Simulated atmospheric concentration of tyre wear in an urban environment

Extended abstract

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Summary

Tyre wear is one of the main emission sources of primary microplastics in Sweden. Tyre wear particles (TWP) can potentially have adverse health effects on humans, and urban areas are hotspots of TWP emissions. The purpose of this study is to estimate the concentration of TWP in urban air, and also to present previous research and future research needs.

Mathematical modelling is used to estimate the emissions and concentrations of TWP in urban background air complemented with street level simulations at three busy streets surrounded by buildings. The emissions are calculated with the NORTRIP model, taking into account both direct and resuspended tyre wear emissions based on road traffic data and road weather conditions. The particle concentration in air is calculated with a wind model and a gaussian model for the background concentrations and with a street canyon model for the selected streets, taking buildings into account. The simulations cover the year 2019.

The results show that TWP are ubiquitous in urban air, although in much higher concentrations close to roads with heavy traffic or roads surrounded by buildings. The average yearly roof level concentration varies from around 0.2 µg m^{-3} in areas with moderate traffic to 1.17 µg m^{-3} close to busy roads. The concentrations decline fast with increasing distance from roads. The yearly mean concentration at the selected streets is 0.6-0.9 µg m^{-3}. The simulated concentrations correspond to 3-4 % of the total observed PM_{10}.

Future research should focus both on improving the emission estimates, measurement methods and health effects of TWP.

Foreword

This project is financed by the Swedish Environmental Protection Agency. This extended abstract is a short summary of a manuscript prepared for publication in a scientific paper.

1. Introduction

Microplastics (plastic particles <5 mm in diameter) are present everywhere in the environment, in both water, soil and air. Many studies have focused on the transport of microplastics in water, but the airborne component has received less attention. Microplastics can be transported for long distances in air and have for example been found in remote mountain areas (Allen et al., 2019) and in Svalbard (Bergmann et al., 2019). Urban areas are likely hotspots for microplastic emissions, which can pose risks for living organisms and the environment. There have been some studies investigating the effect of microplastic inhalation in people, showing adverse health effects, eg focusing on workers in synthetic textile factories who are exposed to high levels of microplastic fibers (Prata et al., 2020). However, more evidence is needed to support these findings (Prata et al., 2020).

One of the major sources of primary microplastics to the environment is traffic, which gives rise to emissions mainly from tyres, but to a small degree also from road markings and asphalt containing polymer modified bitumen (Andersson-Sköld et al., 2020). In Sweden, the tyre wear emissions amount to approximately 13 000 tonnes per year (Magnusson et al., 2016) which correspond to about half of the total microplastic emissions (Sundt et al., 2014). Measurements of deposition of microplastic particles in Sweden have shown that tyre wear dominates in large cities, while other types of microplastics are more common at large distance from cities (Magnusson et al., 2020). This was one of the few studies investigating the regional variation in airborne microplastics which also took tyre wear into account. Tyre wear particles have also been shown to comprise 34 % of the measured particle concentration close to busy roads (Sommer et al., 2018).

Tyre wear emissions arise from the friction between rolling tyres and the road surface. Some studies suggest that high tyre temperatures may also cause emission through volatilization (Andersson-Sköld et al., 2020). Tyres loose 10–20 % percent of their mass during their lifetime (Andersson-Sköld et al., 2020). The TWP are emitted directly into air, in contrast to several other types of microplastics, eg artificial turf, laundry fibers and personal care products, which are mostly transported in water, sewage systems and in soil. Emissions from tyre wear are affected by several factors, such as tyre properties (summer/winter tyre, inflation pressure, alignment, brand, dimensions etc.), road surface properties, vehicle properties (weight etc.), driving style and temperature (Andersson-Sköld et al., 2020). Tyre wear particles come in a range of sizes from 10 nm to several 100 µm (Kole et al., 2017). Usually, the PM_{10} fraction (particles <10 µm) is considered airborne.

