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Comprehensive approach to national tire wear emissions: Challenges and implications

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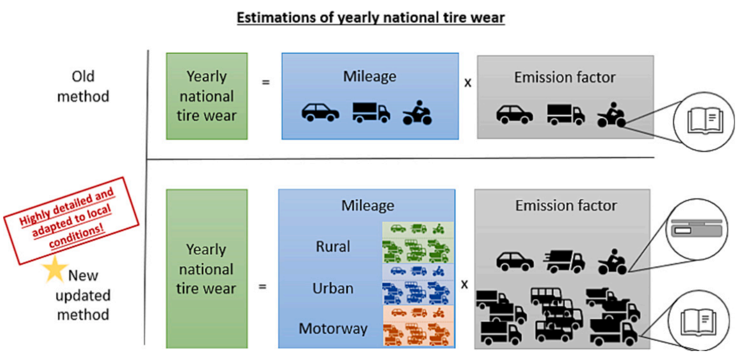
HIGHLIGHTS

- A detailed framework has been developed for the estimation of national tire wear emissions.
- The developed method includes new emission factors based on weighing of 586 tires.
- Tire emissions in Sweden during 2019 amounted to 11,040 t.
- Tire wear emissions are dominated by passenger cars and LDV (65 %).
- HDV contributes to 31 % of the total tire wear emissions in Sweden.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of vehicle tires has been identified as a major source of microplastics in the environment and an increasing source of urban particulate air pollution. In light of increasing traffic volumes, increasingly heavier and more powerful vehicles due to trends and electrification, and the lack of tire wear regulation, methods to estimate and monitor changes in national emissions are needed as input for environmental impact assessments. Emission estimations of tire wear are made either based on the mileage approach or the sales approach. This study aims to investigate if and how the mileage approach can be improved by using emission factors for passenger cars and LDVs based on our own measurements and emission factors from the literature for HDVs and buses. An approach with emission factor adjustments based on weight and number of tires in combination with highly detailed mileage data has been evaluated. Sales approach calculations have been used to validate the method. A secondary aim was to use the new mileage approach framework to calculate the national tire wear emissions for Sweden. These calculations resulted in slightly lower total emissions than previous estimations provide, but with higher emissions for passenger cars and light-duty vehicles, and lower emissions for heavy-duty vehicles and motorcycles. Passenger cars constitute more than half of the total emissions. It is concluded that even though the framework offers greater detail, thus increasing the possibilities to adjust for changes in emission factors and mileages in specific vehicle categories, the challenges posed by such factors as the lack of

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measured emission factors for heavy-duty vehicles and uncertainties regarding the quality of mileage statistics makes the estimations uncertain. Important future suggestions for research include establishing reliable emission factors, especially for heavy-duty vehicles, and initiating research to better understand how climate, road networks, surface properties, and vehicle fleet characteristics affect emission factors.

1. Introduction

The problem of microplastic (MP) pollution in the environment has become a matter of great concern and debate in recent times. The question of understanding and quantifying the risk of microplastic particles to the environment is highly relevant and has been addressed by the EU (European Commission, 2022). This topic has been extensively reviewed in, for example, Knight et al. (2020) and Baensch-Baltruschat et al. (2020, 2021).

Tire wear particles (TWP) produced by friction between vehicle tires and road pavement are a significant source of microplastic pollution (Kole et al., 2017; Wagner et al., 2018a, 2018b; Baensch-Baltruschat et al., 2021). Approximately 1.3 million tons are emitted yearly in the EU (Wagner et al., 2018a, 2018b). Environmental concerns have been raised due to the high emissions and the potential toxicity of the components in the rubber mix. One example is the additive 6PPD; it reacts with ozone to form 6PPD-quinon, which has been shown to be toxic to some aquatic organisms (Tian et al., 2020; Hua and Wang, 2023). Additionally, tire wear is an increasing fraction of traffic-related non-exhaust emissions (Fussel et al., 2022).

Two different model-based approaches have been used to estimate how much TWP contributes to national MP emissions: the mileage approach and the recycling/sales/material flow approach (Baensch-Baltruschat et al., 2021). The mileage approach relies on emission factors based on tire wear per vehicle kilometer and vehicle mileage. It has been used in studies of tire wear emissions in countries such as the Netherlands (Verschoor et al., 2016), Norway (Sundt et al., 2014), Sweden (Magnusson et al., 2016), and South Korea (Lee et al., 2020). The recycling/sales approach combines either the tire sales figures or records of the number or mass of tires collected for recycling for a set area with the estimated lifetime mass loss of the average tire (Blok, 2005).

The mileage approach allows for greater detail regarding the type of emissions source and emissions distribution in the environment, such as emission factors for specific vehicle types and traffic activity data, which can be further divided into urban and rural roads and motorways. This facilitates the assessment of the impact on emissions from changes in vehicle design or traffic and the development and assessment of possible regulations and measures against TWP emissions, such as the Euro-7 emission standard. However, since tire wear is influenced by such factors as climate, road topology, and road surface properties and conditions, national emission factors are expected to differ between countries.

Unfortunately, as shown by Mennekes and Nowack (2022), the emissions factors chosen for different tire types are often poorly justified and based on previous studies rather than one's own measurements. Of the studies that used their own measurements, half were carried out in the 1970s; one analyzed only light-duty vehicles, and one only considered buses. Only three non-peer-reviewed studies were considered to provide reliable results, which were cited a maximum of three times in the network. Thus, the available numbers for tire wear emissions are highly uncertain. The studies also rely on country-specific parameters, which can make the results less suitable to apply in other geographic regions. One example is the geographically variable use of winter tires, which have different wear rates than summer tires (e.g., ADAC, 2021). Vehicle fleets, especially heavy vehicles, may differ in terms of vehicle combinations and weights, the most common vehicle types used, and transportation regulation practices.

This study is part of a governmental assignment to estimate the national TWP emissions for Sweden, so this was its primary aim. While measurements of tire wear for passenger cars and light-duty vehicles could be carried out, measurements of heavy-duty vehicle tire wear were not feasible. As a result of the many challenges faced, focus was shifted during the work towards developing the mileage approach by providing measurement data for tire wear emission factors from passenger cars and exploring how literature-based emission factors for heavy-duty vehicles (HDVs) and buses can be adapted to local conditions. This is the primary aim of this paper. In addition, the challenges encountered when developing the mileage approach and the implications of this work for the scientific community and stakeholders are highlighted. Sweden is a suitable case study for these assessments since there is a significant amount of well-documented and online-available statistics and data on traffic activity and vehicle characteristics.

The structure of the article reflects its methodological focus. The methodology section describes the data collection for the tire wear emission factors for passenger cars and light-duty vehicles. Further, it elaborates on adapting literature-based emission factors for HDVs and buses to the Swedish vehicle fleet and combining the emission factors with detailed mileage data to produce the model outcome. In parallel with the development of the mileage approach, the authors explored the sales approach to compare the emissions estimation for heavy-duty vehicles. The results and discussion section presents the outcome of the developed emissions-based mileage approach and discusses the objectives and challenges in estimating national tire wear emissions.

2. Methods

In this project, both the mileage and the sales approach methods have been used. The following sections will describe the general equations used for each model, followed by a methodological description of how the required input data has been estimated.

2.1. Mileage approach equations

The tire wear emission factor (EF) represents the tire wear generated per kilometer traveled for one tire [g/tire/km]. However, this factor can vary among different vehicles and tire types. Additionally, factors such as driving style, road conditions, weather, and tire positioning on a free or driven axle can influence wear. The EF must reflect an average across various drivers, vehicles, and road conditions to be applicable for national-level tire wear estimations. Any subdivision into groups should be done carefully to ensure the validity of the specific wear emission factor.

In this study, tire wear has been categorized for different vehicle types, with passenger cars further divided into various tire types. Since tire wear is influenced by acceleration, braking, and steering frequency, which differ on different road classes, separate wear emission factors have been employed for three road classes: urban, rural, and motorway. Urban driving involves frequent maneuvers at low speeds, motorway driving occurs mainly at high speeds, and rural driving at intermediate speeds.

