermal desorption. Pyrolysis-GC/MS can only analyse small sample volumes, and requires extensive sample preparation to be able to analyse tyre and road wear particles in road dust, why thermal extraction and desorption GC/MS, which does not require the same careful sample preparation and is able to handle larger sample volumes, is considered more promising for analysis of field samples (Renner et al, 2018; Prata et al, 2019).

Tyre wear markers have been used to determine whether particles in a sample are tyre or road wear particles. One example is a study where the concentrations of tyre and road wear particles in sediments from three different continents were analysed using Pyr-GC/MS by Unice et al (2013). The study also compared the metal concentrations in the sediments and found that it was possible to correlate tyre and road wear particles to lead, zinc, and copper, assumed to originate from the brake pads of vehicles. Other studies have analysed specific tyre components, intended for use as markers for tyre and road wear particles, including dibenzopyrenes (PAHs with high molecular weight). In some cases, zinc has also been used as a marker (Sadiktsis et al, 2012; Wagner et al, 2018; Klöckner et al, 2019).

7.2. Sample preparation

Before analysis of microplastics from road and tyre wear can be carried out, preparation is required to provide concentrated and clean samples (Nguyen et al, 2019; Pico et al, 2019; Prata et al, 2019). In the preparation, processes are used to separate inorganic materials, such as silicates, carbonates, and minerals, and to break down organic materials, like humic compounds, bacteria, and cellulosic materials (Braun et al, 2018). Samples are often prepared in multiple steps.

Larger particles and grit are removed by sieving, after which the samples are treated using oxidation to break down more readily degradable organic materials that are of no interest and may disturb the analysis (Bläsing & Amelung, 2018). Oxidation with hydrogen peroxide (H_2O_2) is the most commonly used method, however, treatment with ozone, strong acids or alkalis, as well as with enzymes are sometimes used (Braun et al, 2018). This is followed by density separation, before the sample is finally filtrated in multiple steps with different pore sizes. Different analytical methods require different types of preparation. The preparation methods for soil, water, and sediment samples also vary (Pico et al, 2019). The choice of preparation method for analyses of microplastics from road and tyre wear also depends on the analytical method used, and whether other types of plastics will be analysed in parallel, and if so, which ones. Size and density of the particles also influence the choice of analysis and preparation method.

In density separation, a salt solution is used, e.g. in a sedimentation or flotation tower (Imhof et al, 2012). Commonly used salt solutions include sodium chloride (NaCl) ≤ 1.2 g/cm^3, zinc chloride ($ZnCl_2$) ≤ 1.7 g/cm^3, sodium polytungstate (SPT[13]) ≤ 3.2 g/cm^3, sodium iodide (NaI) ≤ 1.9 g/cm^3, calcium chloride ($CaCl_2$) ≤ 1.4 g/cm^3, and potassium bromide (KBr) ≤ 1.6 g/cm^3 (Liu et al, 2020; Nakajima et al, 2019). The choice of salt solution is determined by the density of the plastic materials to be analysed. The density of tyre and road wear particles in the environment has been estimated to approximately 1.8 g/cm^3 (Unice et al, 2019b). Based on previous studies, tyre wear particles have a density of 1.2 g/cm^3 and the density of road surface materials, including asphalt wear, is around 2 g/cm^3. A study by Klöckner et al (2019) estimated the density of carbon black, used as a filler in tyres, to 1.8 g/cm^3, and the density of styrene butadiene rubber to 0.94–1.0 g/cm^3, which gives an estimated density of tyre materials of 1.1–1.2 g/cm^3. The density of bitumen, which is used as a binding agent in asphalt, is 1.0–1.1 g/cm^3.

Based on these figures, salt solutions with a density above 1.8 g/cm^3 are recommended for separation of tyre and road wear particles (e.g. Järlskog et al, 2020), to ensure the particles will float and therefore can be further separated using filtration. Good separation of tyre and road wear particles has been achieved using saturated solutions of zinc chloride ($ZnCl_2$) (Karlsson et al, 2019). Centrifugation, which is often used to separate biological samples, is less tested for analysis of microplastics, but may be a way to boost separation (Nguyen et al, 2019). It is, however, difficult to separate pure tyre and road wear particles in field samples, as the particles are often bound to materials with a complex composition (e.g. sediments, water, or biota) as well as road dust and gravel, which have a higher density. This means that there is a significant risk that some of the tyre and road wear particles have a density above 1.8 g/cm^3 and will therefore no longer be present in the analysis steps that follows the density separation. For density separation of heavier particles, like tyre and road wear particles which may have a higher mineral content, the use of a SPT salt or NaI solutions are recommended (Vogelsang et al, 2019; Järlskog et al, 2020).

7.3. Microscopy methods

Examples of microscopy methods are light microscopy and electron microscopy. Electron microscopy is described in section 7.4.1 (Electron microscopy with x-ray detector). This section covers light microscopy, which is sometimes used as a standalone method for microplastic analysis, but with advantage it can be used in combination with micro-spectroscopic and gas chromatography-mass spectrometry methods.

A high-resolution light microscope (stereo microscopy) can be used to identify thermoplastic particles, i.e. plastic fibres, plastic fragments, plastic chips, and plastic film, as well as other particles, including black road particles, i.e. black elastomers such as rubber and bitumen (GESAMP, 2019). To verify whether a particle is an elastomer or a thermoplastic, the method can be combined with e.g. melt tests. Rubber and bitumen particles can be identified using visual assessment, prodding with tweezers, or melt tests (Aronsson et al, 2018; Järlskog et al, 2020), see Figures 22 and 23.

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[13] Sodium polytungstate (SPT), $3Na_2WO_4 \cdot 9WO_3 \cdot H_2O$.

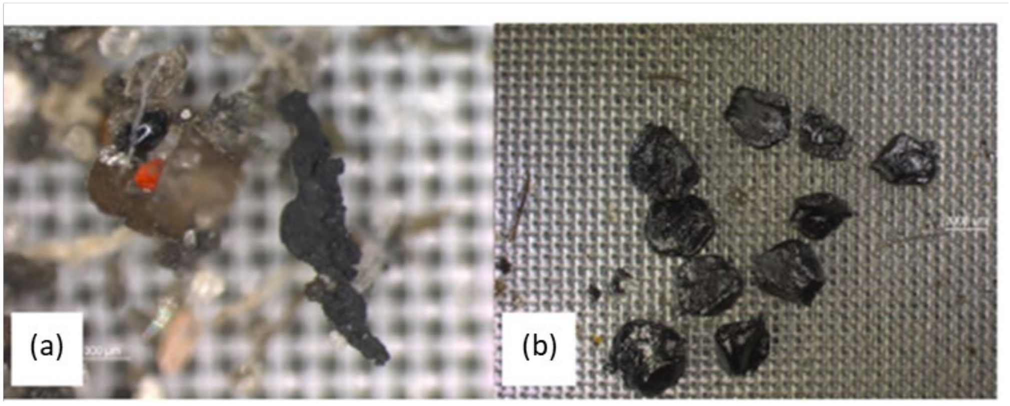

Figure 22. Particles from tyre and road wear with density ≤ 1.2 g/cm³ identified using microscopy. (a) Rubber particle from vehicle tyre. (b) Tar-like particles, probably bitumen from asphalt. Photo from Aronsson et al (2018).

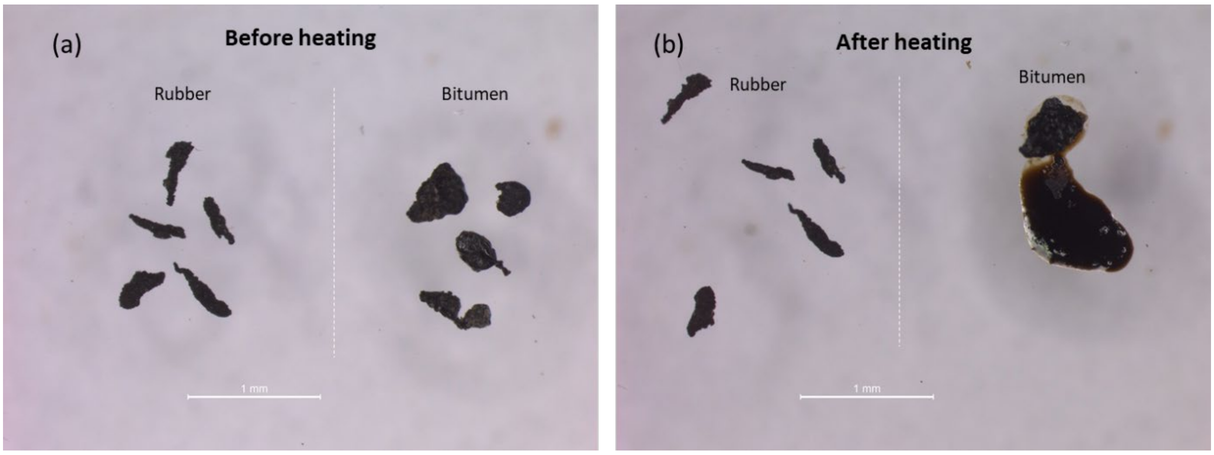

Figure 23. Rubber and bitumen particles (a) before heating; (b) after heating. Photo: Kerstin Magnusson, IVL (Modified from Järlskog et al, 2020).

Microscopy methods require extensive sample preparation, such as sieving, oxidation, and density separation, and the method is very time-consuming if the number of particles in a sample is to be determined (Wang et al, 2017). If the density separation of sediment samples is not sufficiently effective, sediment particles or other particles may interfere with the microplastic particles the analysis was intended for. In addition, the analysis may be complicated by biological organic materials not fully degraded during sample preparation (GESAMP, 2019).

Another disadvantage of microscopy is that this method is based on visual assessment, which means that it is subjective and requires long experience. Standard analytical protocols have been recommended, both to standardise sieving and filtration, and to define particles more based on appearance, size and shape, than on type of plastic (Bläsing & Amelung, 2018). The resolution limit for regular microscopy is approximately one micrometre, but colourless particles smaller than 100 µm without a specific shape, such as rubber from tyre wear and bitumen in asphalt particles, are difficult to characterise (GESAMP, 2019). IVL (the Swedish Environmental Research Institute) has analysed rubber and bitumen particles in sizes down to 20 µm in stormwater samples (Aronsson et al, 2018).

7.4. Micro-spectroscopy methods

7.4.1. Electron microscopy with x-ray detector (SEM-EDX)

Electron microscopes use electrons instead of light illumination. The resolution limit is 0.1 nm, which makes it possible to analyse much smaller particles, including single atoms. The resolution varies, a common magnification rate is 30,000 times, but much higher resolutions are available (magnification up to 2,000,000). There are different types of electron microscopy.

With transmission electron microscopy (TEM), an electron gun produces a beam of electrons, which is focused using an electromagnetic condenser lens so that only a very narrow beam hits the sample under investigation. This method works for very thin samples (approx. 20–50 nm). The thicker the sample, and the greater the electron density of the material, the more the electron beam will spread, and the more secondary electrons will be excited from the sample material, which leads to blurring.

Scanning electron microscopy (SEM) involves an electron microscope that scans objects in vacuum, using an electron beam with a raster pattern that interacts with the atoms on the surface of the object, which produces signals with information about the object's surface topography, composition, and other characteristics, such as its conductivity (Brouwer, 2006). A detector then measures the signals emitted by the electrons hit by the beam. The signals are amplified and depicted on a screen, where each pixel corresponds to its position on the sample, and is shown as a light dot if many electrons were detected, and a dark dot if few electrons reached the detector. This method has been extensively tried and tested, and scanning electron microscopes are among the most frequently used instruments for analysis of surface topography, chemical composition, and conductivity of polymer materials (Yang, 2018).