There are only a few measurement studies of atmospheric microplastic concentration or deposition available today. The concentrations range from 0-175 particles per m^3 in urban air (Abbasi et al., 2019; Asrin and Dipareza, 2019; Gaston et al., 2020; Liu et al., 2019) and the deposition rates from 29-602 particles per m^2 and day. (Zhang et al., 2020). However, most of these measurement studies had a minimum size detection limit larger than 10 µm and not all of them included tyre wear in their definition of microplastics, meaning that they are likely to underestimate the real values. Panko et al., (2013) and Rausch et al., (2022) measured specifically the PM_{10} tyre wear concentration in urban areas to 0.004-1.34 µg m^{-3} and 0.28-2.24 µg m^{-3} respectively.

Recently, measurements of atmospheric microplastic concentration were performed in Stockholm with an innovative method for automated detection and classification of microplastic particles (Rausch et al., coming paper). The results showed tyre wear (PM_{5-10}) concentrations ranging from 0.7-2.2 µg m^{-3} during different time periods and in two different highly frequented streets. The tyre wear comprised

5-15 % of the total PM_{10} concentration. Tyre wear particles were the main type of microplastic particle found. Measurements with the same method were also performed in Switzerland, where tyre wear comprised 21 % of the total PM_{10} concentration (Rausch et al., 2022). The lower percentage of tyre wear in PM_{10} in Stockholm is mainly related to a higher contribution from mineral particles, as a result of studded tyre use and winter sanding.

Modelling studies of airborne microplastics are limited to trajectory modelling in order to determine possible source or downfall regions (Zhang et al., 2020). To our knowledge, no modelling study of the microplastic concentration in air has been performed. In this study we use model simulations to predict the concentration of TWP in an urban area, Stockholm, Sweden, a location where tyre wear will be an important source of microplastics due to the large amounts of traffic.

2. Method

The tyre wear concentration in Stockholm, Sweden, during one year is modelled. Stockholm is the capital of Sweden with approximately 1.5 million inhabitants. Especially in the city center, buildings are commonly flanking the roads, creating low ventilation and the possibility for high pollution levels.

Urban scale background concentrations are modelled using the NORTRIP (NOn-exhaust Road TRaffic Induced Particle) emission model (Denby et al., 2013b, 2013a) in combination with the Airviro wind model and Gauss dispersion model (Apertum, 2021). Results are evaluated at a height of 2 m above ground (or above roof level where there are buildings) for a grid of size 100×100 m at 1 hour time steps. The NORTRIP model calculates the direct and resuspended non-exhaust emissions from road traffic based on traffic, meteorology and road cleaning/maintenance activities. For this study, only tyre wear is activated, while road and brake wear are set to zero. The Gauss model calculates the dispersion of particles based on gaussian plumes extending from the emission sources based on meteorological data.

The emission factors for light vehicles are based on measurements of tyre weight loss and emission factors for heavy vehicles are based on literature values recalculated to the Swedish urban vehicle fleet, according to the methods described in Polukarova et al., (2022, in prep.). The traffic data is based on the emission data base maintained by the East Sweden Air Quality Management Association, which contains information of the weekly and diurnal traffic variation, the light and heavy traffic amounts, speed and tyre type on all roads in the network. The amount of heavy traffic is 6-8 % on most of the smaller urban roads and 10-20 % on some of the transit routes. Mean daily traffic vary from a few thousand on the smaller streets to 50 000–80 000 on the motorways through the city. The light vehicles are assumed to have studded or studless winter tyres during the winter season, both of which have higher emission factors than summer tyres. The studded tyre share varies from 40 % in the inner city to 55-60 % in the suburbs.