For a specific vehicle type, with an average yearly traveling distance D, and with the total number of tires in traffic being N, the total yearly emissions (mass/year) are:

$$\mathrm{E} = \mathrm{EF} \cdot D \cdot N \tag{1}$$

If wear emission factors are known for different tire types, the total yearly emissions for tire type i are:

$$E_i = \mathrm{EF}_i \cdot D_i \cdot N_i \tag{2}$$

where D_i is the average yearly traveling distance for tire type *i*, and N_i is the total number of tires of type *i* in traffic. The emissions can further be subdivided for different road types as:

$$E_i = E_{i,urban} + E_{i,rural} + E_{i,motorway} \tag{3}$$

An emission factor for a specific road type *j*, can be defined by using a dimensionless correction factor C_{ij} which relates the emission rate for the specific road type to the average emission rate for all road types.

$$\mathrm{EF}_{ij} = \mathrm{EF}_i \cdot C_{ij} \tag{4}$$

The average yearly traveling distance can be subdivided with respect to the different road types as:

$$\mathrm{D_i} = D_{i,urban} + D_{i,rural} + D_{i,motorway} \tag{5}$$

The emissions for a specific tire type can then be written as:

$$E_i = \sum_j E_{ij} \cdot D_{ij} \cdot N_i = \mathrm{EF_i} \cdot \mathrm{N_i} \cdot \sum_j \mathrm{C_{ij}} \cdot \mathrm{D_{ij}} \tag{6}$$

From comparing Eqs. (2) and (6) it is clear that

$$\sum_j C_{ij} \cdot D_{ij} = D_i \tag{7}$$

If relative wear ratios for the different road types with respect to a reference road type are known, the correction factors can be determined from

$$C_{ij} = \frac{r_{ij}}{\sum_j r_{ij} \cdot \mathrm{Sh}_{ij}} \tag{8}$$

with r_{ij} being the relative wear ratio, and $\mathrm{Sh}_{ij} = D_{ij}/D_i$ is the vehicle mileage share for tire type *i* on road type *j*.

The total tire wear emissions from a specific vehicle type are calculated as:

$$E = \sum_i E_i \tag{9}$$

2.2. Sales approach equations

The sales approach takes into account the fact that if total tire wear does not change much between different years, the number of tires that need to be replaced per year is a reasonable estimate of the total number of tires consumed during the year. The number of tires that need to be replaced can be estimated from tire recycling numbers or the sales numbers of new tires, although the latter is more common.

For a specific vehicle type, the total yearly wear emissions (mass/year) can be calculated as

$$E = S \cdot W \tag{10}$$

where *S* is the annual sales of tires for this vehicle type in Sweden, and *W* is the average weight loss of a tire during its lifetime. Care must be taken so that the sales numbers represent tires to be replaced on the existing vehicle fleet.

If different tire types are used, the total yearly emissions for tire type *i* is

$$E_i = S_i \cdot W_i \tag{11}$$

2.3. Input data used for calculations

In principle, obtaining relevant data should be straightforward. For the sales approach, statistics on the number of yearly scrapped tires should be combined with estimates of the average tire lifetime weight loss. The latter could be determined from weighing a sample of randomly selected scrapped tires and comparing the results for each tire with manufacturer-supplied data of the tire weight for new specimens.

For the mileage approach, to determine representative emissions factors, a combination of vehicle mileage statistics and the weight of scrapped tires (as with the sales approach) was used. In addition to the average tire lifetime weight loss, the average tire lifetime is needed. However, determining the average lifetime requires a larger set of samples than for weight loss since driver-specific and geographical differences will have a much more pronounced influence. Alternatively, the lifetime can be determined from tire sales data. A drawback is that results from the sales and mileage approach cannot be compared since they are based on the same input data.

A complication when attempting to separate vehicle types is that these types may use the same kind of tires. One example is tires for heavy buses and trucks; another is passenger cars and light-duty transport vehicles. In addition, tire sales statistics tend to lump certain vehicle types together, further complicating the analysis. A possible solution would be to use a relationship between wheel load and tire wear for establishing a relationship between emission factors for different vehicle types. A model approach seen in dynamic-based vehicle wear studies uses a linear correspondence between tire wear and wheel load (e.g., Li et al., 2012; Venkatachalam et al., 2021). Such a model refers to the use of the same tire at different loads, and it is highly plausible that tires made for higher wheel loads are constructed to handle the load better. Due to a lack of data in the literature on how wear scales with load between different tire types, we decided to use a linear one-to-one scaling in this study. Such scaling should, however, only be used within relatively small load ranges and preferably between similar vehicle types. Here, scaling was used between passenger cars and light-duty commercial vehicles, where the latter vehicle type is, on average, 30 % heavier.

2.3.1. Passenger cars and light-duty vehicles

Passenger cars are vehicles designed to carry passengers and have a seating capacity of no more than nine persons, including the driver. They have a gross vehicle weight (GVW) under 3.5 metric tons. Light-duty vehicles (LDVs) in Sweden are defined as duty vehicles with a total weight also under 3.5 metric tons. Over the past decade, the number of LDVs on Swedish roads has increased by 30 %, and their total mileage has doubled between 2000 and 2019. In 2019, LDVs had the second-highest mileage after passenger cars (Transport Analysis, 2020c, 2020d, 2020e). In contrast, passenger car mileage has remained relatively stable, with only a 1 % increase from 2010 to 2019, compared to a significant 23 % increase for LDVs.

2.3.1.1. Mileage on different roads. The total mileage and the average number of passenger cars on Swedish roads were obtained from statistics provided by Transport Analysis (2020c), which are based on data collected during yearly vehicle inspections.

The distribution of kilometers traveled across different road types was assigned according to WSP (2015) and Ericsson (2019). These studies indicated that 28 % of the total distance covered by passenger cars in Sweden in 2017 was on urban roads, 48 % on rural roads, and 24 % on motorways. Since no specific studies were available for LDVs' traffic volume on different roads in Sweden, the same proportions as for passenger cars were used.

Regarding winter tires, the proportion of passenger cars using studless winter tires during the winter season was set at 37.6 %, while the remaining passenger cars used studded tires according to statistics from the Swedish Road Administration (2019). The same proportions were applied to LDVs. While using studded tires is not allowed outside the period between October 1 and April 15, studless winter tires may be used throughout the entire year. According to an investigation carried out 2020, approximately 7 % of the passenger cars in Sweden used studless winter tires throughout the year (Swedish Road Administration, 2021).

Due to the winter tire regulation and the fact that all-season tires were prohibited in Sweden until 2019, essentially all light vehicles have been equipped with a double set of tires. Thus apart from the 7 % that use studless winter tires all year round, each passenger car and LDV was considered to be equipped with a set of 4 summer tires and a set of 4 winter tires. The total number of tires in traffic for each tire type was then determined based on the number of vehicles in traffic and the proportion of different winter tires. The vehicle mileage and the number of vehicles and tires in traffic are listed in Table 1.

2.3.1.2. Tire sales. The annual sales of passenger car tires and LDV tires during 2018 and 2019 are shown in Table 2. The two tire categories are aggregated in the statistics from the tire manufacturers, which most likely is due to the similarity between these tires.

Estimating the lifetime for each tire type can be determined from the yearly replaced number of tires for the existing vehicle fleet. The vehicle mileage for the combined vehicle types (passenger cars and LDVs) remains relatively stable between subsequent years, which is why the annual replacement provides a representative number. The results of this estimate are presented in Table 3.

To calculate the total number of tires to be replaced each year, replacement tires that are sold and tires that are replaced when a new car replaces a scrapped one were considered. Typically, new cars always come with a set of summer tires, which are not included in the aftermarket sales statistics. Tires on scrapped cars are generally not worn down to the end of their lifetime. Therefore, the number of worn tires from scrapped cars listed in Table 3 may be slightly higher than the actual number due to unknown variations in the average degree of wear. This leads to a slight overestimation of the total tire wear and thus a slight underestimation of the lifetime.

2.3.1.3. Tire wear emission factor. Over 1000 discarded tires were collected from a recycling station and tire replacement/fitting stations in Stockholm, Sweden in order to estimate the tire wear factor for passenger cars. Most of the winter tires were obtained from the recycling station, which covers a significant area in Mideastern Sweden (Fig. A1).

Table 1
Vehicle mileage and number of vehicles and tires in traffic in 2019. Figures in italic for LDVs are estimated to be the same as for passenger cars due to a lack of data.

Parameter	Unit	Passenger cars	LDVs
Total yearly mileage[a]	km	67.14 × 10^9	9.327 × 10^9
Average yearly mileage[a]	km/vehicle	11,710	13,390
Number of vehicles in traffic[a]		5.733 × 10^6	6.967 × 10^5
Proportion of mileage on urban roads[b]	%	27.7	27.7
Proportion of mileage on rural roads[b]	%	47.8	47.8
Proportion of mileage on motorways[b]	%	24.5	24.5
Proportion of vehicles using studless winter tires[c]	%	37.6	*37.6*
Proportion of vehicles using studded tires[c]	%	62.4	*62.4*
$N_{\text{summer tires}}$[d]		21.33 × 10^6	2.592 × 10^6
$N_{\text{studless winter tires}}$[d]		8.623 × 10^6	1.048 × 10^6
$N_{\text{studded tires}}$[d]		14.31 × 10^6	1.739 × 10^6

[a] From Transport Analysis (2020c).

[b] From Ericsson (2019) and WSP (2015).