A disadvantage with scanner electron microscopy is that the sample must be conductive to generate a potential difference between the sample and the detector. This means that non-conductive samples need special preparation, e.g. with a thin metal coating. Examples of detectors include some that produce high-resolution graphic images of the material (this type of detector scans secondary electrons and is known as a secondary electron detector imaging, abbreviated SE or SEI). Another type of detector provides information about the chemical elements found (this type of detector reads back scattering electrons, BSE). Back scattering electron detectors are used to differentiate between particles consisting mainly of heavy chemical elements and particles consisting mainly of light chemical elements. Some x-ray detectors (Energy Dispersive X-Ray analysis or Energy Dispersive X-Ray Spectroscopy, abbreviated EDX or EDS) have also been used for microplastic analysis (GESAMP, 2019). Scanning electron microscopy with x-ray detection provides information about the elemental composition of particles, however, this is an expensive instrument and currently requires extensive sample preparation before analysis can be carried out. The analysis itself is also time-consuming (GESAMP, 2019).

Scanning electron microscopy with x-ray detection has also been used for microplastics from road and tyre wear. A study by Sommer et al (2018) analysed particles larger than 10 µm in samples collected using passive sampling of air in different road environments. More than 500 particles and 1,500 spectra were analysed to determine the particles' size, shape, and volume, as well as their chemical composition. In this study, the majority of the collected samples (over 90% by volume) contained wear particles from tyres, asphalt, and brake pads. The results show that tyre wear contributes to the spread of microplastics in the environment, however, no quantification of the emissions was carried out.

The importance of the choice of sampling method to the analysis of particle shapes becomes clear when the findings from different studies are compared. A study by Kreider et al (2010) collected samples from a road using a specially designed collection device, mounted behind a tyre. Two Dyson vacuum cleaners (1,200 W) were connected to the device and used to collect the particles with a powerful suction force. In this study, the analysed particles from tyre and road wear had an elongated shape and were present in sizes between 0.3–100 µm. In samples taken with the WDS (Wet Dust Sampler), which uses a much less powerful suction force, some black rubber particles also had an irregular flake shape (Aronsson et al, 2018). In Hassellöv et al (2018), both elongated, curled, black, rubber elastomers, and flakes of elastomers, were found (Figure 24). This shows that the assumption that all tyre and tyre wear particles have an elongated shape may lead to underestimation of the number of tyre and tyre wear particles in field samples.

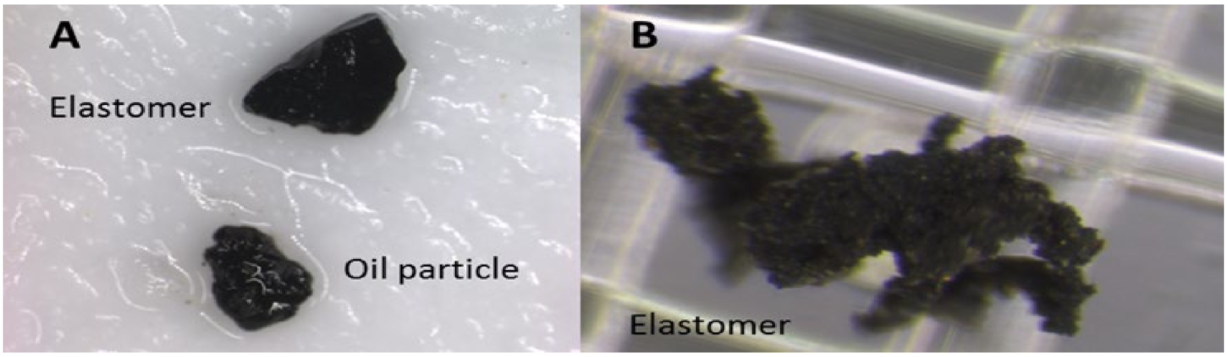

Figure 24. Black micro-sized particles from sediments in an urban stream. A. Two categories of black anthropogenic particles, a rubber-like elastomer with jagged edges, and a sticky oil particle. B. Elastomer particle with a crumbly appearance, Photos from Hassellöv et al (2018).

Microplastic particles from trawlers, and in fish, in the Atlantic and Pacific Ocean have also been investigated using scanner electron microscopes with x-ray detection, to investigate whether this method can be used for fast screening of samples, and to find out whether it is possible to differentiate between different types of plastic (Wang et al, 2017). The results showed that scanner electron microscopy with x-ray detection gave a high-resolution image of the surface texture of the particles, which led to easier characterisation of microplastics. As an example, PVC gave very obvious peaks, while polypropene and polyethylene were more difficult to detect. However, no particles from tyre and road wear were analysed. The conclusion from this study was that scanner electron microscopy with x-ray detection in combination with optical microscopy can accelerate the identification of microplastics in a sample compared to µ-FTIR or Raman, in particular for samples with a high content of non-plastic particles (Wang et al, 2017). Wagner et al (2018) recommend scanning electron microscopy with x-ray detection for the detection of e.g. trace elements like zinc and sulphur that are included in, or can be related to, tyre wear. It should, however, be noted that both zinc and sulphur may come from many other sources, both anthropogenic and natural.

Particles sized 10–80 µm in air have been collected near roads with passive samplers, for identification and characterisation of particles by light microscopy and scanning electron microscopy with x-ray detection (Dietze et al, 2006; Tian et al, 2017; Sommer et al, 2018). The tyre particles were characterised as round, kidney-shaped, or elongated, fully or partly covered in road and brake wear particles, typically with chemical elements like carbon and sulphur, and containing smaller proportions of zinc, silicon, aluminium, sodium, calcium, potassium, magnesium, iron, copper, titanium, molybdenum, manganese, barium, tin, and tungsten. However, in the judgement of the authors, the presence of other particles means that it is not possible to use scanning electron microscopy with x-ray detection as a standalone analytical method for identifying tyre particles. The same conclusion was drawn by Hassellöv et al (2018), and in GESAMP (2019). Sommer et al (2018) also concluded that neither silicon oxide nor zinc oxide can be considered suitable indicators of tyre wear. Instead, it is suggested that tyre and road wear particles are identified based on the shape, surface, and texture of the particles, using a combination of light microscopy and scanning electron microscopy. The study by Sommer et al (2018) showed that approximately 90 percent of the collected particles were tyre and road wear particles, and that around one third of these were tyre wear particles. In volume, tyre wear particles made up just over fifty percent of the particles, and it was concluded that tyre wear is an important source of microplastic emissions from road traffic.

7.4.2. Fourier transform infrared spectroscopy (FTIR)

Infrared spectroscopy is a spectroscopic method that measures the absorbed, or emitted, energy from an infrared light source with a wavelength range of 2–20 µm. Different bonds between the atoms included in a molecule absorb infrared light with different wavelengths. By analysing an absorption spectrum within the infrared light region, it is possible to identify the bonds present in a chemical compound. Each chemical compound has its own substance-specific spectra, i.e. their 'spectral fingerprint', based on the bonds it includes. An infrared spectrum can be used to identify, and sometimes even quantify, different chemical compounds. Reference libraries are available for many chemical compounds, to which the spectra returned when a sample is analysed can be compared, to determine what the sample is composed of (Käppler et al, 2018; Renner et al, 2018; Yang, 2018).

Fourier transform infrared spectroscopy (FTIR) is an interferometer-based infrared spectrometer. This is an advanced form of infrared spectrometry, which has become the industry standard. An interferometer-based infrared spectrometer generates an interferogram, which requires Fourier transformation to be converted into a spectrogram. Fourier transform infrared spectrometry measures the absorbance within an infrared spectrum. Micro-Fourier transform infrared spectroscopy (µ-FTIR) is an improved version of this method, used e.g. to determine the molecular structure of polymers and organic compounds (Berthomieu & Hienerwadel, 2009). Fourier transform infrared spectroscopy is a relatively fast analytical method, which can be used on samples in solid, liquid and gaseous form, with a few different sample preparation techniques (Yang, 2018). A disadvantage of all types of Fourier transform infrared spectroscopy is that they require a reference library to enable easy identification of the sample content. Spectra can, however, be interpreted to identify the bonds of a chemical compound, which can be used to identify which chemical compound(s) the sample may contain. This process is very time-consuming and requires specialist competence, and should preferably be complemented by new reference spectra of the chemical compound(s) the sample is considered to consist of.

New reference spectra can also be used to expand existing reference libraries. A complicating factor is that, depending on what the sample contains, the relative intensity of 'peaks' compared to other peaks in a spectrum may change. This can make identification difficult, in particular when the contents of the sample are unknown and there is uncertainty regarding which reference library it should be compared to. Fourier transform infrared spectroscopy can be used for quantitative analysis, provided the availability of appropriate calibration and reference materials.

To enable analysis of black particles, such as tyre and road wear particles, i.e. particles that absorb infrared light almost completely, Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) can be used. The required instrument is equipped with a crystal with high optical density, e.g. germanium crystal or diamond, which has a high refractive index (Manohar et al, 2017; Sarma et al, 2018). It measures the changes that occur in an internally reflected infrared beam when the beam comes into contact with a sample. The infrared beam is directed at the crystal at a certain angle. The internal reflectance generates an evanescent wave, which extends beyond the surface of the crystal and into the sample, which is in contact with the crystal. In the regions of the infrared spectra where the sample absorbs the energy, the evanescent wave is returned to the infrared beam, which exits on the opposite side of the crystal and continues to the detector in the spectrometer.

This technology has been used to localise carbon black in different phases of rubber blends (Sarma et al, 2018), but also to determine the composition of vulcanised rubber containing carbon black (Manohar et al, 2017). A study has compared µ-Fourier transform infrared spectroscopy with attenuated total reflectance with µ-Raman for quantification of microplastics in seawater (Cabernard et al, 2018). The results of the Raman analysis showed much higher concentrations of microplastics, but took significantly longer to perform. In the same study, both methods were also able to identify the presence of rubber particles in the size range 10–500 µm. In a study comparing µ-Fourier transform infrared spectroscopy with attenuated total reflectance to pyrolysis-GC/MS (section 7.5.1) both instruments returned consistent results (Käppler et al, 2018). This study did, however, not cover rubber materials. Pyrolysis infrared spectroscopy and thermal gravimetric analysis (TGA) have also been shown to be potential methods for analysis of elastomers from rubber tyres with unknown compositions (Fernández-Berridi et al, 2006). An alternative to µ-Fourier transform infrared spectroscopy with attenuated total reflectance for analysis of tyre and road wear particle, is to use a diamond compression cell to make the particles thin enough for Fourier transform infrared spectroscopy. This method has shown promising results (Karlsson et al, 2019). To enable simultaneous and rapid collection of thousands of infrared spectra over large areas of a sample, a focal plane array (FPA) detector can be connected to the Fourier transform infrared spectroscopy system (Renner et al, 2017). The analysis can be carried out using either emitted or reflected light.

Primpke et al (2019) have developed a protocol for hierarchical cluster analysis. In a study by Simon et al (2018), the authors developed a method for estimating the mass of microplastic particles in the size range 10–500 µm. One conclusion from this study was that mass concentration and number of particles may be appropriate complimentary metrics to use. To identify the polymer type based on assumptions about particle thickness turned out to be difficult, as the samples, which came from a water treatment plant in Denmark, contained multiple polymers with varying shape, size, and surface characteristics. Organic materials and other chemical compounds accumulated on the particles also disturbed the analysis, which made the spectra difficult to interpret. Although tyre and road wear particles were not covered by these studies, they highlight some of the difficulties that may arise, and factors that generally need to be considered in relation to the complex field sample materials (road dust, sediments, stormwater, etc.) in which tyre and road wear particles occur.

As is the case with other optical and spectroscopic methods, careful and time-consuming preparation of samples is often required before analysis using µ Fourier transform infrared spectroscopy can be performed. Similar to sample preparation for scanning electron microscopy, it can be complicated to remove biological organic materials, as plastic is hydrophobic, meaning that organic materials are prone to accumulate on its surface (Borg Olesen et al, 2017). For many types of analysis, Fourier transform infrared spectroscopy does not require particles to be extracted individually by hand, instead entire filters can be screened, although this requires specific criteria and reference materials. Today, this is carried out by hand before analysis. Development is currently underway to enable screening and a move away from this time-consuming approach.