In addition to the urban background concentrations, street level concentrations are also calculated for a selected number of streets with the NORTRIP-OSPM model. The OSPM model is a street canyon dispersion model, taking into account the effect of buildings. All three selected streets (Hornsgatan, Folkungagatan and Sveavägen) are flanked by homogenous buildings on both sides of the relatively narrow street canyons and have daily traffic volumes of 14 000–22 000 vehicles. Therefore, these streets are some of the worst pollution hotspots in the city center.

3. Results

Figure 1 shows the calculated yearly mean emission rate and concentration of tyre wear in the Stockholm region. The total yearly PM_{10} emissions of tyre wear sum up to 96 tonnes in the model area. The yearly mean urban background concentrations vary from 0-1.17 µg m^{-3} in the modelled area.

Calculated concentrations are compared to the measured total PM_{10} concentration at four of the city's permanent measurement stations at Hornsgatan, Folkungagatan, Sveavägen and at Lilla Essingen. The later represents an open spot by the E4/E20 motorway. The results show that the modelled tyre wear concentration corresponds to 3-4 % of the measured total PM_{10} concentration, i.e. in the lower range of the measurements by Rausch et al. (comping paper) in Stockholm. However, direct comparison of modelled and measured values will contain uncertainties.

There is a clear pattern with highest concentrations along roads with heavy traffic. The maximum concentrations are found along the E20/E4 motorway, with 50 000–80 000 vehicles per day, running through the city from southwest to northwest connected through a ring road around the city center. This pattern is also indicated by measurements. For example, Rausch et al., (2022) found that the percentage of TWP in PM_{10} was 21 % at a kerbside location and 6 % in urban background.

In the city center, the roof level concentrations are relatively uniform, whereas the street level concentrations (points in Figure 1), are substantially higher, due to the lower ventilation in these locations. Residents will be exposed to the street level concentrations where there are buildings flanking the streets, as is often the case in the inner city. At more open locations, such as along the motorways, the Gauss model concentrations are more representative.

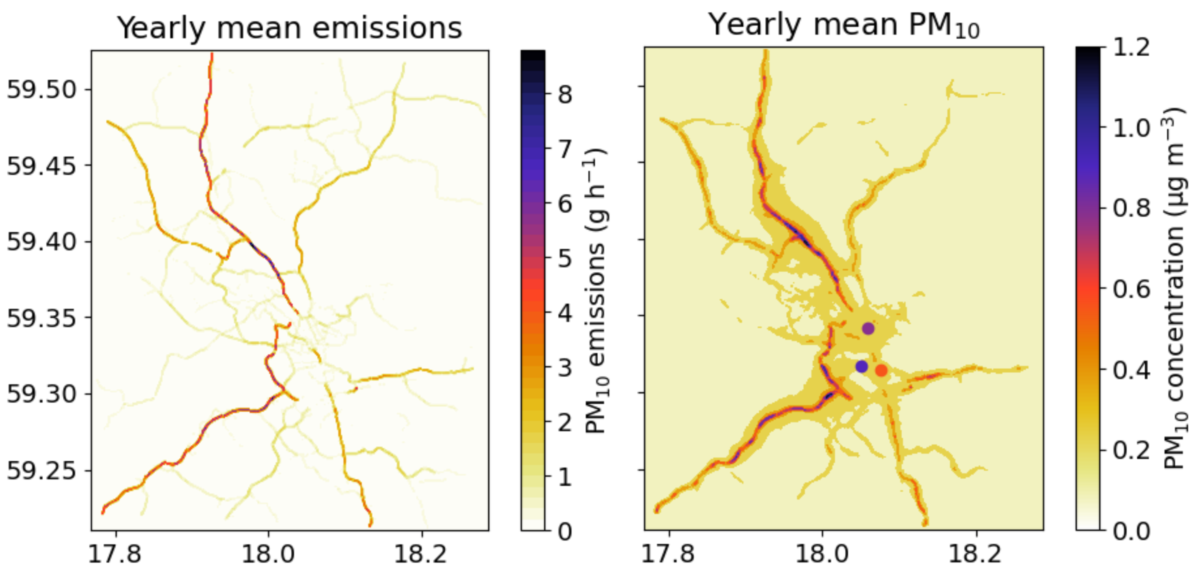

Figure 1: Emission and concentration of TWP smaller than 10 µm over the Stockholm urban area calculated with the NORTRIP-Gauss model (shading). The three points show the street level concentrations calculated with the NORTRIP-OSPM model.