[c] From the Swedish Road Administration (2019).

[d] Estimated from number of vehicles and proportion of different winter tires.

Table 2
Passenger cars and LDVs: number of yearly replaced tires, tires on scrapped vehicles and tires on new vehicles.

	2018	2019
Replacement tires sold	6.194 × 10^6[a]	5.792 × 10^6[a]
passenger cars + LDVs		6.052 × 10^6[b]
Summer tires sold (replacement)[b]		2.526 × 10^6
All-season tires sold (replacement)[b]		48,400
Studless winter tires sold (replacement)[b]		1.588 × 10^6
Studded winter tires sold (replacement)[b]		1.888 × 10^6
Number of scrapped passenger cars[c]	199,000	186,000
Number of scrapped LDVs and Heavy Trucks[c]	37,300	30,100
Estimated number of scrapped LDVs[d]	33,000	26,200
Number of new passenger cars[c]	366,000	367,000
Number of new LDVs[c]	58,700	55,600
Tires on scrapped passenger cars[e]	7.961 × 10^5	7.454 × 10^5
Tires on scrapped LDVs[e]	1.318 × 10^5	1.050 × 10^5
Tires on new passenger cars[e]	1.462 × 10^6	1.468 × 10^6
Tires on new LDVs[e]	2.346 × 10^5	2.224 × 10^5

[a] From SDAB, Fredrik Ardefors, personal communication (2021).

[b] From STRO, Arne Sköldén, personal communication (2021).

[c] From Transport Analysis (2019, 2020d, e).

[d] The share of scrapped LDVs out of the total scrapped LDVs and HDVs is assumed to be the same as for new vehicles sold, i.e., 88 %.

[e] Calculated from the number of vehicles given in the table.

Table 3
Number of tires to be replaced per year and estimated lifetime for passenger cars and LDVs based on yearly tire sales.

Tire type	Number of tires in traffic (millions)	Numbers of replacement tires sold (millions)	Numbers of replaced tires from scrapped vehicles (millions)	Total number of tires to be replaced per year (millions)	Estimated lifetime (years)
Summer	23.9	2.57	0.85	3.43	6.9
Studless winter	9.67	1.59	0	1.70	6.1
Studded	16.0	1.89	0	2.07	8.5

The summer tires were collected at tire replacement stations in the Stockholm region, which implies they were driven mainly in urban environments. After excluding tires that had exploded, were excessively dirty, and had no initial weight data, 586 tires were used for estimating the mass loss during their lifetime: 286 summer tires, 122 studless winter tires, and 178 studded tires. The tires were carefully cleaned and weighed using a calibrated scale (Mettler PM16 with 1 g accuracy), and the initial weight was subtracted to calculate the weight loss. The tires' DOT numbers, which contain the manufacturing date, size, maximum velocity, and load information, were also recorded. Since it may be challenging to remove all dirt during the cleaning process, the tire weights may be somewhat overestimated, leading to an underestimation of the weight loss during the tires' lifetime. For studded tires, the loss of studs may lead to an overestimation of the weight loss for that tire type. However, these effects could not be precisely quantified and should be considered as potential uncertainties. The measurements were conducted as part of a bachelor thesis project and details are available in Agewall and Wallgren (2019).

According to the industry experts, summer tires are put into use approximately 160 days after the manufacturing date (190 days for winter tires) (DRF [National Association of Tire Specialists] Peter Buhre, personal communication, August 20, 2020). The tires' lifetimes were thus calculated assuming that they had been used until the date of the field measurements. For summer tires, the lifetime was estimated to be 4.0 ± 0.3 years, compared to 5.0 ± 0.5 years for studless winter tires and 9.1 ± 0.7 years for studded winter tires. The uncertainties were calculated based on a normal distribution assumption, with the samples being representative of the entire population of tires. Comparing these numbers to the estimated lifetime from tire sales in Table 3 implies that the lifetime of the selected tires in the study may not be representative of the entire Swedish passenger car fleet. The lifetime of the summer tires may be especially doubtful since these were all collected in the city. Therefore, it was decided to utilize the estimated lifetime from the sales data (Table 3) to calculate both the average and minimum yearly weight loss of tires. Consequently, tire wear estimated through both the mileage and sales approaches will yield the same total values since both models are based on the same data. An advantage of using sales numbers for lifetime estimates is that the results will be representative of the entire country, which may be difficult to achieve by sample measurements.

The average weight loss for summer, studless winter, and studded tires was found to be 1.2 kg, 0.9 kg, and 0.8 kg, respectively, which is consistent with the information provided by the Swedish tire industry, which states that there is a 1 kg weight loss for the average tire. A recent study by Lee et al. (2020), which also weighed tires to calculate the wear emission factor, reported an average weight loss of 0.9–1.1 kg for passenger car tires during their warranty period of 6 years.

To ensure the representativeness of the three tire groups in terms of weight loss for the entire Swedish passenger car fleet, their tire sizes needed to be determined. The tire width distributions of the measured groups are depicted in Fig. 1. According to tire experts (Emil Sundström, Nokian Tires, personal communication, April 2019), this distribution provides a representative view of tire dimensions in Sweden.

To adjust the emission factors for different road types, they were scaled in proportion to the scaling used for Dutch roads. However, it remains uncertain whether the differences between Dutch rural roads, urban roads, and motorways are similar to those in Sweden.

For LDVs, the wear and emission factors were scaled up from those of passenger cars by using the ratio between curb weights. The mean weight of a passenger car was 1660 kg in 2019 (Transport Analysis, 2020c). The curb weight of LDVs was estimated from the mean curb weight of the ten most common vehicles registered between 2017 and 2021 using the most up-to-date model data on LDV mileage from Transport Analysis.

For a specific tire type *I*, the emission factor is calculated as.

$$\mathrm{EF}_i = \frac{W_i}{L_i \cdot D_i} \qquad [\mathrm{mass/tire/km}] \tag{12}$$

where w_i is the average weight loss during the lifetime L_i (measured in years) of tire type *i*. The yearly driving distance D_i for the different tire types is unknown and had to be estimated.

To do this, it was assumed that passenger car and LDV traffic is constant throughout the year, and that winter tires are used during the winter period and summer tires during the rest of the year. Thus, introducing the usage factor $U_i = 1/3$ for winter tires and $U_i = 2/3$ for summer tires, we have

$$D_i = U_i \cdot D \tag{13}$$

where *D* is the mean yearly traveling distance for the passenger car and LDV vehicle categories.

U_i was assigned based on the Swedish regulation which requires all vehicles to be fitted with winter tires from December 1 to March 31 if the winter road conditions are as expected. Since 7 % of the total passenger cars use studless winter tires throughout the entire year, the effective usage factor for studless winter tires becomes 0.46, which is higher compared to the general assumption of 0.33 (corresponding to 4 months) for cars that are not exclusively using winter tires.

It is necessary to note that when calculating the yearly emissions for each tire type (combining Eqs. (2) and (11)), the yearly driving distance is cancelled out.

$$E_i = \frac{W_i \cdot N_i}{L_i} \tag{14}$$

This means that the usage factor assumption does not affect the calculated yearly emission values for the passenger car tires or the yearly driving distance. Only lifetime, total mass loss over the tires' lifetime, and total number of tires in traffic are of importance for the result.

Since it was not possible to determine which vehicle type the measured tires belonged to, it was assumed that the calculated $\mathrm{EF}_{i.}$ (Eq. (12)) represents a combined value for the wear of the passenger car and LDV tires. To adjust these estimated emission factors to a specific vehicle type (defined by its gross vehicle weight, GVW, and tire number), the following equation was used. The emission factor of the combined vehicle types is the averaged vehicle mileage value of the individual emission factors:

$$\mathrm{EF}_{combined} = \mathrm{EF}_{PC} \cdot \mathrm{Sh}_{PC} + \mathrm{EF}_{LDV} \cdot \mathrm{Sh}_{LDV} \tag{15}$$

where Sh_{PC} is the passenger car share of the total vehicle mileage (passenger cars and LDVs combined), and this is the same for Sh_{LDV}. To solve Eq. (15), a relationship between the emission factor for passenger cars and LDVs is needed. Based on the assumption that the tire wear for LDVs is proportional to vehicle weight (see details in Appendix B) we can calculate that $\mathrm{EF}_{LDV} = 1.3 \cdot \mathrm{EF}_{PC}$. The corresponding emission factors for the three types of tires are shown in Table 4.

It is straightforward to calculate representative emission factors for both the average passenger car tire (summer and winter tires combined) and average LDV tire using the averaged vehicle mileage value of the individual emission factors. Although these average emission factors are not used further in the analysis, the numbers are listed in Table 4 for comparison with values used in other studies.