7.4.3. Raman spectroscopy

Raman scattering occurs when light (photons) is scattered from chemical compounds in the solid, liquid, or gaseous phase. In Raman spectroscopy a sample is illuminated with a laser beam with a wavelength of 500–800 nm (Yang, 2018). When the sample is illuminated, the energy of the photon can either remain unchanged (Rayleigh scattering), decrease as the molecules in the sample are excited (Stokes scattering) which causes a shift towards the red end of the light spectrum, or increase as the molecules in the sample are de-excited (anti-Stokes scattering) which causes a shift in the light towards the blue end of the spectrum. Both Stokes and anti-Stokes scattering are defined as Raman scattering. The excitations that interact with the photons are often vibrations, but may also be of a magnetic of electronic nature. An advantage with Raman is that even small particles, in the 1µm size range, can be detected (Anger et al, 2018; Mai et al, 2018). A disadvantage is that the signal strength is low. In likeness with other microscopic and spectroscopic methods, extensive sample preparation is required before analysis. Dispersive Raman spectroscopy uses a diffraction grating spectrometer (with similar function to a prism) with a multi-wavelength detector, from which the signals are converted to a Raman spectrum.

Raman spectroscopy is not considered a suitable method for analysis of tyre and road wear particles, as black particles absorb all light directed at them within the wavelength range in question, and therefore do not spread or emit any light that can be detected. This means that it is not possible to generate a specific spectrum (Renner et al, 2018; Wagner et al, 2018). One option is to analyse the rubber particles using Fourier transform Raman spectroscopy, using a laser with a wavelength close to the infrared region (Ellis et al, 1990). Fourier transform Raman spectroscopy is designed to eliminate the issues with fluorescence that occur with conventional Raman spectroscopy. Fluorescence can be avoided by using an excitation frequency just below the threshold for all fluorescence processes. Fourier transforming Raman systems use an interferometer to create an interference pattern, a so called interferogram, which can be converted to a Raman spectrum. For particles in the size range 10–500 µm, automated single-particle exploration coupled to µ-Raman (ASPEx-µ-Raman) has shown very promising results for analysing microplastics extracted from seawater samples. It was also possible to identify rubber particles in the same samples, although not as well as with µ-Fourier transform infrared spectroscopy with attenuated total reflectance, which was used as a comparison (Cabernard et al, 2018).

Confocal Raman microscopy is an analysis technique that uses a standard optical microscope in combination with a Raman spectrometer for high-magnification visualisation of samples, and to carry out Raman analysis on the sample, using a microscopic laser beam. Research is currently underway on the use of Raman spectroscopy to improve the signal quality using better detectors, and spectrum management, automated particle selection, and to extend the reference library for spectral matching and identification (Araujo et al, 2018).

7.5. Gas chromatography mass spectrometry methods (GC/MS)

This section describes pyrolysis-gas chromatography with mass spectrometry, followed by thermal extraction and desorption gas chromatography with mass spectrometry, both defined as thermal gas chromatographic methods.

7.5.1. Pyrolysis-gas chromatography with mass spectrometry (Pyr-GC/MS)

Analysis using pyrolysis-gas chromatography[14] with mass spectrometry (pyrolysis-GC/MS, often abbreviated Pyr-GC/MS) involves rapid heating of a sample to degradation, which produces small molecules that are separated using gas chromatography, and detected with mass spectrometry. Pyrolysis is a form of dry distillation, where the sample is heated in an inert environment (usually to 400–900 °C), and where the organic compounds decompose without incineration. Long polymer chains are broken down into smaller molecule fragments, which are then identified using gas chromatography (Yang, 2018). Pyrolysis-gas chromatography may also require time-consuming sample preparation (Nguyen et al, 2019) although a study by Unice et al (2012) was able to perform pyrolysis directly on field samples on filters, as well as on sediments and soil samples of up to 20 mg. One advantage of pyrolysis-gas chromatography is the ability to determine both polymer type and content of organic additives, like phthalates, benzaldehyde, and alkyl phenols, in a single analysis (Fries et al, 2013). Low pyrolysis temperature gives slower degradation, and by-products with a higher boiling point may be generated. If the temperature is too high, the molecule fragments may instead be too small to be characterised, why it is important to carry out the pyrolysis at the correct temperature to avoid destroying the sample (Yang, 2018). A pyro-gram is generated, in which each ‘peak’ represents a polymer fragment, and all degradation products are included. The peaks are identified and quantified in the same manner as with conventional gas chromatography.

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[14] A standard is available for chemical analysis of pure rubber products, Swedish standard ·SS-ISO 7270-1 https://www.sis.se/produkter/gummi-och-plastindustri/gummi/ssiso72701/. This is, however, not relevant for field samples, or for differentiation between rubber and bitumen.

Pyrolysis-gas chromatography is often used in combination with mass spectroscopy (MS). In a mass spectrometer, organic molecules eluted from the gas chromatographic column are under vacuum bombarded with electrons, which cause the degradation of the molecules into positively charged fragments, identified by mass and charge. Individual organic compounds always degrade in the same way in the mass spectrometer, why a characteristic mass spectrum is produced for each unique molecule. The ions are sorted after mass and charge, after which a mass spectrum is generated. The height of the peaks in a mass spectrum show the relative signal strength of the ions, and is not correlated to the amounts of different ions, as the ions have different signal strengths. For this reason, each peak for a specific organic compound must be quantified using calibration curves from reference substances (Mellon, 2003; Yang, 2018). Identification of chemical compounds is achieved via analysis of reference substances, both by comparison of retention times, and by searches in libraries of known mass spectra for thousands of elements.

The results of analyses using pyrolysis-GC/MS varies between different laboratories, depending on how the samples have been prepared, the type of pyrolyser used, and the way in which the pyrolysis gases are transferred into the gas chromatograph (Nguyen et al, 2019). Of the available pyrolysers, the so-called Curie-point pyrolyser is the most useful, as it can analyse samples of up to 20 mg. However, the composition of the pyrolysis gases is the same within the temperature range 480–980 °C. The analysis method is fast, offers high accuracy, and enables correct quantification of the included chemical compounds, as the temperatures are sufficiently high to avoid unpyrolised residual materials. The Curie-point pyrolyser can now be used on field samples without extensive sample preparation.

Tyre and road wear particles were quantified in sediments from France, Japan, and the United States using pyrolysis-GC/MS in almost all (97%) of the 149 sediment samples analysed (Unice et al, 2013). The measured concentrations of tyre and road wear particles in the sediment samples varied from 26–11,600 µg per g. The quantification method used was based on quantification of characteristic pyrolysis products from rubber tyres (Unice et al, 2012). In the study, 20 mg of dry sediment was pyrolysed at 670 °C in a Curie-point pyrolyser, and the degradation products of the rubber particles were identified using pyrolysis markers (dipentene, vinyl cyclohexene, isoprene, butadiene, and styrene) and quantified using deuterium labelled compounds added to the samples as internal references and standards. The concentration of other rubber products and the total content of tyre and road wear particles in the sediment samples were then calculated from known relationships between rubber in tyre and road wear particles (Kreider et al, 2010).

Pyrolysis-GC/MS has also been used to analyse sediments in a fjord in Norway, but tyre and road wear particles were unfortunately not included in this study (Gomiero et al, 2019). The study used a ceramic oven pyrolyser, which is only able to analyse very small sample volumes, which meant that an extensive sample preparation was required. Fischer & Scholz-Böttcher (2017) have tested pyrolysis-GC/MS on eight of the most common types of plastic. They found that this method complements Fourier transform infrared spectroscopy and Raman well, as it makes it possible to determine the amounts (mass concentrations) of different polymers in a sample. As part of this study, extensive sample preparation was also carried out, despite using a Curie-point pyrolyser that does not require sample preparation. Pyrolysis-GC/MS has also been compared to µ-Fourier transform infrared spectroscopy with attenuated total reflectance (Käppler et al, 2018). The results showed that these methods can be combined with positive results, as Fourier transform infrared spectroscopy provides information about particle numbers, and pyrolysis-GC/MS gives the mass concentrations.

7.5.2. Thermal extraction and desorption gas chromatography mass spectrometry (TED-GC/MS)

Thermal extraction and desorption gas chromatography with mass spectrometry (TED-GC/MS) is a method designed to enable analysis of unknown organic chemical compounds and polymers. With this method, the sample is first gradually heated in a separate device, where it forms gaseous decomposition products. These are then concentrated on a sorbent which is injected into the gas chromatography system using thermal desorption. The gas chromatography system is used to separate the decomposition products in an inert atmosphere, and the mass spectrometer is used to identify the product in the same way as with pyrolysis-GC/MS.

The main difference is that thermal gravimetric analysis (TGA) is used instead of pyrolysis, and that the gases formed are concentrated on a sorbent, after which the entire content of formed thermal products can be injected into the gas chromatographic system. When field samples are analysed using TED-GC/MS, samples of up to 100 mg can be analysed without sample preparation (Dümichen et al, 2019). A method for analysing microplastics has been developed, in which samples of around 20 mg are weighed into an aluminium crucible, which is then positioned for thermal gravimetric analysis and heated to 600 °C (Elert et al, 2017). The decomposition products from the thermal extraction are then concentrated on sorbent cartridges connected to the gas outlet of the instrument, after which the cartridges are analysed using thermal desorption, with automatic injections for the cartridges and cryo-focusing. There is now also the possibility to couple the entire system for fully automated analysis using TED-GC/MS (Dümichen et al, 2019).

Tyre and road wear particles have also been analysed using this technique and without time-consuming sample preparation (Eisentraut et al, 2018). To analyse the reference materials, samples of 0.2–0.4 mg were used. For field samples, dry samples of 10–50 mg were used. The results showed that a number of different markers for rubber tyres could be identified, including decomposition products of rubber, antioxidants, and vulcanisation agents. It was also shown that real field samples could be analysed, in which different rubber materials and thermoplastics could be quantified with a single analysis. This method can be used for relatively large field sample volumes without extensive sample preparation. A disadvantage of TED-GC/MS is that this method does not provide any information about the number of particles, or the particle sizes and forms. The method is, however, a very good complement to Raman and Fourier transform infrared spectroscopy, which do provide this information. The method offers good repeatability and the entire range of particle sizes can be analysed in a single sample.

7.6. Conclusions

- There are no standardised methods for preparation and analysis of tyre and road wear particles.
- All analytic methods described above, except Raman spectroscopy, can be useful in the analysis of tyre and road wear particles, road marking particles, and other microplastics; however, they are all more or less complicated and time-consuming. Extensive sample preparation is often necessary and there is a lack of e.g. reference spectra that can be used to fast, easy, and reliably identify the particle content.
- The two items above mean that analyses are very expensive, and that it can be difficult to get accesses and time at the expert laboratories performing the analysis.
- Development work is underway to improve detection limits and to automate and simplify both the analysis methods and the sample preparation for tyre and road wear particles.
- Different methods provide different types of information, meaning that at least two complementing methods must be used to obtain information about particle numbers, shapes, sizes, and mass in different media.

8. Measures

As mentioned previously, tyre wear is considered to be the by far largest source of microplastics from road traffic. The factors that influence tyre wear have been described in chapter 5, and these are used in the identification of potential measures discussed in this chapter. There are a number of different measures that could reduce the emissions and spread of microplastics from tyre and road wear[15]. However, few measures have been evaluated. In general, the measures can be divided into measures that reduce generation at the source, i.e. measures aimed at preventing the generation of particles, and measures aimed at reducing further spread of already generated microplastic particles.

8.1. Source-reducing measures

Potential measures for reducing emissions at the source relate to factors such as the use of studded tyres, tyre pressure, tyre wear rates, tyre design and dimensions, wheel alignment, speed and driving behaviour, vehicle-kilometres, composition of the vehicle fleet, road design and surface texture, use and application of road markings, and winter maintenance.

8.1.1. Use of studded tyres

The use of studded tyres influences the emission of microplastics in several ways. The studs cause abrasion on the road, resulting in the release of microplastics from road markings and polymer modified bitumen. The studded tyres also roughen and abrade the asphalt surface, whereas non-studded tyres have a polishing effect. It is probable that the roughened surface leads to more tyre wear particles being generated than would have been the case if the surface had not been roughened. Decreased use of studded tyres would, therefore, likely reduce emissions of microplastics both from non-studded tyres, and from road markings and polymer modified bitumen. No data has been found on whether the studded tyres themselves wear more or less than non-studded tyres (Sköldén, The Scandinavian Tyre & Rim Organisation, personal communication, autumn 2019). The impact of studded tyres on tyre and road wear is described in section 5.4.