Table 1 shows yearly, daily and hourly mean concentration of PM_{10} from tyre wear from the model simulations. The results agree reasonably well with the few available literature estimates: 0.004-1.34 Panko et al., (2013), 0.28-2.24 Rausch et al., (2022) and 0.7-2.2 µg m^{-3} Rausch et al., (coming paper). The concentrations are below the environmental quality regulations for PM_{10} of 40 µg m^{-3} yearly mean and 50 µg m^{-3} daily mean. Even though the TWP fraction of PM_{10} is small, every additional µg m^{-3} can contribute to exceedances of the air quality limits. As it is yet unknown how this fraction affects the toxicity of PM_{10}, it is important to estimate in order to describe the magnitude of the problem.

Table 1: Statistics of PM_{10} tyre wear concentration from the simulations. For the Gauss model, the 90th percentile is calculated based on the maximum anywhere in the domain, i.e. not from the time series in any specific grid box.

	Gauss	Hornsgatan	Folkungagatan	Sveavägen
Yearly mean concentration (µg m^{-3})	1.17	0.9	0.6	0.8
Daily mean concentration (max/90 %tile) (µg m^{-3})	10.3/1.4	3.1/2.0	1.8/1.2	3.7/1.7
Hourly mean concentration (max/90 %tile) (µg m^{-3})	80.2/6.3	6.7/2.6	4.3/1.7	7.2/2.5

Figure 2 shows the daily and hourly time series as a maximum calculated over the whole area (NORTRIP-Gauss max) and in the three city streets. The time variations are largely due to meteorology and road conditions. Most of the very high concentration events take place in winter when stable meteorological conditions are common, limiting the pollutant dispersion. Time periods with zero concentration also occur in winter due to snow- or ice-covered roads, inhibiting tyre wear emissions, e.g. during 22 jan–7 feb. The highest monthly average concentration occurs in April when there is almost no precipitation and high levels of resuspension of particles that were trapped in snow and ice on the road during winter.