The tire wear emission factor for the average passenger car tire is 23 mg/km, while the corresponding value for the average LDV tire is 29 mg/tire/km. These numbers are similar to the 22.5 mg/tire/km for passenger cars reported by Gustafsson (2001), which served as the source for the emission values used by Magnusson et al. (2016) in their previous estimate of Swedish tire emissions. It is worth noting that Gustafsson's data dates back to 1987, a time when both passenger cars and tires were quite different from today's standards.

In other countries, attempts to estimate total tire wear, such as in Norway (Sundt et al., 2014) and Denmark (Lassen et al., 2015), relied on emission factor values recommended by the United Nations Economic

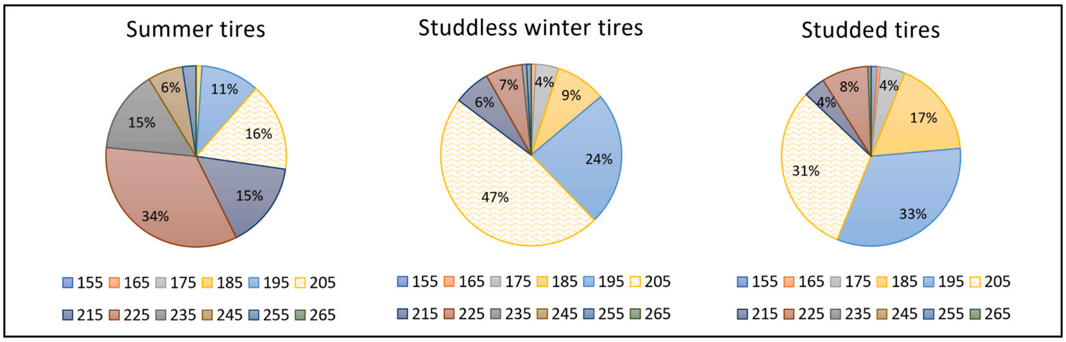

Fig. 1. The distribution of the width [mm] of tires investigated by Agewall and Wallgren (2019), which is used in this study.

Table 4
Estimated tire wear emission factors for passenger car and LDV tires in Sweden. For the average tire lifetime weight loss, 95 % confidence intervals from a variance analysis are given.

	Tire type			
	Summer	Studless winter	Studded winter	Average tire
Number of measured tires	286	122	178	–
Average lifetime (years)	6.9	6.1	8.5	–
Average weight loss over their lifetime (g)	1210 (±90)	900 (±80)	830 (±80)	–
Estimated yearly driving distance (km)	7928	5440	3964	–
Combined emission factor (mg/tire/km)	22	27	25	–
Passenger car tire Emission factor (mg/tire/km)	21	26	24	23
LDV tire emission factor (mg/tire/km)	28	34	31	29

Commission for Europe (UNECE), which is 33 mg/km for passenger car tires and 51 mg/km for an LDV tires. These values were based on a Russian study from 2003 which used generic values for the average tire lifetime mileage and relatively high values for the lifetime weight loss: 1.4–1.9 kg for passenger car tires and 3.4–4.0 kg for LDV tires. An up-to-date dataset by ADAC (2021) based on on-road tests of 94 sets of new tires indicates emission factors of 23–33 mg/tire/km for summer tires and 27–35 mg/tire/km for winter tires, which is in the same range as the emission factors determined in this work.

Since the assumed usage factor for the general use of winter tires will affect the emission factor estimates, sensitivity to changes in the usage factor was investigated. The results are shown in Table 5 for passenger cars. Corresponding values for LDVs can readily be calculated by multiplying the values by 1.3. In most cases, the summer tires have lower emission rates than the winter tires, which is in line with what has been observed in other studies. The difference becomes smaller as the winter usage factor increases. After a period of 5 months, the relationship is reversed, which indicates that the real period is shorter. For all cases, the studded winter tires generally have a lower emission rate compared to the studless winter tires. This is to be expected since studded tires are more common in the northern part of Sweden, where the roads are covered with more ice and snow during the wintertime, which should lead to less tire wear.

Compared to a collection of reported emission factors (Appendix Fig. B1), the emission factors from this study are within the middle range of the reported estimates from the literature. Emission factors can differ significantly depending on the road type or traffic situation. To differentiate the emission factors in this work, road-type-specific emission factors were based on a recent study by Geilenkirchen et al. (2020), who presented road-type-specific tire emission factors based on previous studies by ten Broeke et al. (2008) and Velders et al. (2009). These studies categorized the emission factors by urban roads, rural roads, and motorways. Rural roads exhibited the lowest emission factor, while the emission factors for motorways and urban roads were 24 % and 57 % higher, respectively. These figures were applied to differentiate the Swedish emission factors based on road type using Eq. (8) (Table B2).

Table 5
Emission factors for passenger car tires based on different assumptions regarding the length of winter tire use.

Winter tire usage	3.5 months	4.0 months	4.5 months	5.0 months
EF Summer	20.0	21.3	22.7	24.3
EF Studless winter	28.3	26.2	24.4	22.8
EF Studded winter	27.2	23.8	21.1	19.0

2.3.2. *Motorcycles*

2.3.2.1. Tire wear emission factor. For motorcycles, the same calculation as for light-duty vehicles is used, which is scaling the wear factor for two-wheelers with a weight correction factor (the ratio between mean weight and the weight of a mean passenger car, see Appendix B). The wear factor for summer tires was used since motorcycles are not used in winter in Sweden. Mean weights of five motorcycle classes, based on cylinder volume, were provided by The Moped and Motorcycle Association in Sweden (N. Kristoffersson, personal communication, April 19, 2021). To account for a mean driver, 70 kg were added to the weights (see Table B3).

2.3.2.2. Mileage on different roads. Due to the small wear amounts compared to other vehicle classes, no differentiation of emissions based on road types was made. The total mileages of the five motorcycle classes for 2019 were provided by Transport Analysis (2020c). The resulting calculations are presented in Table B3.

2.3.3. *Heavy-duty vehicles*

2.3.3.1. Mileage statistics and mileage on different roads. In this study, heavy-duty vehicles (HDVs) are defined as vehicles (or vehicle combinations) with a total weight exceeding 3.5 metric tons. These can be classified into three groups: domestic transport, which refers to the work performed by Swedish-registered HDVs on Swedish roads excluding cross-border transport; international transport, which involve cross-border transport performed by Swedish-registered HDVs; and foreign HDVs on Swedish roads.

Yearly statistics on the vehicle mileage on Swedish roads are provided by the governmental agency Transport Analysis (Table 6). The agency utilizes two separate methods to estimate mileage: a model-based approach and a survey-based approach, both of which yield notably different estimations of the vehicle mileage.

The model-based approach combines mobility measurements from a number of randomly selected spots on the national road system with vehicle mileage readings from annual vehicle inspections of Swedish-registered vehicles (Transport Analysis, 2013). The total 2019 mileage for HDVs on Swedish roads was estimated to be 4.6×10^9 km (Transport Analysis, 2020c), and no distinction is made between Swedish and foreign registered vehicles. The HDVs in these statistics are divided into three groups based on their Gross Vehicle Weight (GVW): trucks with a GVW of 3.5–16 metric tons, trucks with a GVW of 16–26 metric tons, and trucks with a GVW $>$ 26 metric tons. However, detailed information regarding vehicle configuration and characteristics is not provided.

More detailed traffic activity data for Swedish-registered HDVs on Swedish roads was obtained using the survey approach (Transport Analysis, 2020a). The data were collected through questionnaires sent to Swedish vehicle owners four times a year. While the proportion of international transport on Swedish roads is not explicitly given, an earlier

Table 6
Mileage of Swedish registered and foreign vehicles on Swedish roads during 2019.

Estimation method	Domestic transport	International transport on Swedish roads	Foreign HDVs on Swedish roads	Total domestic and foreign transport.
Survey-based	2.9×10^9 km[a]	0.5×10^8 km[a]	6.1×10^8 km[b]	**3.6×10^9 km**[a,b]
Model-based				**4.6×10^9 km**[c]

[a] From Transport Analysis (2020a, 2020b).

[b] Estimated from Transport Analysis (2020a, 2020b) and Transport Analysis (2018b).

[c] Transport Analysis (2013) and Transport Analysis (2020c).

analysis estimates this part to be 30 % (Transport Analysis, 2013). However, there are no detailed survey data on mileage for foreign HDVs on Swedish roads. Instead, Transport Analysis (2018b) provides general results from surveys performed between 2012 and 2016 by EU countries collecting statistics on the carriage of goods by road according to Commission Regulation (EC) No. 6/2003. These results indicate that the vehicle mileage of foreign HDVs accounts for 17 % of the total HDV mileage. The total mileage of surveyed HDVs, Swedish and foreign combined, is 3.6×10^9 km, which is lower than the modelled mileage estimates. Transport Analysis (2020a) reports that survey mileage data may be underestimated due to response problems, thus leading to an underestimation of the assumed average yearly mileage for vehicles that did not report their activity, incomplete representativeness in the selection of the HDVs included in the survey, and the failure to include empty transport vehicles since the informants sometimes forgot to report these (Transport Analysis, 2020a).