8.1.2. Tyre pressure

Air pressure in tyres affect tyre wear (see section 5.1). A cost-benefit analysis from the Netherlands found that adjusting to optimal air pressure led to a significant decrease in tyre wear (Verschoor & Valk, 2018). This applied particularly to older vehicles without a tyre pressure monitoring system (TPMS). Tyre pressure monitoring systems have been introduced on passenger cars within the EU, and must be fitted to all newly registered cars from November 2014 (EU Directive 2010/48/EU). Sweden chose not to introduce this requirement. According to the Swedish Transport Administration, the reason was that the main aim of the directive was already achieved, as tyre pressure is always checked when tyres are changed between winter and summer, which takes place twice a year (Swedish Transport Administration, 2014). However, according to a survey by Däckrazzia (2018) one in seven cars (14%) had at least one tyre with an air pressure that was 30 percent too low, which leads to increased tyre wear (see section 5.1).

Verschoor & Valk (2018) have estimated that tyre wear can be reduced by 14 percent if all Dutch vehicles not fitted with a tyre pressure monitor system, or with only an indirect system, were to install a direct system. A direct tyre pressure monitoring system is a sensor-based system that measures the pressure and temperature of each tyre, whereas an indirect tyre pressure monitoring system only measures the rotational speed of each tyre. Both systems are designed to issue warnings in case of malfunction. In a follow-up study, Vreeker (2018) estimated that 13 percent of drivers who had one tyre with air pressure at least 0.2 bar too low could reduce tyre wear by installing and using a specially

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[15] 'Road traffic' here includes the entire road traffic system, i.e. both vehicles and road infrastructure.

designed tyre monitoring system app. To introduce the app an information campaign highlighting the benefits of the app and of tyre monitoring systems has been proposed. Such a campaign is expected to result in more tyre monitoring systems being installed. This is in turn expected to lead to tyre pressures being adjusted on the 8,000–59,000 Dutch vehicles fitted with tyres where the air pressure is at least 0.2 bar too low, which is 0.1–0.7 percent of all Dutch vehicles (Vreeker, 2018). An updated study on the potential benefits of introducing tyre pressure monitoring systems in Sweden, where the connection to both tyre wear and the generation and dispersal of microplastics are considered, could be relevant to carry out.

8.1.3. Tyre tread wear labelling

Another proposed measure by Verschoor & Valk (2018) is the introduction of 'labelling' of tyres, to indicate their wear rate. There is currently a European labelling for fuel efficiency (rolling resistance), wet grip, and noise levels. There is also a rating system for tyre tread wear, called TWR (Tread Wear Rate), which many tyres have. This is, however, designed for American customers and conditions, and has not been shown to correlate well with wear tests in laboratories (Grigoratos et al, 2018). Introducing labelling for tread wear may help raise awareness among consumers, and perhaps also impact the market. However, for this measure to be effective, the basic awareness of the labelling among consumers needs to increase. According to the Swedish Energy Agency, more information is required to assess the benefits of introducing this type of labelling system before such measures are introduced (Swedish Environmental Protection Agency, 2017). For this to work, a standardised method for measuring the wear performance of tyres, valid for Swedish as well as European conditions in general, should be developed. The ETRMA (European Tyre and Rubber Manufacturers' Association) is currently (2019) running an initiative to achieve this.

8.1.4. Tyre design and dimensions

The design and constituents of the tyre may be affected by increasing demands on low wear rates and low content of hazardous chemicals. If eco-design requirements for tyres would be introduced it could be an effective measure against both tyre wear and hazardous chemicals in tyres. Other aspects related to the design is the development of "airless tyres" which may have the potential to produce less deflections in the tyre/road contact patch which could reduce tyre wear.

The tyre dimension can also be assumed to influence tyre wear and thereby microplastic emissions. A narrower tyre gives higher pressure against the road surface. Increased pressure leads to increased abrasion. On the other hand, a narrower tyre means a smaller tread area in contact with the surface, which leads to decreased abrasion. We have not been able to find any data that shows which of these effects dominates for different tyre dimensions. A changing vehicle fleet e.g. more electric vehicles may lead to changes in tyre dimensions.

8.1.5. Wheel alignment

Another measure proposed by Verschoor & Valk (2018) to reduce emissions caused by tyre wear is stricter control of wheel alignment. Tyres with so called toe-in or toe-out alignment, i.e. tilted in the direction of travel, wear faster than properly aligned tyres. If the vertical alignment is incorrect, i.e. the so-called camber angle is high, the tyres wear unevenly, but do not necessarily generate higher amounts of rubber. The tyre industry estimates that incorrect wheel alignment may increase tyre wear by 10 percent (Verschoor & Valk, 2018). According to investigations by Däckrazzia (2018) one in two of 161 examined cars in Sweden had unevenly worn tyres and needed wheel alignment.

8.1.6. Speed limits and driving behaviour

Introduction of new (lower) speed limits and encouraging drivers to drive more smoothly and accelerate, brake, and take corners more gently, are other potential measures to decrease tyre wear and thereby emissions of road-related microplastics and other particles (Verschoor & Valk, 2018). This is supported by studies by Gustafsson et al (2008) and Kwak et al (2013), which showed that higher vehicle speeds lead to increased tyre wear, and by Foitzik et al (2018) who showed that driving at high speeds through bends can lead to increased emission of ultrafine wear particles.

Based on the above, increasing the awareness among drivers about the impact of driving behaviour on tyre wear and how this can be reduced is a possible measure (Verschoor och Valk, 2018). As driving behaviours such as fast acceleration and deceleration are assumed to influence tyre wear (Jekel, 2019) traffic planning solutions that encourage smoother driving may also contribute to a reduction in tyre wear.

8.1.7. Total vehicle-kilometres

The total road traffic, i.e. the total number of vehicle-kilometres, influences tyre and road wear. According to the latest baseline projection from the Swedish Transport Administration, the total number of passenger-kilometres and tonne-kilometres in Sweden is expected to increase significantly for both passenger cars and trucks (see section 5.5). Various government inquiries in Sweden have found that the increase in total vehicle kilometres must be limited if Sweden is to achieve its goal of reducing greenhouse gas emissions from domestic transportation (not including domestic flights) by at least 70 percent from 2010 to 2030 (SOU, 2013a, 2013b; Swedish Transport Administration, 2016). A reduction in total number of vehicle-kilometres would have other positive impacts on the climate and environment (reduced noise pollution, less air pollution, etc.) in addition to contributing to a reduction in the emissions of tyre and road wear particles.

8.1.8. Composition and development of the vehicle fleet

Changes to the composition of the vehicle fleet may also affect tyre wear. Examples include changes to the weight of the vehicle fleet, but also to the vehicles’ ability to accelerate. There is currently a trend, both in Sweden and internationally, towards heavier passenger car, as a result of an increase in the proportion of sport utility vehicles (SUV), in parallel with an increase in the number of electric cars, which are both slightly heavier and able to accelerate faster than conventional vehicles (see also section 5.5.). Controlling the composition of the vehicle fleet may, therefore, be a way to influence the tyre wear, as well as the emissions of tyre and road wear particles.

8.1.9. Road design and road surface texture

It can be assumed that the design of the road impacts both tyre and road wear, and the wear of road markings. A road with curves and bends, sharp bends in particular, causes more wear than a road with no bends. Similarly, a road with hills causes more wear than a road with no hills. Another influencing factor is the extent to which the design of the road leads to frequent and large speed changes. One example is traffic lights, which lead to breaking and acceleration, which can be assumed to increase abrasion.

The texture of the road surface (both micro and macrotexture) influences tyre wear (Swedish Environmental Protection Agency, 2017). A coarse texture can be assumed to cause more emissions from road wear than a smoother surface. When road surface materials are chosen, there are already requirements today relating to friction, noise, durability, and stability (Swedish Transport Agency, 2014). It is worth considering whether it would be appropriate to introduce requirements regarding rolling resistance, which correlates to the texture of the surface, in order to reduce tyre wear (European TRWP Platform, working document under preparation).

The micro-texture of a road surface is affected by e.g. the use of studded tyres, and the aggregate sizes and mineral composition of the asphalt. Some minerals are e.g. harder than others, which may impact tyre wear. How the included minerals cleave or fracture when subjected to pressure and abrasion also varies. This may also influence tyre wear. The relationship between the road surface and its interaction with the tyres is complex, and studies are needed to identify whether, and if so, how, road surfaces can be optimised in relation to tyre wear.

8.1.10. Use and application of road markings

Different types of road markings are wear-resistant to different degrees (see section 4.6.6). This means that one way to reduce wear is to choose a type of road marking that is more wear resistant. Another factor that can influence the wear of road markings is the application method. Rather than applying the road marking to the asphalt surface, so that it protrudes above the surrounding asphalt surface, it can be placed recessed in grooves cut into the surface, and thereby will be less exposed to wear. Road markings recessed in grooves have been investigated by e.g. the Norwegian Transport Agency (Norwegian Public Roads Administration, 2010) and have been found to reduce wear, but also to perform well in relation to wet and dry retro-reflection.

8.1.11. Winter maintenance

Winter maintenance, ploughing in particular, causes significant wear on road markings. Steel blades on the ploughs, can be reasonably assumed to cause more wear than rubber blades, and fixed blades more than spring-loaded. However, it has not been possible to find any assessment on how much wear different plough blades and other winter maintenance activities than ploughing (e.g. sanding and salting) cause on road markings in the literature. Even though only a small proportion of the total amount of microplastics from the road environment has been estimated to originate from road marking wear (Magnusson et al, 2016), it may be relevant to take measures to also reduce these emissions. A first step would be to generate more knowledge about the road marking wear that arises due to winter maintenance machines, and to raise general knowledge on the amounts of road marking-related microplastic particles present on road surfaces, in soils near roads, and in stormwater.

8.1.12. Synergies

Several of the above-mentioned measures do not only impact the amount of microplastics being emitted. Measures that limit total vehicle-kilometres and reduced vehicle weight also lead to reductions in other air pollutants, including greenhouse gas emissions, decreased noise pollution, fewer operation and maintenance efforts, less congestion, a reduction in the area occupied by road traffic, etc. Lower speeds also result in lower emissions of other air pollutants and less noise. Speed reductions also reduce the number of serious road accidents.

8.2. Reduced dispersal of already emitted microplastic particles

The measures that would be appropriate for already generated traffic-related microplastic particles vary depending on whether the particles in question are transported through air (suspension, splash and spray) or stormwater (runoff).

8.2.1. Microplastics in stormwater: combined sewers

Treatment at wastewater treatment plants may be an effective way to remove microplastics from stormwater in systems with combined sewers. Several studies have evaluated the removal efficiency of microplastics in municipal wastewater treatment plants, but to our knowledge no studies specifically on microplastics from roads and tyres have yet been published. The particles removed from the water end up in the sludge. A study of three Swedish treatment plants found that the removal efficiency for microparticles larger than 300 µm was over 99 percent (Magnusson & Wahlberg, 2014). For smaller particles larger than 20 µm the removal efficiency varied between 70 and 90 percent. Another study of a wastewater treatment plant reported a removal efficiency of above 99 percent for particles in sizes between 10 and 500 µm (Ljung et.al., 2018). Combined sewer systems were only built in larger Swedish cities until the 1950s, why only a few percent of all stormwater is currently treated in wastewater treatment plants in Sweden (Stahre, 2004; Swedish Environmental Protection Agency, 2016). According to statistics from Swedish municipalities, only eight percent of the stormwater in urban areas is treated to remove particles and other pollutants from the water, the rest (92%) runs untreated straight into lakes and watercourses (Swedish Environmental Protection Agency, 2016).

8.2.2. Microplastics in stormwater: separate sewers

There are a number of different treatment techniques for polluted stormwater (not managed in a combined system). However, there is considerable need for evaluating the effectiveness of these techniques in removing tyre and road wear, and other microplastics. Below is a description of the most common techniques and their removal efficiencies.