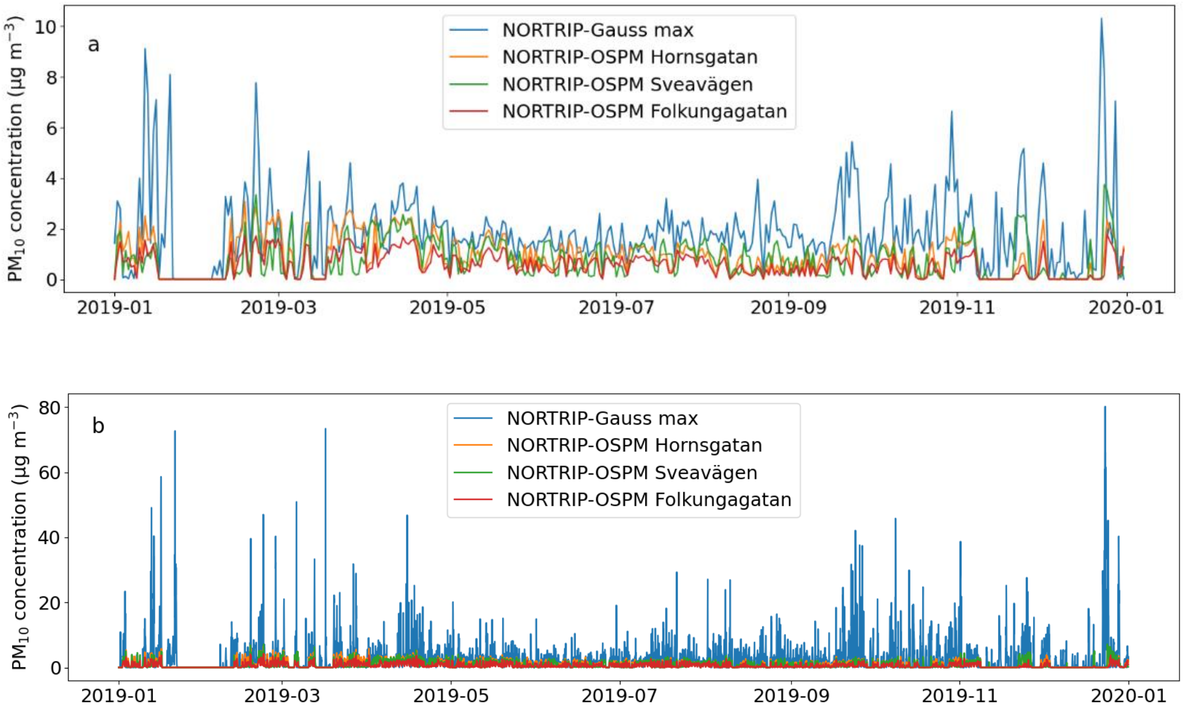

Figure 2: Time series of a) daily mean and b) hourly mean time series of PM_{10} concentrations in the Gauss model and in the three street canyons. The Gauss values are maximum values from anywhere in the domain.

From the simulations with NORTRIP-OSPM at Hornsgatan some more detailed data could be obtained. The results show that the average diurnal variation of TWP concentration follows the traffic pattern, with peak concentrations during rush hour at 16 local time and high values approximately between 7 and 20. On average, 75 % are direct emissions and the rest are due to resuspension from the road surface. Heavy traffic give rise to 25 % of the total tyre wear (all sizes), although comprising only 8 % of the number of vehicles.

4. Discussion

This study presents simulations of atmospheric tyre wear concentration in an urban area. Roof level concentrations are calculated in a grid covering the city, complemented with street level concentration for three busy streets surrounded by buildings.

The results show that TWP are ubiquitous in urban air, although in much higher concentrations close to roads with heavy traffic or roads surrounded by buildings. The average yearly roof level concentration varies from 0.2 µg m^{-3} in areas with moderate traffic to 1.17 µg m^{-3} close to busy roads. The concentration declines fast with increasing distance from roads. Since the grid boxes are of size 100×100 m, even higher values can be expected close to roads. The calculated street canyon concentrations are substantially higher than the roof level concentrations, due to the low dilution in these locations. The simulated concentrations correspond to 3-4 % of the total observed PM_{10}. As PM_{10}, regardless of composition, is a health issue, every extra µg m^{-3} risks to exceed the stipulated limit values and affect public health negatively. During days where PM_{10} concentrations are close to the limit value, also a few micrograms of TWP can contribute to an exceedance. The toxicity of TWP by its own and as part of PM_{10} is also not well understood, why it is important to estimate its concentration in order to motivate further studies.

Previous measurement studies have shown that microplastics are observed in urban areas, but they have only been snapshots in time and space and have often not included tyre wear, which is a very large source of microplastics. Our simulations show that there is a large variability of tyre wear concentration across the city and over time, indicating how important it is to measure at different locations and to cover a range of meteorological conditions.

However, to improve modelled estimates, better emission factors are needed. There is a large variation in the emission factors in literature and especially a large uncertainty regarding the effect of speed, cornering, acceleration and braking on the emission rate. There is also less data on tyre wear from heavy vehicles, which is a group of vehicles with large variations in terms of size, load, number of tyres etc.

More measurements of airborne microplastics would also be useful for model validation and to investigate e.g. regional and seasonal differences in microplastic concentration. In order to achieve this, tyre wear identification methods have to be further improved. Many previous studies have relied on a large amount of manual work for particle identification and classification. Especially fine particles (<2.5um) have been harder to identify, although they are likely more abundant and more relevant from a health perspective.