The data from the two methods are summarized in Table 6. Although there is a significant difference in results between the two approaches, it is challenging to determine which method provides the most representative results (Transport Analysis, Anette Myhr, personal communication, January 28, 2021). Nevertheless, in the current study, it has been decided to use the data gathered through the surveys since they provide a more detailed picture of the mileages for different types of HDVs (Fig 2). This choice allows for a comprehensive assessment where the properties of different HDVs can be accounted for and provides a detailed understanding of the road environments in which emissions from a certain group of HDVs occur.

As shown in Table 6, domestic transport constitutes the predominant portion of transport activities in Sweden. Most (55 %) domestic transport uses straight trucks, with or without trailers, and tractor units that weigh 60–70 metric tons (GVW) (see Fig. 2 and Table C2) (Statisticon, Mats Nyfjäll, personal communication, November 19, 2020). It is important to note that this statistic only encompasses domestic transport. Foreign heavy vehicles operating within the Swedish borders are also included in the analysis but with slightly less accuracy due to the limited availability of data describing the GVW of foreign vehicles. The data pertaining to domestic and foreign transport were provided by Statisticon and Transport Analysis (Transport Analysis, 2020a and 2020b; Statisticon, Mats Nyfjäll, personal communication, November 19, 2020; Transport Analysis, 2018b; Transport Analysis, 2022). Foreign transport consists of vehicles registered in EU countries, Switzerland, Norway, and Liechtenstein (Transport Analysis, 2018b).

According to statistics from 2012 to 2020, foreign HDVs transported an average of 14–15 metric tons of goods per vehicle, while domestic transport HDVs transported 10–11 metric tons (Transport Analysis, 2018b). This suggests that the foreign vehicle fleet possesses a similar load capacity, number of tires, and design as the vehicle fleet for domestic transport.

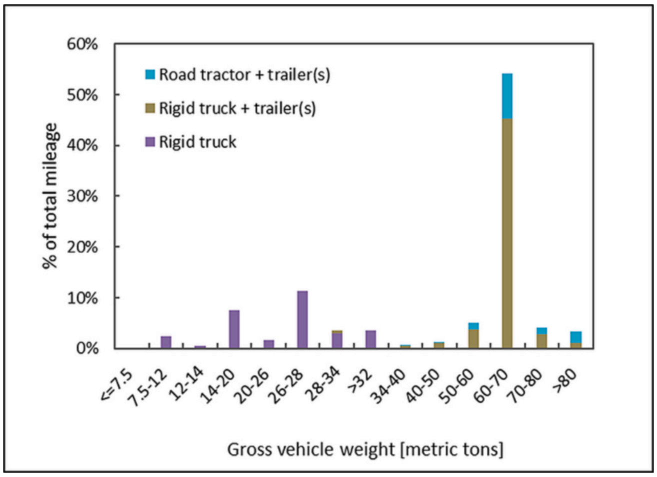

Fig. 2. Percent of total mileage covered on Swedish roads by Swedish registered HDVs with different GVW (gross vehicle weight) classes (Statisticon, Mats Nyfjäll, personal communication, November 19, 2020).

Detailed information regarding the mileage of various types of HDVs and the distribution of kilometers covered by HDVs across different road types was obtained from a study conducted by the Swedish Environmental Research Institute (IVL) (data supplied by IVL, Cecilia Hult, personal communication, May 4, 2020). Specific mileage distribution data for straight trucks/tractor units with trailers having a GVW over 60 metric tons was not available. It was, therefore, assumed that the mileage distribution for transport by these vehicles would be similar to that of straight trucks/tractor units with trailers having a GVW of 50–60 metric tons.

2.3.3.2. Tire wear emission factors. For this study, it was not feasible to weigh HDV tires to calculate representative wear factors. Due to the lack of specific wear studies on HDV tires in Sweden, we relied on emission factors for HDVs from Geilenkirchen et al. (2020), which were applied to differentiate factors for urban, rural, and highway traffic in Sweden.

Geilenkirchen et al. (2020) provided tire wear emission factors for two HDV categories: straight trucks and tractor units. These vehicles were assumed to have trailers, and their gross vehicle weight (GVW) was estimated based on mileage data from the Netherlands statistics (CBS) and a Weighing in Motion (WiM) exercise conducted by Ligterink (2015). The average GVW for straight trucks with trailers was estimated at 19 metric tons, while the GVW was 27 metric tons for tractor units with trailers. Both categories were attributed to have on average 11 tires each, corresponding to a tire load of approximately 1.7 metric tons for straight trucks with trailers and 2.5 metric tons for tractor units with trailers.

The emission factors reported by Geilenkirchen et al. (2020) varied between 50 and 61 mg/tire/km for straight trucks and between 38 and 50 mg/tire/km for tractor units. These factors were derived from a study by ten Broeke et al. (2008), who, in turn, referred to studies performed by the European Association of the Rubber Industry and the Zink Oxide Producers Association (BLIC and ZOPA, 2001). That study compiled data on tire wear from various test vehicles, including HDVs, but provided only limited information about tire and vehicle characteristics.

Straight trucks and tractor units in Sweden are, in general, heavier than in the Netherlands. Straight trucks without trailers in Sweden weigh 24 metric tons (GVW) on average, while straight trucks and tractor units with trailers weigh 64 metric tons and 67 metric tons, respectively (see Table C3). Given that the tire emission factors provided by Geilenkirchen et al. (2020) apply to HDVs with a tire load of 1.7–2.5 metric tons, the corresponding average number of tires for the Swedish straight trucks and tractor units was calculated. Note that since Geilenkirchen's emission factors only describe tire wear on Dutch HDVs, the calculated number of tires on Swedish HDVs might not be equal to the actual number of tires.

When studying the estimated tire load for HDVs in the Netherlands and their corresponding tire emissions according to Geilenkirchen et al. (2020), one may notice a contradiction. The wear of tires on straight trucks (50–61 mg/tire/km) is higher than the wear of tires on tractor units (38–50 mg/tire/km) even though they carry a lower load per tire (see Table B2). This discrepancy could be attributed to trucks potentially experiencing more tire wear on curved roads due to their stiffer construction, thus inducing more slip. However, Geilenkirchen and colleagues did not comment on these differences, and the detailed methodology for estimating these emission factors could not be found. As a result, this study assumes that tire load was the most influential parameter for tire wear. Thus, Geilenkirchen's EF_j, tractor unit, was applied to vehicle combinations with an average GVW $<$ 20 metric tons, and EF_j, straight truck, was applied to vehicles with an average GVW $>$ 20 metric tons.

When estimating the number of tires for HDVs with different GVWs, several assumptions were made. For single trucks with GVWs above 32 metric tons (3.5 % of total HDV mileage), the average GVW was assumed to be 32 metric tons. The same assumption was made for vehicle combinations with GVWs over 80 metric tons (3.6 % of total HDV mileage). Vehicles with GVWs $\leq$ 7.5 metric tons were assumed to have an average GVW equal to 7.5 metric tons. For the remaining HDVs, which had GVWs within certain ranges, the mean value for each vehicle configuration was used to calculate the average GVW.

The calculated average emission factors for Swedish HDVs on urban roads, rural roads, and motorways ranged from 675 to 1620 mg/vkm, 431 to 1026 mg/vkm, and 531 to 1269 mg/vkm, respectively (Table B3).

To calculate the total tire wear emissions for HDVs, the emission factors from Table C3 were combined with the mileage data from Table C1. For foreign goods transport, the total tire wear emissions were estimated by multiplying the calculated total tire emissions from domestic transport with the percentage of foreign HDVs' mileage on Swedish roads during 2012–2016 (16–19 %).

2.3.4. *Buses*

2.3.4.1. Mileage on different roads. Buses considered in this study are Swedish-registered vehicles used for the carriage of passengers which have more than eight seats in addition to the driver's seats. The data describing the mileage of foreign buses on Swedish roads are not available at present. Therefore, this study provides only an estimation of tire wear emissions from Swedish-registered buses on Swedish roads. Five bus classes were considered: Class I, II, III, A, and B, based on directive 2001/85/EG. Furthermore, 8 % of the total bus mileage in Sweden is from buses with unidentified classes, and these vehicles were also included in this study.