Wet and dry ponds, infiltration basins, ditches, and constructed wetlands are common types of stormwater facilities (Erickson et al, 2013). Approximately 80 percent of all facilities for stormwater treatment from roads in Sweden are stormwater ponds (Holmsten, 2014). Well-designed ponds can trap suspended particles and any pollutants that may be bonded to them by sedimentation (Erickson et al, 2013; Blecken, 2016). However, sedimentation ponds for runoff from roads are only designed to trap particles in sizes from 10 µm to 5 mm (Blecken, 2016). Stormwater ponds and wetlands can be an effective way to separate microplastics. High separation efficiencies of 90–100 percent for microplastic particles larger than 20 µm have been demonstrated (Jönsson, 2016), but the separation efficiencies for tyre and road wear particles specifically have not been studied.

Filter techniques for treatment of road runoff, such as gully pot filters and underground sedimentation facilities and percolation storage, where particles are separated by sedimentation, take up less land areas than stormwater ponds. Assessments of filters carried out by Venghaus et al (2017) showed that some filter techniques were able to separate 61–98 percent of microplastic particles in stormwater in sizes from 14 to 125 µm. The separation efficiencies for tyre particles larger than 125 µm were 78–98 percent. Suspended materials are assumed to be in the size range 0.7–2.0 µm. Particles smaller than 0.7 µm are, therefore, not captured by these filters (Nielsen et al, 2015). As the removal efficiency of the filters is greatly dependent on the size of the particles, there is a need for increased knowledge about the sizes of tyre and road-related microplastics, to enable evaluation of the treatment efficiency.

Ways to solve the problems with high stormwater flows and pollutants today include on-site management by Low Impact Development (LID), i.e. using different local solutions and natural processes, such as green roofs, rain barrels, infiltration in ditches, permeable asphalt, and bio retention filters (also known as raingardens) (Tedoldi et al, 2016; Eckart et al, 2017; Funai & Kupec, 2017). How effective these systems are at managing and separating microplastics from stormwater is not currently known and should, therefore, be studied.

8.2.3. Street sweeping, snow clearing, and dust binding

Street sweeping as a method to reduce the amounts of dust and pollutants on roads has been investigated in several studies (Amato et al, 2009, 2010; Gustafsson et al, 2011a; Männikkö et al, 2014; Janhäll et al, 2016; Järlskog et al, 2017; Järlskog, 2018; Polukarova et al, 2020). Despite the relatively large number of studies carried out, there are no clear conclusions about the efficiency of street sweeping for reducing the number of smaller (< 5 mm) particles, and the pollutants they can transport (either due to their chemical content or as pollutants bound via sorption). The fact that no clear conclusions can be drawn may be that the studies have been carried out for different reasons, and that there are variations in both study methodologies and street sweeping methods. The studies can be divided into those investigating street cleaning to reduce the concentrations of PM_{10} and $PM_{2.5}$ in air, those focusing on stormwater quality, and those that describe the efficiency of individual street sweeping machines for removal of particles from the road surface. The cleaning efficiency of the machines may depend on factors such as the speed of the machine (Järlskog et al, 2017; Snilsberg et al, 2018), the rotational speed and angle of the brushes, as well as its inclination and design (Abdel-Wahab et al, 2011; Vanegas-Useche et al, 2015). For instance, Snilsberg et al (2018), who studied the cleaning efficiency of six cleaning machines, individually and in combination, showed that the design of the machines can be very important to the cleaning efficiency.

Other factors that may affect the cleaning efficiency include precipitation (Vaze & Chiew, 2002), and the texture and dampness of the road surface (Abdel-Wahab et al, 2011; Snilsberg et al, 2018). Vaze & Chiew (2002) showed that precipitation in the form of rain reduces the number of particles and leads to a higher proportion of large particles among the particles found on, but not bound to the road surface. The reason for this is that smaller particles are more easily transported away from the road by the rainwater. At the same time, the amounts and proportion of fine materials increase in the dust bound to the road surface according to Vaze & Chiew (2002). The general effect of street sweeping on stormwater and air quality is difficult to assess, as the amounts, intensity and frequency of precipitation vary over the year, and have a big impact on the measured concentrations of pollutants, both on the road and in the sweep sand and sweep water. Recently published studies, however, have shown that some street sweepers are able to capture small particles, including nanoparticles and microparticles (Järlskog et al, 2017; Polukarova et al, 2020). These studies show that the water from street sweeping contains nanoparticles (1–300 nm), but also very high concentrations of organic pollutants, such as aliphatics, volatile aromatics, phthalates, and polycyclic aromatic hydrocarbons (PAH), why water from street sweeping should be treated before it is released into the environment. Aronsson et al (2018) have also shown that street sweepers are able to capture microplastic, rubber, and bitumen particles in sizes equal to or larger than 100 µm.

To make street sweeping more effective, the European TRWP Platform (n.d.) proposes that street sweeping should be coordinated with weather forecasts. As an example, sweeping could be performed prior to predicted heavy or intense precipitation. As many cleaning machines use brushes made of plastic to collect road dust, wear materials from the brushes may also end up in stormwater. No known studies have yet quantified the amounts of wear materials generated by the brushes of the machines.

During the winter, particles and pollutants from road traffic may accumulate in snow from roads and streets (Björklund et al, 2011; Moghadas et al, 2015). The current recommendation is that collected snow as far as possible should be placed on nearby land and left to melt. In Sweden, dumping of snow masses from road environments in water areas is generally not permitted, as the risk that pollutants contained in the snow spread and the expected environmental impact is considered greater in water than on land. Where there is a lack of places to deposit snow, exemptions from the rules are sometimes granted, and the dumping of snow in water may be allowed (Swedish Agency for Marine and Water Management, 2018). The Swedish Agency for Marine and Water Management estimates that the pollutants introduced into water courses with dumped snow constitute a limited proportion of the total amount of pollutants introduced. However, there is currently no data on the concentrations of tyre and road-related microplastic particles that can be expected in the snow. For this reason, there is a need for studies investigating the quantities of microplastics and nanoplastics in snow in urban areas. These studies are important to be able to assess the extent to which the snow piles pose an environmental risk, and whether the snow should be treated before being deposited on land.

Dust binding, by the application of hygroscopic salt solution on the road surface is used on some national and municipal roads to reduce the amount of dust being whirled up, and thereby the levels of inhalable particles in the air during spring (Gustafsson et al, 2019a, 2019b). This method efficiently reduces the amount of dust being whirled up but does not remove the dust from the system. Instead, it is transported into the stormwater, either by active hosing of the roads or by precipitation. The binding of dust probably hampers the ability of street sweepers to collect dust particles from the road surface, finer particles in particular, why these measures should be coordinated to optimise the reduction of dust containing microplastics in streets and road environments.

8.2.4. Choice and implementation of policy instruments and measures

8.2.4.1. Prioritisation of measures and policy instruments

The benefits of several of the measures mentioned above will, as emphasised by Verschoor & Valk (2018), depend on how they are implemented. As an example, the effectiveness, and therefore benefit, of a measure may depend on whether it is combined with government support by financial incentives, or whether information campaigns are run. To assess the potential benefits of a measure, cost-efficiency assessments, cost-benefit analyses, and multi-criteria assessments can be carried out of different policy instruments and measures, as well as of the implementation methods to be used. These types of studies are generally not carried out at present.

To enable prioritisation, on objective grounds, between different policy instruments and measures, many different types of knowledge are required. Knowledge is needed about the effectiveness of individual measures, e.g. knowledge about the extent to which a measure will decrease microplastic emissions. We also need data on e.g. the magnitude of the emissions before the measure is put in place. To be able to carry out a cost-benefit analysis, we also need information about the harm current emission levels cause, and the relationship between different levels of emissions and damage caused. It can also be assumed that the harmfulness varies depending on e.g. the type of microplastic being emitted, the size of the particles, and the environment in which the emissions take place. The complexity and lack of knowledge about the relation between different measures and their effects etc., means that it is unlikely that it will be possible to, within the foreseeable future, carry out quantitative calculations of cost-benefit type without broad assumptions and large uncertainties.

8.2.4.2. Measures justified by other reasons than the reduction of microplastic emissions

Taken together, the above means that it is currently difficult to determine whether, and if so which, measures should be taken. Some measures can, however, be justified by other reasons than the fact that they reduce the emissions of microplastics. A measure can e.g. be justified because it achieves another goal unrelated to microplastics. As mentioned above, the total vehicle-kilometres must decrease to make it possible for Sweden to, in a reasonable way, achieve its goal of reducing greenhouse gas emissions from domestic transportation by at least 70 percent from 2010 to 2030. Another example is the fact that speed limits may need to be reduced to achieve road safety targets. These measures will also reduce emissions of microplastics.

Sometimes the value of that part of the benefit of a measure that can be calculated with reasonable certainty exceeds the cost of implementing it. When this happens, the measure should be put in place, regardless of knowledge gaps concerning the relation between measures and their effects, the size of emissions, or the effects of microplastics. In some cases, a measure may be justified by being financially favourable, irrespective of its impact on microplastic emissions. If the application of road markings recessed in grooves cut into the asphalt leads to decreased costs for road markings, due to reduced wear, and the additional cost for this method of application is lower than the money saved by reducing the wear, the measure should be implemented, irrespective of its effectiveness in reducing emissions. To calculate whether this is the case would be relatively simple, however, no such studies have been found in the literature.

Another similar example would be a tyre that wears less than traditional tyres. If the lifetime of the tyre is therefore longer, it may be financially beneficial for car owners to buy it, even at a slightly higher purchase price. This action may therefore also be justified irrespective of its effects on emissions of wear particles.

8.2.5. Knowledge, information, and regulations

Sufficient knowledge is required to on an objective basis identify, evaluate, and prioritise which measures to implement, and when. The Swedish Environmental Protection Agency has stressed the need to expand our knowledge about emissions of microplastics from road traffic (Swedish Environmental Protection Agency, 2017). At a more general level, the Chief Scientific Advisors to the European Commission have highlighted the need for increased knowledge about microplastics in their Scientific Opinion 6/2019. Their proposals include fostering of international and cross-disciplinary collaboration, e.g. by promoting the establishment of a global scientific platform on plastic and microplastic pollution, enabling shared and cross-border access to standardised data (European Commission, 2019).

The European Commission's (2019) scientific advisors also suggest that steps should be taken to enable the scientific community to fill knowledge gaps regarding the presence, concentration, and behaviour of nanoplastics in the environment, and (also for microplastics in general) to ensure that decision makers are regularly informed and equipped to take preventative or risk-mitigating measures, should scientific evidence emerge concerning ecological or human health risks specific to nanoplastics.

The advisors also suggest that measures be taken to promote the development of better sampling and analysis methods and risk assessment approaches for microplastic pollution. To achieve this, it is for instance suggested that transparent, rigorous, and detailed disclosure of experimental procedures and metadata be fostered. To create a balanced knowledgebase the importance of also publishing no-effect studies is mentioned. Furthermore, there is a need for standards for measuring and monitoring of microplastic pollution and its effects on ecosystems and human health, to give a globally coherent picture of the nature and threat of microplastic pollution (European Commission, 2019).

The scientific advisors emphasise the importance of taking into account e.g. the relative impact of different sources when measures are chosen. They suggest targeting measures at those sources of microplastics that pose the highest risks, i.e. the main sources, and microplastics with intrinsic properties that make them particularly harmful to the environment, as well as the emissions that give rise to the most exposure. As previously mentioned, knowledge about the magnitude of different sources, the hazards to the environment and human health posed by different types of microplastics, and their fate in the environment is very scarce. The scientific advisors also mention the potential to exploit current provisions in existing legal instruments to prevent and attenuate the presence of microplastics in air, soil, and water (e.g. directives applicable to urban stormwater treatment, use of sewage sludge as fertiliser, and air quality). They also believe that the EU should promote a global treaty aimed at tackling the sources of microplastics and other plastic waste.

The European Tyre and Road Wear Platform expresses the need for a joint platform for compilation of knowledge on evaluated methods for reducing emissions of tyre wear particles. One measure could be to increase consumer awareness about tyre condition and labelling, and about the importance of driving style. The importance of these measures is emphasised by the European TRWP Platform, which claims that the measures can have a high impact within a short space of time. The car industry can also decrease tyre wear, by e.g. investing in producing vehicles with a pre-programmed 'comfort mode' (European TRWP Platform, working document under preparation).