To model the fate of microplastics over longer distances and find out where they are deposited, it is important to improve the understanding of the TWP properties, such as size, density, shape, and their behaviour in air, e.g. rate of deposition, aggregation, degradation, their effect on cloud physics etc.

The simulated TWP concentration corresponds to more than 1000 particles per m^3 close to busy roads, implying that a significant amount of TWP will be inhaled by residents. Microplastic particles may be harmful in themselves when inhaled, but also act as vectors for other substances (Prata et al., 2020). Due to their large surface area, potentially harmful microorganisms and chemicals, eg, PAH:s from vehicle exhaust, are easily adsorbed to the surface of microplastic particles (Prata et al., 2020). Tyre particles also contain additives, some of which are hazardous for the environment and human health, which may leach from inhaled TWP (Andersson-Sköld et al., 2020; Prata et al., 2020). With the aid of model studies, like this, data for exposure calculations can be obtained.

As well as being possibly harmful to humans, the tyre wear emissions also pose a possible threat to the environment. Larger or heavier particles are likely deposited close to the source, ending up in soil, sediment or being moved during road cleaning. Smaller particles will tend to be transported longer distances. As Stockholm is situated at the Baltic Sea coast and the governing wind direction being towards the sea, much of the particles will likely be transported by the winds and deposited over sea, where they could have negative effects on marine life and where they will persist for a long time. More research on the effects TWP and other microplastics on the environment is also needed.

Traffic is projected to keep increasing in future (Trafikverket, 2020a, 2020b), implying increased tyre wear emissions. Electric vehicles will likely replace a large share of the vehicle fleet in the near future. Electric vehicles are heavier than similarly sized combustion engine vehicles and accelerate faster, factors which could increase the emissions (Beddows and Harrison, 2021). On the other hand, tyres for electric vehicles are created to withstand wear better and the improved traction control may decrease the spin (Johannesson and Lithner, 2021), factors which may decrease the tyre wear. Also, driving behaviour is likely to be different in electric vehicles. These issues are investigated in an upcoming survey-based report (Mirzanamadi and Gustafsson, 2022). Except for the electrification, also heavier and stronger fossil fueled cars, like SUV:s are trending and probably adding to tyre wear.

There are numerous ways to reduce tyre wear, from technical solutions to policies (Johannesson and Lithner, 2021). Some obvious ways are by reducing traffic, speed limits or vehicle size. Better control of tyre pressure and wheel alignment and a smoother driving style also reduces tyre wear. New techniques to collect the tyre wear particles at the wheel may also be possible to restrict the emissions.

5. Conclusions

From this study it can be concluded that:

- Modelling of TWP concentrations using the NORTRIP model seems to give relevant results compared to previous findings
- TWP are ubiquitous in urban air, although in much higher concentrations close to roads with heavy traffic or roads surrounded by buildings
- Yearly average TWP concentrations range from 0.2-1.17 µg m^{-3} in urban background and from 0.6-0.9 µg m^{-3} at three inner city streets flanked by buildings
- Mean daily concentrations can be up to 10.3 µg m^{-3}
- Street canyon concentrations are substantially higher than the roof level concentrations
- There is a large variability of TWP both in time and space indicating the importance to measure at different locations and at different periods of the year
- The contribution of TWP to daily mean PM_{10} can cause exceedances during days where concentrations are close to the air quality limit value
- The Stockholm area is likely a large source of airborne microplastics to the sea
- There is a need for improvements of emission factors for TWP, with emphasis on driving style and vehicle types
- On-going trends including heavier, stronger and electric vehicles in combination with increasing traffic is likely to increase TWP contribution to PM_{10} and risk additional exceedances of daily limit values
- The effects on human health and the environment are still not well understood, and more research is needed

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