The activity data for the traveling distance of buses in Classes I, II, II, and "unidentified" was provided by Statistics Sweden (Magnus Nyström, personal communication, October 19, 2020). The total mileage for buses in Sweden in the year 2019 was 9.3×10^8 km. Literature regarding the traffic flow of buses on Swedish roads is scarce and often not publicly available. This is mainly due to the lack of data describing the Annual Average Daily Traffic (AADT) exclusively for buses, as buses are often included in an HDV category. The traffic volume distribution was based on unpublished data provided by the IVL Swedish Environmental Research Institute (Cecilia Hult, personal communication, May 4, 2020), which divides buses into two categories based on the vehicle's GVW (under or over 18 metric tons). The data shows that heavier buses drive on urban roads to a greater extent than buses with a GVW under 18 metric tons, while lighter buses drive more often on rural roads and motorways.

2.3.4.2. Tire wear emission factor. Class A and B buses have much lower GVWs than those in Classes I-III (Statistics Sweden, Magnus Nyström, personal communication, October 19, 2020), resulting in the use of smaller tires. Tire wear emissions for these buses were calculated similarly to LDVs. The average GVW of Class A and B buses was estimated to be 5175 kg (Statistics Sweden, Magnus Nyström, personal communication, October 19, 2020), and the emission factors derived from tire weighing measurements (as described in Section 2.3.1.3) was adjusted using the same weight correction approach as for LDVs and MCs (Appendix B, Table C4). The emissions were then estimated using Eqs. (1)–(8).

For buses in Classes I-III, weighing the tires to calculate wear factors was not feasible. Only one study (Lindström and Rossipal, 1987) provided a tire wear emission factor (170 mg/tire/km) for a bus (6 tires) in Sweden. As there were no updates to this study, tire wear emissions from Geilenkirchen et al. (2020) were applied to the Swedish data. These emission factors for HDVs were derived from ten Broeke et al. (2008), but unfortunately, they do not provide detailed information about how these values were estimated and what kind of buses they apply to. It was therefore assumed that these factors still do represent tire wear for Dutch buses, whose characteristics were studied further.

Considering that the average GVW for buses (2 axles) in the Netherlands is 19.5 metric tons (TNO, Norbert Ligterink, personal communication, October 22, 2020), and assuming that their average number of tires is 8 (Kuiper and Ligterink, 2013), the average tire load was calculated to be 2438 kg. The average GVW for Swedish buses in Classes I-III (22 metric tons, Table C4) was derived from Statistics Sweden (Magnus Nyström, personal communication, October 19, 2020). Assuming that other parameters influencing bus tire wear, such as design and driving style are similar in both the Netherlands and Sweden, the tire number for Swedish Class I-III buses was determined, and the emission factors were calculated similarly to HDVs (Appendix C).

The total wear of bus tires was calculated using Eqs. (1)–(8). Here, the usage factor (Ui) was set to a value of 1 since bus tires are assumed to be used throughout the entire year. The correction factor (Cj) is irrelevant in these calculations since a literature-based EFj was used. Therefore, Cj was also set to 1.

2.3.5. *Heavy duty vehicles: Tire sales approach*

The number of heavy vehicle tires replaced in Sweden during 2018 and 2019 was obtained from SDAB, the Swedish tire recycling company. The total number of replaced tires for the existing heavy vehicle fleet was estimated by combining this data with the number of retreaded tires obtained from DRF, the National Association of Tire Specialists. Additionally, the number of worn-out tires on the yearly scrapped heavy vehicles was estimated using statistics retrieved from Transport Analysis and assuming an average of 8 tires per vehicle. It is important to note that tires on scrapped vehicles may not be worn to the same degree as replaced tires. However, due to the lack of available data or studies indicating the average tread depth for scrapped HDV tires, these tires were assumed to be worn to the same degree as the replaced ones. The specific numbers are provided in Table 7.

The average lifetime weight loss of HDV tires operating on Swedish roads was estimated based on the calculation of tread depth volume and

Table 7
Replaced heavy vehicle tires in Sweden in 2018 and 2019.

HDV + Heavy bus tires	2018	2019
New[a]	364,300	381,900
Retreaded[b]	185,000	185,000
Scrapped HDVs[c]	4350	3840
Scrapped heavy buses[c]	1100	1370
Estimated number of worn-out tires from scrapped HDVs and buses[d]	43,700	41,600
Estimated total number of replaced tires	593,000	608,500

[a] From the Swedish Tire Recycling Association (SDAB).

[b] From Däckspecialisternas Riksförbund (DRF).

[c] From Transport Analysis (Trafikanalys). The share of scrapped HDVs out of the total scrapped LDVs and HDVs is assumed to be the same as for sold new vehicles, i.e., 12 %.

[d] Assumes eight tires in general.

assuming a tread depth between 4 and 5 mm when the tire is replaced. This assumption is supported by an industry study from 2001 (BLIC and ZOPA), which found that the average tread depth for scrapped truck tires in Europe was 4.55 mm. Additionally, input from a large retreading company in Sweden confirms that the tread depth of tires they receive for retreading is typically above 5 mm in the fall and around 3 mm during the rest of the year (Colmec, Patrik Sjölin, personal communication, June 8, 2021).

To estimate the average lifetime weight loss, the dimensions and typical new tread depth of the six most common HDV tire types on the Nordic market (accounting for 82 % of the market share) were obtained from a representative of the Nordic tire market. Using a worn tread depth of 4.5 mm, a tread width representing 85 % of the tire width, and an average fill rate of 80 % of the tread pattern, the average lifetime weight loss was calculated in Table C5. The fill rate may vary during the tire's lifetime and across different tire types, so a sensitivity analysis was conducted in Table C6 to explore different values of worn tread depth and fill rate. Based on this analysis, an average lifetime weight loss of 9.0 kg appears to be a justified assumption for HDV and heavy bus tires in Sweden.

The weight of a new HDV tire in Sweden was estimated to be approximately 60 kg (see Table C5), resulting in an average weight loss of 15 % during the tire's lifetime. This can be compared to BLIC and ZOPA (2001), which estimated an average lifetime weight loss of 11.5 % for HDV tires in Europe based on road tests and extrapolations of the residual tread depth of used tires. According to that study, the average weight of new large truck tires was 55 kg, leading to an average lifetime weight loss of 6.3 kg.

Sundt et al. (2014) reported an estimated average lifetime weight loss of between 10 and 15 % for Norwegian HDV tires, but no value of the average new tire weight was given. In comparison, the estimated 15 % lifetime weight loss in our study seems slightly high, and it is possible that an analysis including a larger part of the market share would lead to a lower value.

3. Results and discussion

This chapter begins with a presentation of the results and a brief data-specific discussion, followed by a general discussion of the study.

Figs 3, 4 and 5 show the resulting tire wear emissions in Sweden during 2019 for different vehicle classes calculated using the mileage approach. Detailed data is presented in Table E1. The results indicate that passenger cars contribute most to total tire wear emissions in Sweden (55 %), followed by the HDVs (31 %), LDVs (10 %), buses (3 %) and motorcycles (0.09 %). The highest share of these emissions occurs on rural roads. Although the winter season in Sweden is only one-third of the year, the emissions from winter tires contribute to 44 % of the passenger car tire emissions, which is due to the higher emission factor values for these tire types compared to summer tires. This information is important for designing and implementing emission control technologies and snow treatment technologies and practices. It can also help to inform the drivers about the benefits of driving more carefully during the winter, especially when using winter tires on pavement that is not covered by snow or ice.

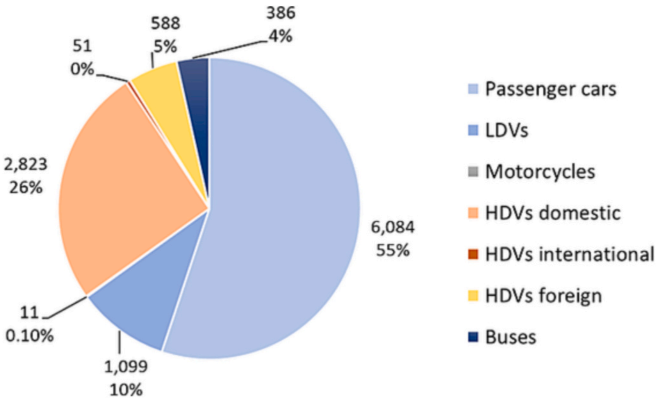

Fig. 3. Total tire wear emissions (in metric tons per year and percent) originating from different vehicle types in Sweden. The emissions were estimated using the mileage approach.

The total emissions of tire wear particles (TWP) in Sweden estimated using the mileage approach amount to 11,040 metric tons per year (Table 8). The sales approach gives a slightly higher value of 12,560 metric tons per year. For passenger cars and LDVs, both approaches result in identical values since they are based on the same data. However, for heavy vehicles, the mileage approach leads to lower emission estimates compared to the sales approach. The latter approach estimates 5400 metric tons of tire wear for 2019, taking into account 600,000 replaced HDV tires and an average lifetime weight loss of 9 kg (see Section 2.3.5).