8.3. Conclusions

- Two types of measures are available, firstly measures aimed at reducing the generation of microplastic particles, so called source prevention measures, and secondly measures aimed at reducing the spread of already emitted particles.
- Any measures taken should primarily target those emissions that have the highest negative impact on the environment and human health. The magnitude of the effect depends on

emission volumes, the physical and chemical properties of the emitted particles, and extent of exposure. Measures should also be cost-effective, i.e. reduce the impact on the environment and human health as much as possible per monetary unit.

- To prioritise between different policy instruments and measures on an objective basis, requires many different types of data that are currently not available. Knowledge is needed about the effectiveness of different measures, i.e. about the extent to which a measure reduces microplastic emissions. To perform a cost-benefit analysis also requires knowledge about the harm caused by current emissions, and the relationship between different levels and types of emissions in different media and the damage caused. Due to the complexities and knowledge gaps in relation to effectiveness and other aspects, it is unlikely that it will be possible to, within the foreseeable future, carry out quantitative calculations of cost-benefit type without far-reaching assumptions and significant uncertainties.
- In some cases, a measure that helps reduce emissions or dispersal of microplastic particles may be justified for other reasons than the fact that it can reduce the generation or spread of microplastic particles. One example is that a reduction in passenger- and tonne-kilometres may be necessary in order to achieve the target of a 70 percent reduction in greenhouse gas emissions from domestic transports in Sweden (except flights) from 2010 to 2030.
- Several of the measures that can limit the generation of tyre and road wear particles also contribute to mitigating one or multiple other environmental issues, such as emissions of carbon dioxide and other exhaust fumes, noise pollution, accidents, congestion, and road wear. A combination of lighter vehicles, improved wheel alignment, optimal tyre pressures, lower speeds, and reduced traffic flows could together lead to a measurable reduction in the generation of microplastics from tyre and road wear.
- There are a number of methods available for managing polluted stormwater. Common stormwater facilities include wet and dry stormwater ponds, infiltration basins, ditches, and constructed wetlands. Different filtration systems are also in use. Knowledge on how efficient the different methods are at separating microplastics from tyre and road wear is, however, very scarce, and further research and evaluation is required.
- When it comes to stormwater treated in wastewater treatment plants, microplastic particles can be more or less efficiently removed depending on the design of the plant and the size of the particles. No data has been found on how efficiently microplastics specifically from tyre and road wear are separated. This is another area where further research and evaluation is required.
- Pilot studies are needed to test and compare the effectiveness of different measures, or combinations of measures, aimed at reducing the generation and spread of microplastic and nanoplastic particles from road traffic. Examples of areas where research and evaluation is required include street cleaning, as well as the management and reduction of tyre and road wear particles in road dust, sand from street sweeping, stormwater, stormwater sediments, and soil from ditches and bio retention filters.

9. General conclusions

At the end of each chapter above, except chapter 1, a number of conclusions have been provided in bullet form. In this chapter, the most important of these conclusions concerning microplastics from tyres, road surfaces, and road markings are compiled and discussed.

Only a small number of the existing studies on microplastics relate to microplastics from road traffic, and the ones that do almost exclusively consider tyre wear particles. Studies about particles from the wear of road markings and polymer modified bitumen are almost non-existent. The least is known about the very smallest particles, i.e. the nano-sized ones.

For this reason, one important conclusion is that our knowledge about microplastics from road traffic is very limited. This report shows that there is almost no, or very limited, knowledge on microplastics from tyre and road wear within all the areas it covers, with the possible exception of the physical and chemical characteristics of microparticles, where the current knowledge could be rated as insufficient. This means that there are significant knowledge gaps regarding: the amounts of microplastic particles emitted as a result of tyre, road, and road marking wear; the sizes of the generated particles; how they spread and potentially change in the environment; at what concentrations they are present in different environments; the extent of human and ecological exposure to these particles; and the environmental and human health hazards posed by microplastics from road traffic.

There are also significant knowledge gaps regarding different methods that can be used to limit the generation of microplastics from road traffic, and their respective effectiveness. When combined with the above-mentioned knowledge gaps, the conclusion is that we do not have the knowledge required to, on an objective basis, make well-grounded prioritisations between different policy instruments and measures, or to assess the cost-effectiveness of different measures.

Sources, dispersal and presence

Based on present knowledge and mapping of microplastic sources in Sweden, it can be assumed that at least half of the Swedish microplastic emissions relate to tyre wear particles. Other traffic-related emissions of microplastics include wear particles from the road surface, such as road markings and polymer modified bitumen.[16]

A sizeable proportion of the tyre wear particles consists of relatively large particles, larger than 20 micrometres, and are, therefore, assumed to be mostly deposited on or near the road. This means that a large portion of the dispersal of tyre particles takes place via runoff from the road surface and due to vehicle movements and wind, snow removal and street cleaning. A smaller proportion, up to 10 percent, is assessed to consist of airborne particles.

In urban environments, the majority of the emitted particles end up in stormwater systems. A small proportion of the stormwater is transported to wastewater treatment plants, some of which have been shown to very effectively remove microplastics from wastewater, although there are no studies specifically on tyre wear particles. The removed microplastic particles end up in the sewage sludge, which is managed in different ways. One part is used for soil improvement, why microplastic particles can be deposited on arable land.

Wet and dry ponds, infiltration basins, ditches, and constructed wetlands are common types of stormwater facilities in Sweden, where road traffic particles accumulate (see also *Measures* below).

The presence of tyre wear particles has been demonstrated in road dust, air, stormwater, and different types of sediments, however, the number of studies is too small to determine what constitutes high or low concentrations in different media. There are no studies on presence in sewage sludge, in terrestrial

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[16] Other traffic-related sources of microplastics, that are not connected to tyre and road wear, such as vehicle break-downs/crashes, littering and wear from some types of brake pads, are not covered by this report.

environments (other than traffic environments), or in organisms in nature. Recently performed studies have identified microparticles from tyre wear in sediments from the west coast of Sweden, as well as in watercourses and stormwater in areas close to roads.

Effects and risks

Among the chemicals used to produce tyres, road marking products, and polymer modified bitumen are some that are hazardous to human health and the environment. However, there is currently very limited, or in some cases no, knowledge about which substances are present in the tyre and road wear particles and the extent to which these substances are released from the particles.

The few studies on effects of microplastics from tyre and road wear have mainly focused on the toxicity of leachates from tyre tread particles. These show that toxic substances are leached and that the concentrations causing effects on test organisms vary between different tyres and studies. Organisms have also been shown to ingest tyre particles. It is difficult to judge the relevance of these studies for assessing effects in the natural environment, where organisms are exposed to much lower concentrations, but for longer time periods than in laboratory studies.

The knowledge gaps regarding e.g. exposure, sensitivity of different organisms, concentrations in the environment, and the importance of particle size and other characteristics, mean that there is insufficient data to draw any certain conclusions about the risks to human health and the environment posed by microplastic particles from road traffic. The fact that these particles are likely persistent, that emissions are significant, and that the particles can affect organisms negatively, means that there are good reasons to reduce emissions. The importance of reducing emissions of microplastics has also been emphasised by the Group of Chief Scientific Advisors to the European Commission.

Characteristics and chemical composition

As mentioned above, a sizeable proportion of the tyre wear particles consists of relatively large particles, larger than 20 micrometres.

Tyre and road wear particles are composed of polymers, different chemical additives, and fillers. The polymers used in tyres are elastomers, which are thermoset polymers. The polymers in road markings and polymer modified bitumen can be thermoplastics, thermosets, thermoplastic elastomers, or elastomers. Sweden uses mainly thermoplastic road marking compounds, and the most commonly used polymer in polymer modified bitumen is styrene butadiene styrene (SBS).

There are large variations in the physical characteristics of microplastic particles from tyres, road markings, and polymer modified bitumen, for instance concerning shape, size, and density. The chemical composition also varies. This, in turn, influences their behaviour and the potential risks they pose to humans and the environment.

Wear

The assumption that microplastic particles from tyres in Sweden constitute at least half of the primary emissions of microplastic particles by weight is based on mapping of sources and calculations of tyre wear. There are, however, major uncertainties in the calculation methods used. Moreover, there are no studies on whether tyre wear varies between studded tyres, friction tyres, and summer tyres, or whether, and if so to what extent, the wear rate varies between different tyres of the same tyre category, depending on e.g. tread pattern, dimension, or chemical composition. A number of other factors, apart from the tyres themselves, also influence tyre wear. Some of the most important are load, wheel alignment, vehicle speed, driving behaviour, and road surface characteristics.

The wear of road markings is influenced by e.g. traffic volume, the use of studded tyres, driving behaviour, and maintenance and management measures, such as ploughing, sanding, and sweeping, as well as the weather conditions. The use of studded tyres has a significant impact on the wear of the road surface, and therefore also on emissions of polymer modified bitumen, where this is a constituent in the road surface material.

Sampling and analyses

There are no standardised methods for neither sampling nor analysis. This means that different methods are used, which makes comparisons between different studies difficult.

There are three main types of sampling strategies used for microplastics in aquatic environments: selective sampling, bulk sampling, and volume-reduced sampling. For each sampling strategy, there are also many different types of sampling methods. The choice of sampling method is determined by the medium to be sampled (although there may be several different methods to choose from), and the sample volume required is determined by the substances or particles to be analysed.

Many different aspects must be taken into account to ensure that the collected samples are relevant and representative. One such aspect is the fact that the density of the microplastic particles influences how they spread and where they accumulate. The density is affected by e.g. whether the particle is a pure tyre particle or consists of a mixture of tyre, bitumen, and minerals from the roadway.

The available analysis and preparation methods are complex and time-consuming, and can only be performed by a small number of experts. This makes them costly, and means that it may be difficult to get analysis done. Different analytic methods provide different information, meaning that a combination of at least two methods is required to obtain data on the number, shape and mass of particles in different media. Development efforts are currently underway both in Sweden and internationally, to automate and simplify both the preparation and analysis of samples.

Measures

Measures to reduce exposure to microplastics in the environment can be divided into two main categories: measures that reduce the generation of microplastic particles, and measures that prevent or decrease the spread of already emitted microplastic particles in the environment. There are good reasons to take measures to reduce the generation and spread of microplastics from road traffic, however, there is insufficient knowledge to on an objective basis determine which measures to prioritise.

A good, and often cost-effective, starting point when selecting a measure is to take action as close to the source as possible. In this case, this would mean firstly preventing or reducing the generation of microplastics from road traffic, and secondly stopping or decreasing the spread of microplastics from road traffic as close to the source as possible. More knowledge about the effectiveness of different measures is required.

Examples of measures that can reduce the generation of microplastic from road traffic include measures that decrease total vehicle-kilometres and vehicle weight, limit speed, reduce the use of studded tyres, lead to calmer driving behaviour, result in a trend towards lighter vehicles, optimise tyre pressure and wheel alignment, and make the road surface smoother. Maintenance and operation of roads, such as sanding, ploughing, sweeping, also influence the generation of microplastics. Several of the measures that reduce the generation of tyre and road wear particles from road traffic also lead to a reduction of many other negative aspects and effects, such as emissions of carbon dioxide and other exhaust fumes, noise pollution, accidents, congestion, and road wear.

Measures that can reduce the spread of microplastics from road traffic for instance include a number of techniques for managing polluted stormwater. A small proportion (a few percent) of the stormwater in Sweden finds its way to wastewater treatment plants. It has been demonstrated that wastewater treatment plants can remove microplastics from wastewater very efficiently, with a removal efficiency of 70–100 percent (meaning that the particles end up in the sludge). The lower removal efficiency (70–90 %) was identified in a Swedish study and related to particles captured on a 20 µm filter, while the removal efficiency for particles captured on a 300 µm filter was higher (> 99%). Another Swedish wastewater treatment plant showed a high removal efficiency (>99%) for particles in the size range 10–500 µm. There are, however, no studies specifically on microplastics from road traffic.