It is important to note that the 5400-metric ton figure only accounts for Swedish-registered HDVs and heavy buses and should be compared to the combined emissions of domestic and international HDVs and buses from the mileage approach. For an accurate comparison, the emissions from international HDVs should include the mileage covered outside Sweden, which is 2.3 times more than the mileage covered within Sweden. The comparable emissions from the mileage approach adds up to 3325 metric tons, approximately 60 % of the sales approach estimate. The sales approach is considered more reliable in terms of total wear amounts, while the mileage approach gives more detailed estimates for different vehicle classes. The discrepancy between the methods could be attributed to the underestimation of vehicle mileage or emission factors.

In Section 2.3.3.1, it was observed that the total yearly domestic HDV mileage from the survey-based statistics used for calculating the emissions was only about 80 % of the model-based statistics mileage. The survey-based statistics were used due to the need for more detailed data for the calculations. If the model-based statistics are closer to the truth, the domestic vehicle mileage needs to be increased by almost 30 %, leading to total comparable emissions of 4100 metric tons for the mileage approach. However, this is still lower than that of the sales approach, indicating that the emission factors may be too low as well. To obtain a similar total amount of wear for both approaches, the emission factors would need to be increased by 30 %.

On the other hand, if the average lifetime weight loss of Swedish HDV tires is overestimated, then the sales approach estimate would also be affected. Assuming an average weight loss per tire of 12.5 % (as in the Norwegian study by Sundt et al., 2014) instead of the 15 % used, the sales approach estimate would total 4500 metric tons, thus requiring less adjustment to the emission factors.

The proposed framework for national tire wear emissions represents the most comprehensive and ambitious approach to date. As outlined in the introduction, the primary aim of this project was to provide measurement data for tire wear emission factors for passenger cars and light-duty vehicles as well as to explore how literature-based emission factors for heavy-duty vehicles (HDVs) and buses could be adapted to local conditions, all while taking into account possible differences. In Section 2, we discussed and achieved this goal. Specifically, we calculated emission factors for heavy-duty vehicles in Sweden by applying statistical methods and theoretical assumptions and accounting for differences between the Dutch and Swedish heavy-duty vehicle fleets. However, other factors such as road pavement type, material, climate, road maintenance, and regulations can also influence emission factors. For instance, the rougher and seasonally snow-covered roadways, hillier terrain, and more winding roads of Sweden, might affect the wear of tires. (DRF [National Association of Tire Specialists], Peter Buhre, personal communication, March 2020).

In addition to our primary aim, we sought to highlight the implications of our work for the scientific community and stakeholders. Our

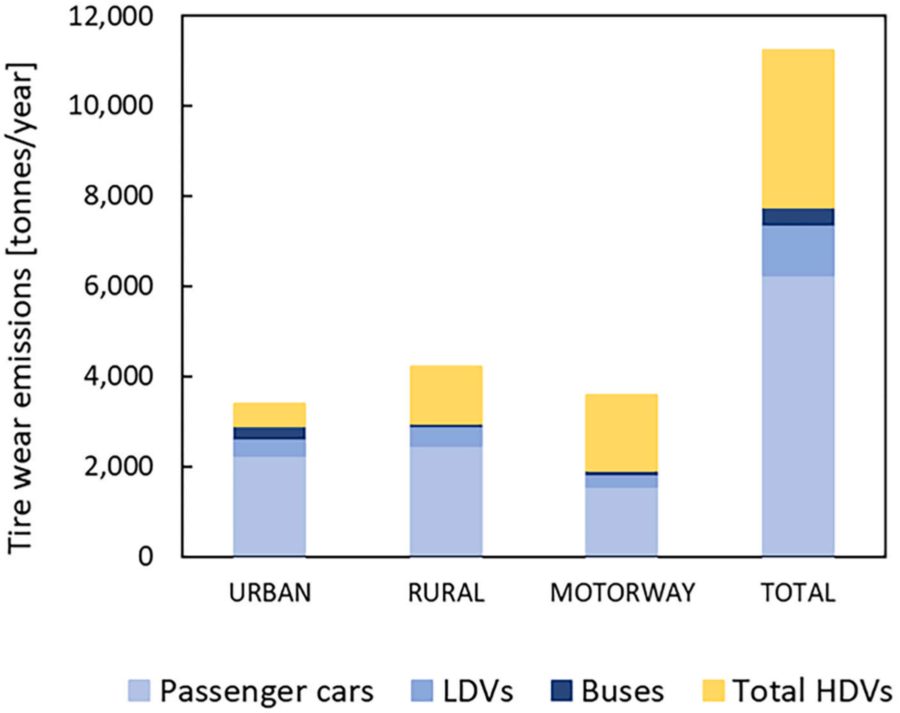

Fig. 4. Total tire wear emissions (in metric tons per year) on different road types (urban, rural, motorway, and total) in Sweden. The emissions were estimated using the mileage approach.

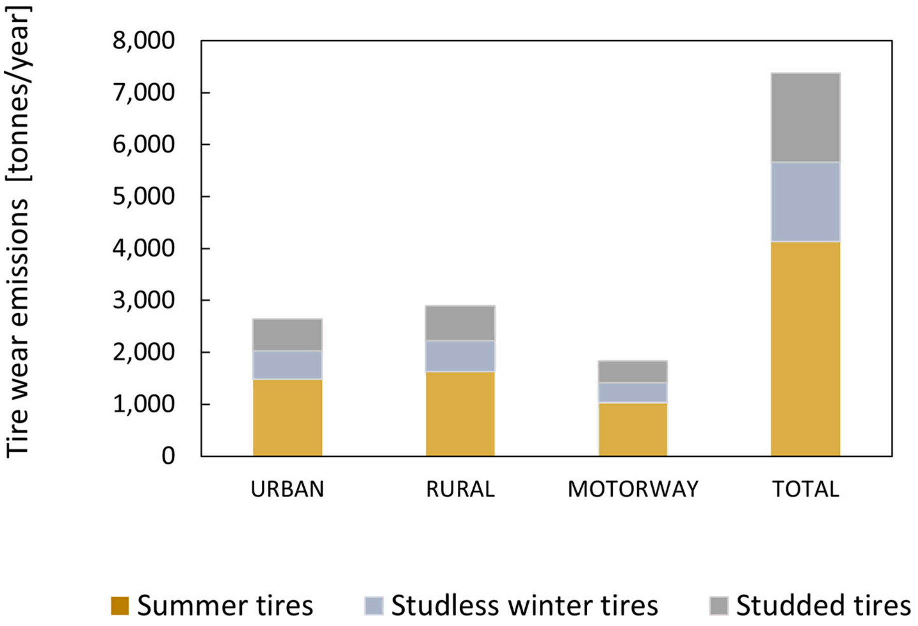

Fig. 5. Total tire wear emissions for passenger cars and LDVs (in metric tons per year) in Sweden. The emissions were estimated using the mileage approach.

article provides detailed information on primary sources of tire wear emissions and their distribution in the environment. This information can be valuable for evaluating measures to reduce emissions. Stakeholders may also gain useful insight into the knowledge gaps that exist before making decisions about research priorities and support. Furthermore, our increased understanding of different vehicle types, their mileages, and data collection tools will hopefully benefit researchers interested in further developing the proposed method. A simplified version of the approach can be used by stakeholders as a framework for calculating yearly national emissions, with possibilities to adjust for changes in vehicle fleet and mileages.

Due to the nature of this study, some important information had to be supplied by branch organizations, tire companies, and governmental authorities, which is normally not published in peer-reviewed scientific journals. The authors are aware that this poses the risk that biased information has been used in the estimations and calculations. Judging from our own long experience from tire research and the tire branch, it is the authors' opinion that this risk is low, and that the data supplied from non-scientific sources are trustworthy.

The subsequent paragraphs discuss the outcomes of our developed

Table 8
TWP emissions in Sweden estimated by mileage and sales approaches for different vehicle types. Values in the column to the right are from Magnusson et al. (2016) (recalculated with respect to tire wear and not rubber wear).

Approach	Mileage approach		Sales approach		Magnusson et al. (2016)	
	Percent	[metric tons/year]	Percent	[metric tons/year]	Percent	[metric tons/year]
Passenger cars	55 %	6080	57 %	7180	48 %	5930
LDV	10 %	1100			6 %	770
Motorcycles	0.09 %	11			0.25 %	30
HDV domestic	25 %	2820	43 %	5380	38 %	4640
Buses	3.5 %	390			8 %	980
HDV international	0.5 %	50				
HDV foreign	5 %	590				
Total		11,040		12,560		12,350

emission-based mileage approach (national tire emission numbers for Sweden), which was both an initial and secondary aim of this study.