Examples of stormwater facilities include wet and dry ponds, infiltration basins, ditches, and constructed wetlands. Different types of filtration systems are also used. Approximately 80 percent of the road stormwater facilities in Sweden are ponds. The ponds are designed to sediment particles in sizes from 10 µm to 5 mm. Stormwater ponds may therefore provide an effective means to separate microplastic particles within this size range. The separation efficiency for specifically tyre and road wear particles has not been studied. It has been shown that ponds can remove 90–100 percent of microplastic particles larger than 20 µm.

The most appropriate policy instrument to implement measures depends on the measure being considered. However, all types of policy instruments, i.e. financial and legislative instruments, as well as information, and increased knowledge through research, could be relevant for reducing emissions of microplastic from tyre and road wear.

10. Research, development, and evaluation needs

As explained in the previous chapter, the knowledge gaps are big or very big in all areas covered by this report concerning microplastic particles from road traffic. More knowledge is therefore required in number of areas, and it is difficult to pinpoint areas where it is extra important to close the knowledge gaps. However, by working from the most important questions to find answers to, and the knowledge required to find these answers, we can identify a few important areas, where the lack of knowledge is especially important to resolve.

Two of the most important questions from a policy perspective are:

1. Does the current and potential future exposure to humans and the environment from microplastic particles generated by road traffic pose a significant environmental or health issue? And if this is the case, how big is this problem?
2. What measures could be put in place to cost-effectively reduce the impact of microplastics from road traffic on the environment and human health?

To answer the first question will for instance require toxicity studies under laboratory conditions, to investigate how different organisms in different media are affected by different levels of different types of microplastics from road traffic over shorter and longer time periods. We also need to know at what concentrations different microplastics from road traffic are present in different environmental compartments, to enable us to assess the levels of exposure to different organisms. The results of the laboratory studies and data on presence and exposure can then be used in the assessment of the impact on the environment.

There are no standards for how to for instance collect, prepare, or analyse samples of microplastics. This makes it hard, and sometimes impossible, to compare different results. This is a major problem, as the number of studies is relatively small, and the available analysis and preparation methods are time-consuming and costly to perform. If standards were in place for the above-mentioned areas, it would enable us to faster, and to a lower cost, obtain the knowledge we need to e.g. determine the risk posed by microplastic particles from road traffic to humans and the environment.

The second question is about reducing the exposure to microplastics from road traffic, for example by making them less hazardous to the environment and human health by changing the chemical composition of tyres. Exposure can be reduced by taking measures to reduce the emissions of microplastics, but also by decreasing their ability to spread. To reduce exposure to microplastics already present in the environment is much more difficult. This would require clean-up of environments, which is sometimes done to remove pollutants from contaminated land. It is, however, unlikely that this would be carried out in relation to microplastics from road traffic at the present time. Human exposure can be limited e.g. by providing people with information regarding the ways in which they can be exposed. Based on current knowledge about risks and exposure, there is, however, no reason to provide such information.

Below are a few specific examples of knowledge requirements:

- More knowledge is needed about how environmentally hazardous and health hazardous different types and sizes of microplastic particles from road traffic are to different organisms, as well as about the exposure to different organisms in different environments.
- There is a need for both laboratory studies (e.g. measuring of sorption, desorption, density and size changes over time and under different conditions, and degradation tests), and field studies (e.g. measuring of concentration, size distribution, distribution of different types of microplastic particles, etc. in different environments). There is also a need for development of models (for estimation of expected dispersal pathways, concentrations, and exposure in different environments).

- Validated, faster, more automated, and more standardised methods for sampling, preparation, and analysis of microplastic particles from road traffic needs to be developed for determination of shape, size, number, chemical composition, mass, etc. of the particles. This is required e.g. to enable comparison of findings from different studies, increase our knowledge about presence and spread, and to enable more accurate evaluation of risks.
- Analyses are often limited to particles within a limited size or density interval, which also makes comparison difficult. For this reason, the size and density of the analysed particles should also be standardised, to enable comparison between different studies, and to increase our understanding of the presence and spread of particles in different media (water, sediments, soil, and air). To measure particles with broader size and density intervals is important to enable both assessment of the overall presence, and modelling of spread and presence in different media.
- Different measures for reducing generation and spread of microplastic particles from road traffic should be identified and evaluated. As an example, studies on the relation between measures and effects concerning emissions and driving behaviour, tyre types, road surfacing materials, tyre pressure, wheel alignment, the structure of the road surface, are needed.
- There are significant uncertainties in the calculation methods and models used to assess the contribution of tyre and road wear particles to emissions, and how this varies for instance for different types of tyres, road surfaces, driving behaviour, seasons, and tyre air pressure. These methods should, therefore, be improved and validated.
- To assess the tyre wear in the road environment, and how it influences the generation of microparticles from tyre wear, measurements need to be carried out in controlled driving simulation studies and in the field, on various types of roads, road surfaces, in different weather conditions, and for different types of tyres.
- Knowledge is needed on what policy instruments, and types of policy instruments, are the most appropriate to achieve desired outcomes under different circumstances. In some situations, financial or legislative instruments may be more suitable, in others increased information and data from research may be more appropriate. There may also be situations where a combination of different instruments is the best option.

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Appendix A. Compilation of aquatic toxicity tests on tyre particles

Table A. Studies on aquatic toxicity of tyre tread particles and tyre wear particles carried out in 2005–2019

Description	Test species	Results/Toxicity	Reference
Acute and chronic toxicity of tyre tread particles (TP) from one new tyre. The TP-particles (size 10–80 µm) were generated with a steel brush against a rotating tyre, and leached in ultra-pure water (50 and 100 g TP/L) by shaking for 24 h at pH 3. Toxicity was tested on leachates without particles, from the two leachate concentrations. Additional leaching tests were made to study the effect of pH (at pH ranging from 3-7), and to study the effect of aggregation on zinc release from tyre tread particles.	Green algae: *Raphidocelis subcapitata* (unicellular freshwater micro algae) Crustacean: *Daphnia magna* (water flea) Frog (embryos): *Xenopus laevis* (African clawed frog)	Results for the dilution series based on 50 g TP/L (leachates without particles) showed the following: • 72-h EC50 (growth inhibition) for *R. subcapitata* was 0.47 g TP/L (calculated from 0.93% concentration of 50 g TP/L) • 48-h LC50 (immobility) for *D. magna* was 26.75 g TP/L • chronic exposure caused all *D. magna* to die after 5 days at 5 g TP/L • 50 g TP/L caused significant embryotoxic effects for *X. laevis* and caused death to 80.2% of the *X. laevis* • 120-h EC50 (malformed larvae) for *X. laevis* was 19.2 g TP/L (calculated from 38.3% of the concentration 50 g TP/L) • the leaching of zinc increased by decreasing pH: 1.2 mg Zn/L at pH 7; and 44.7 mg Zn/L at pH 3 • zinc and organic components were identified as causing the toxicity. Aggregation of rubber particles decreased zinc release. More zinc was released in column tests where the particles were not aggregated than in corresponding leaching with aggregated particles. Toxicity was also less for leachates derived from 100 g TP/L which had more aggregated particles, compared to leachates from 50 g TP/L. Aggregation which reduces the surface area available for leaching was suggested to be a likely cause.	Gualtieri et al, 2005a

Description	Test species	Results/Toxicity	Reference
Acute toxicity of tyre tread particles (TP) from 12 different new tyres. The particles were generated with a rasp and leached in very hard water (hardness 250 mg/L as $CaCO_3$; pH 8.0, according to standard for daphnia test) and incubated for 72 h at 20 ± 2 °C prior to toxicity test. Particles were present during the toxicity test.	Crustacean: *Daphnia magna* (water flea)	The different tyres showed varying toxicity for *D. magna* (exposed to leachates with particles): • 24 h-EC50s (immobility) ranged from 0.29 to 32 g TP/L • 48 h-EC50s (immobility) ranged from 0.0625 to 2.41 g TP/L. The toxicity increased for all tyres with increased exposure time. UV-exposure of leachate with *D. magna* present increased the toxicity for *D. magna* between 1 and 39 times, which (according to Wik & Dave) might be explained by organic substances exhibiting phototoxicity (i.e. substances becoming more toxic when irradiated by UV or visible light) e.g. PAH.	Wik & Dave, 2005
Acute toxicity of tyre tread particles (TP) from 25 different new tyres. The particles were abraded with a rasp and leached in very hard water (hardness 250 mg /l as $CaCO_3$; pH 8.0, according to standard for daphnia test) for 72 h at 44 °C. The leaching temperature was chosen to simulate a worst-case scenario (road temperature on a hot day). The particles were removed with a filter prior to toxicity test carried out at 20 ± 2 °C. Zinc concentrations were measured. Toxicity Identification Evaluation (TIE) was performed with six manipulations of the leachates (C18 SPE extraction, ion exchange tests, EDTA addition, STS addition, and MILLEX filtration).	Crustacean: *Daphnia magna* (water flea)	The different tyres showed varying toxicity for *D. magna* (exposed to leachates without particles): • 24-h EC50s (immobility) ranged from 1.4 to > 10.0 g TP/L • 48-h EC50s (immobility) ranged from 0.5 to > 10.0 g TP/L. Zinc ions (Zn^{2+}) were present in all leachates, in concentrations ranging from 110 to 590 µg Zn^{2+}/L. Of the TIE manipulations only C18 SPE extraction reduced toxicity significantly, indicating (according to Wik & Dave) that non-polar organic compounds caused most of the toxicity.	Wik & Dave, 2006

Description	**Test species**	**Results/Toxicity**	**Reference**
Acute toxicity of tyre tread particles (TP) from new tyre rubber samples with different additives added. The samples had been prepared by a tyre manufacturer specifically for the test***.*** One reference formulation (sample 1), that would represent a typical summer tyre tread, contained the minimum of constituents (ingredients) needed to make vulcanized rubber (e.g. including zinc oxide). From this reference formulation, 21 different samples were prepared by adding different types of known additives in known amounts. These additives were different process and extender oils (5 samples), antidegradents (i.e. antioxidants and antiozonants) (6 samples), vulcanization accelerators (6 samples) and fillers and reinforcing agents (4 samples). Samples were cut in 2 x 2 x 2 mm pieces and leached in very hard water (hardness 250 mg/L as $CaCO_3$; pH 8.0, according to standard for toxicity test) for 72 h. Toxicity tests were performed with particles present.	Crustacean: *Daphnia magna* (water flea)	The tread samples with different additives showed varying toxicity for *D. magna* (exposed to leachates with particles): • 24-h EC50s (immobility) ranged from 0.5 to > 10 g TP/L (varied more than 20-fold) • 48-h EC50s (immobility) ranged from < 0.31 to 7.0 g TP/L (varied more than 22-fold). The two most toxic samples contained para-phenylenediamine antidegradents (which function by migrating to the surface). These were followed by three samples containing benzothiazole accelerators. Six of the samples were more toxic than the reference sample which contained zinc oxide and was also slightly toxic. For some samples, UV-exposure increased toxicity (especially for the sample containing diaryl-p phenylenediamine [DTPD]), which (according to Wik) suggested content of substances exhibiting phototoxicity. The results showed that the choice of additive greatly affects the toxicity.	Wik, 2007

Description	**Test species**	**Results/Toxicity**	**Reference**
Acute and chronic toxicity of tyre tread particles (TP) from 3 different used tyres. The particles were abraded with a rasp and leached six times sequentially in deionised (MilliQ) water. The length of each leaching varied between the different leaching sequences (5, 9, 20, 7, 5 and 11 days). After each leaching sequence, the leachates with particles were filtered and fresh deionised water was added to the TP. Toxicity tests were carried out after each leaching sequence. Zn concentrations were measured, and Toxicity Identification Evaluation (TIE) was performed.	Green algae: *Raphidocelis subcapitata* (unicellular freshwater micro algae) Crustaceans (water fleas): - *Daphnia magna* - *Ceriodaphnia dubia* Fish (eggs): *Danio rerio* (Zebra fish)	The toxicity tests on leachates without particles showed the following: The reproduction of *C. dubia* was the most sensitive endpoint tested. EC50 (reproduction) was 0.01 g TP/L for the most toxic tyre, which was also the newest of the used tyres. The toxicity of all tyre leachates was reduced by the sequential leachings. After the sixth leaching the EC50s were > 0.1 g TP/L for all measured endpoints. • 72 h-EC50s (growth inhibition) for *R. subcapitata* ranged from 0.05–0.77 g TP/L (1st leaching); and from 1.01–2.84 g TP/L (6th leaching) • 48 h-EC50s (immobility) for *D. magna* ranged from 0.67–1.15 g TP/L (1st leaching); and from 5.50–7.70 g TP/L (6th leaching) • 48 h-EC50s (immobility) for *C. dubia* ranged from 0.55–0.84 g TP/L (1st leaching); and from 0.55-5.00 g TP/L (6th leaching) • 48 h-LC50 (lethality) for *D. rerio* was only detected for the most toxic tyre at 0.55 g TP/L (1st leaching). The TIE indicated (according to Wik & Dave) that the toxicity was caused by zinc and organic compounds. There was also a concentration dependent relationship between toxicity and measured zinc concentrations.	Wik & Dave, 2009