In comparison to previous estimations of tire wear emissions in Sweden (Magnusson et al., 2016), the new results show slightly higher emissions for passenger cars and light-duty vehicles, while the emissions of heavy-duty vehicles and motorcycles are lower. The previous estimations, based on assumptions of emission factors without significant experimental support, are surprisingly similar to the values derived in this study. However, this similarity should be considered a pure coincidence. For instance, the earlier study used an emission factor of 1000 mg/vkm for buses, whereas this study uses an emission factor of 415 mg/vkm for the average bus. The earlier study also used the same emission factor for heavy trucks, which is close to the 960 mg/vkm value used for the average domestic HDVs in this study. Thus, the main difference between this estimation and the previous estimation of heavy-duty vehicle tire wear emissions arises from using vehicle mileage statistics based on different approaches.

To compare the emissions estimated in this study with those from other countries, we can use **per capita emissions** as a relevant indicator. Baensch-Baltruschat et al. (2021) compiled estimations from different regions, and emissions range from 0.2 kg/capita per year in India to 3–5.5 kg/capita per year in the United States, thus reflecting car use relative to the population. The mean value for European countries is 1.17 kg/capita per year, with values varying from 0.6 for France to 1.8 for Norway. The calculations in this study show tire wear to be approximately 1.06 kg/capita per year (based on 10.42 million inhabitants in 2021), placing it in the lower half of the European range. A similar method used for South Korea by Lee et al. (2020) resulted in a mean value of 1.03 kg/capita (based on 51.74 million inhabitants in 2021).

The approach developed in this study holds significant promise for monitoring national tire wear emissions and evaluating potential measures to mitigate their impact on the environment. However, it is crucial to understand the degree to which our results are sensitive to the input parameters.

As shown earlier, the mileage data are (Section 2.3.3.1), highly dependent on the data collection approach. Beyond this, however, we must recognize that mileage can change over time. For instance, the wear emissions calculated in this work are based on traffic mileage data for 2019. Overall, mileage for all vehicle classes in Sweden has been increasing. While there was a dip in mileage for passenger vehicles and buses in 2020 and 2021, it started rising again in 2022. Light-duty vehicle mileage has shown rapid growth, with an increase of over 100 % between 2000 and 2019 compared to a 15 % increase for passenger vehicles (Transport Analysis, 2023).

The emission factors are also dynamic parameters. In our study, we scale emission factors based on vehicle weight. Recent trends, such as the surge in SUVs and electrification leading to heavier passenger vehicles, may elevate wear emission factors (Timmers and Achten, 2016; Beddows and Harrison, 2021; Fussel et al., 2022). In Sweden, HDVs are becoming increasingly heavier (Wisell et al., 2020), which could lead to higher tire wear emission factors. On the other hand, an important reason for allowing heavier goods vehicles is to reduce the number of transport vehicles needed to transport a certain weight of goods, which is why the overall emissions might not increase. Nevertheless, current trends point to increasing total mileage for both passenger cars and HDVs registered in Sweden (Transport Analysis, 2023).

However, there are also some factors that could reduce the emissions factors in the future. The upcoming EURO 7 legislation on vehicle emissions is proposed to include both brake and tire wear, which may influence the future development of tire materials and design to reduce emissions (European Commission, 2022). Several initiatives are currently underway to recommend reliable wear rate test methods for passenger car tires, such as that of the United Nations Economic Commission for Europe's (UNECE) Task Force on Tyre Abrasion (TFTA) and those of certain research projects, such as LEON-T (Low particle emissions and low noise tires, www.leont-project.eu). Technical solutions, such as advances in tire materials, lighter vehicle and battery materials, and improved vehicle traction control, could counteract increased tire wear emissions. The introduction of electric vehicles may also influence driving behavior, with some drivers frequently using high torque while others focus on optimizing their range by driving more eco-friendly with slow acceleration, even speeds, and gentle braking, thus resulting in lower tire wear.

4. Uncertainty evaluation and sensitivity analysis

Since the input data for the calculation was based on a number of assumptions, it is of great importance to evaluate the level of uncertainty.

For passenger cars and LDVs, the two parameters to be estimated for the sales model are the lifetime tire weight loss and the yearly number of replaced tires. From a statistical analysis of the field measurements of scrapped tires, the lifetime tire mass loss for the different tire types was estimated with an uncertainty of approximately 10 %. These estimations are valid only if the random selection of tires is representative of the Swedish vehicle fleet. Since tire manufacturers typically do not share detailed statistics on tire sales numbers, it is difficult to quantitatively verify the representativeness of a selected sample of tires. In our case, the distributions of tire dimensions for the measured tires were confirmed to be representative of the Swedish market by a representative from the Swedish tire industry. Thus, the estimated uncertainty of the tire mass loss is considered credible. By comparing the number of replacement tires sold from two different sources (Table 2) the uncertainty of these sales numbers was estimated to be below 5 %. Thus, the total tire wear for passenger cars and LDVs is estimated to be accurate within 15 %.

Since the emission factors for these vehicle types are based on the same data, the uncertainty of the estimated emission factors is at least 15 %. The overall quality of the mileage data for the passenger cars and LDVs retrieved from Traffic Analysis is considered to be good. However, the data partly consist of the modelling results describing the mileage of the vehicles whose mileage could not be measured. Unfortunately, Traffic Analysis could not quantify this uncertainty and no reliable information was provided.

In order to subdivide tires into different types, the length of time that drivers use winter tires needs to be determined. The period during which winter tires must be used is 4 months, but this only applies when winter conditions prevail. With an uncertainty of ±15 days, the corresponding uncertainty of the emission factors is 5 % for summer tires and 10 % for winter tires. For a more in-depth breakdown of how emission factors are affected by different road types (urban, rural, motorway), we used the different modelling approaches in Ericsson (2019). The uncertainties and sensitivity of that referenced source were not stated.

For HDVs, the lifetime tire weight loss could not be estimated through measurements, and a theoretical approach had to be used. As described in Section 2.3.5, the weight loss of the HDV tires has been assumed to be 8.8 kg/tire/year based on mean values for worn tire tread depth and tire fill rate. Using the minimum and maximum simulated values of the worn tire tread depth (3 and 5 mm) and tire fill rate (70 and 85 %) the total HDV tire wear varies from 4500 metric tons/year to 6400 metric tons/year, corresponding to approximately ±20 %.

For a more in-depth breakdown of the emissions in the mileage approach, the most significant uncertainties come from applying the literature-based EFs to Swedish conditions, the data describing the distributions of Swedish HDVs on different road types, and the data pertaining to the total mileage. Quantifying the first uncertainty is impossible due to the insufficient information provided by the sources regarding the characteristics of the vehicles and roads in the Netherlands. The data on the traffic distribution of HDVs across various road types, which are similar to the data on passenger cars and LDVs, lack a description of the uncertainty. As highlighted earlier, this study estimated that using the mileage calculated by the survey-based approach is more useful due to the more detailed accuracy of the results. However, the mileage calculated using model-based approach is 28 % higher than that calculated using the survey-based approach.

5. Conclusions

This study describes and highlights the challenges of using a detailed methodology to calculate total national tire wear from emission factors categorized by tire type, vehicle type, and type of road combined with the yearly mileages of different vehicle categories, especially for heavy-duty vehicles, which have been further categorized based on weight classes and number of tires. The resulting emissions have been compared to simpler calculations based on the sales approach. The following conclusions can thus be drawn:

- For passenger cars and LDVs, the measured emission factors and mileage data used in the mileage approach can be considered robust and, therefore, be a useful tool for estimations of national tire wear emissions from these vehicles.
- The uncertainties found in the tire wear emission factors for HDVs and buses, as well as in the data available for the yearly mileage of different vehicle classes, contribute to lower than expected accuracy when using the mileage approach to calculate total national emissions from these vehicles.
- The method, which includes weighing scrapped tires and comparing the results with the weight of new tires, produces emission factors in accordance with the literature and the latest on-road measurements.
- Statistical sources for vehicle mileage in Sweden differ by almost 30 %, and there is no obvious way to decide which source is the most reliable. In this study, the most detailed data were chosen.
- Tire emissions in Sweden in 2019 amounted to 11,040 metric tons and are dominated by emissions from passenger cars (55 %) followed by domestic heavy-duty vehicles (31 %), light-duty vehicles (10 %), buses (3.5 %) and motorcycles (0.05 %)
- Despite a range of assumptions and choices, the input data selected leads to emissions calculations that are similar to the previous calculations, which is likely to be a coincidence.
- To improve the accuracy of the method used, a top priority would be to develop methods to calculate the wear rate for heavy-duty vehicle tires as well.

CRediT authorship contribution statement

Maria Polukarova: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Mattias Hjort:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Mats Gustafsson:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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