Description	Test species	Results/Toxicity	Reference
Chronic toxicity of tyre particles from ground tire. The ground tyre material (< 0.59 mm) was leached in deionized water and shaken for one week at 19-22 °C. Toxicity tests were performed on filtered leachate without tyre particles.	Mosquito larvae: - *Aedes albopictus* (Asian tiger mosquito - *Aedes triseriatus* (Eastern tree hole mosquito)	The toxicity tests on leachates without particles showed the following: *A. triseriatus* was most sensitive of the two mosquito species. Survival declined steeply • for *A. triseriatus* from 0.1 g tyre particles/L, and there was no or very low survival between 0.1 and 100 g tyre particles/L • for *A. albopictus* from 10 g tyre particles/L, and there was no survival at 100 g tyre particles/L. The zinc concentration in the highest test concentration (100 g/L) was 89 mg/L.	Villena et al, 2017

Description	Test species	Results/Toxicity	Reference
Acute and chronic toxicity, as well as ingestion of tyre tread particles (TP), studied on one used tyre (driven 10,000 km). The particles were generated by using a rotating grindstone and were thereafter sieved (< 500 µm). The number of particles per weight unit was determined (0.29 g corresponding to 1 million particles). Different toxicity tests were made: • Addition of TP for one day to artificial freshwater medium to study ingestion • Acute toxicity of leachates from TP leached in artificial freshwater medium for 48 h at 25 °C and tested both with particles (0–15 000 particles/mL = 0–4.35 g TP/L), and without particles (0–12 5000 particles/mL = 36.25 g TP/L) • Chronic tests on leachates with tread particles present (0-2000 particles/ml = 0.58 g TP/L) with exposure for 21 days. The water was renewed every week.	Crustacean: *Hyalella azteca* (fresh-brackish water amphipod)	*H. azteca* was shown to indiscriminately ingest tyre tread particles (< 500 µm) added to freshwater medium. The particles were seen in the gastrointestinal tract already after one hour and filled the entire gastrointestinal tract after 24 h. After transferal to clean water, *H. azteca* excreted the particles within 48 h, which (according to Khan et al) suggested a gut retention time of 24-48 h. The acute toxicity tests with *H. azteca* showed • 48 h LC50 (mortality) at 1 g TP/L for leachates with particles • 50% mortality within an interval of approximately 1–4 g TP/L (4,000–15,000 particles/mL, read from a diagram) for leachates without particles. LC50 could not be determined. Mortality, reproductive output and net growth for *H. azteca* were all significantly impacted at the higher exposure concentrations following 21-day exposure to leachates with particles: • At 0.58 g TP/L the test organisms died (92.5 ± 6.9%) • At 0.29 g TP/L reproduction was reduced to 2.4 ± 4.3, compared to 18.9 ±5.3 in control beakers • At 0.145 g TP/L growth was reduced from 18–6.7%.	Khan et al, 2019

Description	**Test species**	**Results/Toxicity**	**Reference**
***Acute toxicity of tyre tread particles (TP) from 20 end-of-life car tyres*.** The particles were generated with at stainless steel file, sieved to < 500 µm and leached in filtered sea water (0.5 g TP/L). Samples were taken at different time intervals up to 120 hours and leachates were filtered before algal exposure. In additional test, algae were exposed zinc nitrate in filtered sea water, in zinc concentrations corresponding to those measured in the TP leachates.	Marine macroalgae: *Ulva lactuca* (sea lettuce)	Increasing concentrations of leachates (without particles) resulted in a non-linear reduction in the efficiency of photochemical energy conversion of the micro algae (*U. lactuca)*. Increasing concentrations of zinc from the tyre tread particles increased the uptake of Zn by *U. lactuca*. Results indicated (according to Turner and Rice) measurable toxicity at leachate concentrations as low as 0.025 g TP/L. Zn-concentrations in the samples ranged from 3.98 to 12.53 mg Zn/L. The release of zinc increased with increasing leaching time. Leachates from TP were more toxic than seawater with zinc nitrate. Presence of other forms of zinc, or toxicity also caused by other substances than zinc was suggested as possible causes.	Turner and Rice, 2010
Chronic toxicity of tyre particles from scrap tyres added to laboratory produced sediment. Tyre particles (< 590 µm) were obtained from a scrap facility. The steel belt fragments had been removed. Soil was collected from a spot adjacent to a detention pond for road stormwater. In one treatment 83.8 g tyre particles/kg soil was added. In another treatment zinc chloride corresponding to 10 g Zn^{2+}/kg soil was added. The zinc concentration represented the highest zinc concentration measured in the pond. The spiked soils were mixed with tap water, capped and allowed to age for 8 months. Toxicity tests were performed throughout metamorphosis.	Frog (eggs and larvae): *Rana sylvatica* (wood frog)	Both tyre particle treated sediment and zinc chloride treated sediment caused increased time for larvae to complete metamorphosis by 7 days compared to control. Zinc concentrations in *R. sylvatica* were significantly higher when exposed to sediment treated with tyre particles (212 mg Zn/kg dry weight frog) and zinc chloride (324 mg Zn/kg dry weight frog), compared to concentrations in the control (81.7 mg Zn/kg dry weight frog).	Camponelli et al, 2009

Description	Test species	Results/Toxicity	Reference
Acute toxicity of tire and road wear particles (TRWP) from 3 different tyres in one collective sample. Particles were produced in a laboratory road simulator containing asphalt cassettes, and sieved at 150 µm to remove large pavement pieces. Toxicity tests were made on the following: • Elutriates produced from of clean freshwater sediment that had been mixed with synthetic water (hardness 80–100 mg/L as $CaCO_3$; pH 7.4–7.8), and spiked with TRWP to concentrations 0.1-10 g TRWP/L sediment-water mixture. Mixing was done for 24 h at 22 ± 2 °C, and centrifuged water phase without particles was tested. • Leachates from TRWP (10 g TRWP/L) leached in synthetic water (pH 7.4–7.8; hardness 80–100 mg/L as CaCO3) for 72 h, both at 44 °C in light and at 21 °C in darkness. Filtered leachate was tested. • Elutriates of TWRP leachates (prepared as above, both at 44 °C in light and at 21 °C in darkness) that were mixed with clean freshwater sediment for 24 h, and decanted and filtered, and then diluted with synthetic water to concentrations 0.625-5 g TRWP/L. Toxicity Identification Evaluation (TIE) was made on leachates from high temperature (44 °C) incubation treatment.	Crustacean: *Daphnia magna* (water flea) Green algae: *Raphidocelis subcapita* (unicellular freshwater micro algae) Fish: *Pimephales promelas* (fathead minnow)	The toxicity tests on leachates and elutriates without particles showed the following: Leachates from TRWP incubated in water at 44 °C were acutely toxic to *D. magna*: • In tests on only leachates, EC50 (immobility) was 4.3 g TRWP/L and NOAEC was 1.25 g TRWP/L • In tests on elutriate from sediment mixed with TRWP leachate, EC50 (immobility) was 5.08 g TRWP/L and NOAEC was 2.5 g TRWP/L. No effect on *D. magna* (immobility) was observed for TRWP leachate incubated in water at 22 °C, or for elutriates of TRWP leachates mixed with sediment. No effect was observed for the sediment elutriate incubated at 22 ± 2 °C (EC/LC50 > 10 g TRWP/L) neither on *D. magna* (measured as immobility), nor on *R. subcapitata* (measured as growth), nor on *P. promelas* (measured as survival). EC50 and LC50 were > 10 g TRWP/L. TIE (phase 1) suggested (according to Marwood et al) presence of a cation and an anionic organic compound acting antagonistically.	Marwood et al, 2011 1)

Description	Test species	Results/Toxicity	Reference
Chronic toxicity of tyre tread particles (TP) from 5 used tyres mixed with sediment. The particles (10−586 µm) were generated by grating, cryogenic freezing and subsequent grinding and were merged to one collective sample. This was mixed with sediment in the concentrations 0-100 g TP/kg dw (0-10% dw). Different organisms and toxicity endpoints were tested during 28 d exposure. Intake of particles was also studied. Sediments were analysed for heavy metals and PAHs.	Fresh water benthic macroinvertebrates: - *Gammarus pulex* (amphipod) - *Asellus aquaticus* (waterlouse) - *Tubifex spp* (sludge worm[segmented]) - *Lumbriculus variegatus* (black worm (segmented))	The toxicity tests on sediment with particles showed the following: At the highest test concentration, i.e. 100 g TP/kg dry weight in sediment, no adverse effects were found on: • the survival, growth, and feeding rate of *G. pulex* and *A. aquaticus* • the survival and growth of *Tubifex spp* • the number of worms and growth of *L. variegatus.* The zinc concentration in the tyre tread particle sample was 5.65 g/kg. PAH concentrations did not increase with increasing tyre tread particle concentration in the sediment. For *G. pulex* an average of 2.5 and 4 tyre tread particles were found in bodies and faeces, respectively, after 28 days exposure.	Redondo-Hasseler-harm et al, 2018
Chronic toxicity of tyre and road wear particles (TRW) from 3 tyres mixed with sediment. The particles were generated in a laboratory road simulator equipped with asphalt cassettes and were sieved at 150 µm. TRWP were added to freshwater sediment at concentrations up to 10 g TRWP/kg, mixed for 15 minutes and then equilibrated in cold storage (4 °C) for 48 h. Sediment toxicity tests were carried out on *C. dilutes* (35 days) and *H. azteca* (28 days). Sediment elutriates were tested on *C. dubia* (7 days) and *P. promelas* embryos (32 days). Moderately hard synthetic water was used.	Midge (larvae): *Chironomus dilutes* Crustaceans: *Hyalella azteca* (fresh-brackish water amphipod) *Ceriodaphnia dubia* (water flea) Fish: *Pimephales promelas* (fathead minnow)	Exposure to TRWP spiked sediment caused mild growth inhibition (20%) in *C. dilutes*, and no adverse effect on growth or reproduction in *H. azteca*. Exposure to elutriates (without particles) from sediment spiked with TRWP resulted in slightly (but not significant) diminished survival in larval *P. promelas,* but had no adverse effect on growth or reproduction in *C. dubia*.	Panko et al, 2013 1)

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1) Funded by *the Tire Industry Project*, an international consortium of 11 tyre manufacturers.

Abbreviations in table A.1

$CaCO_3$ = calcium carbonate

C18-extraction = a column which contains octadecyl bonded silica (molecule with 18 carbons) and is used to sorb non-polar compounds.

EC50 = *Half maximal effective concentration*. The concentration of a test substance which cause effect in 50 percent of the test organisms.

EDTA = Ethylenediaminetetraacetic acid. A substance used to bind metals and form complexes.

Elutriate = the water phase after mixing sediment with water and allowing sediment to settle.

h = hour(s)

LC50 = *Half maximal lethal concentration*. The concentration of a test substance that kills 50 percent of the test organisms.

MILLEX = a filter

NOAEC = *No Observed Adverse Effect Concentration*. The highest concentration of a substance that under defined conditions of exposure causes no observable/detectable adverse effect (alteration) on morphology, functional capacity, growth, development, or life span of the test animals.

STS = *Sodium thiosulphate*.

UV = ultraviolet

ABOUT VTI

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Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

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