Particle number emissions of 2022-24 for the Dutch emission inventory

Results and methodology report

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Inhoudsopgave

Bijlage

Summary

Exposure to particulate matter has adverse impacts on human health. Recently attention for the health impacts of ultrafine particles (UFP) has been growing. To get a better insight into ultrafine particles and their possible impact on health, the Dutch Health Council (‘Gezondheidsraad’) advised to get a better understanding of UFP in a broad sense, including its sources. UFP are defined as particles with a diameter less than 100 nanometer (nm). Due to their small size, the particles contribute little to total particulate mass. Therefore, the best way to estimate releases of these extremely small particles is by counting the number of particles emitted. However, particles above 100 nm, which are excluded from the UFP emission, also contribute to ambient particulate number and mass concentrations. They are therefore also relevant to take into account in the inventory, especially since size and composition of particles change upon release in the atmosphere.

This document describes the methodology and results for the emission inventory of total particle numbers (TPN) in the Netherlands which has been prepared by TNO in close collaboration with RIVM and the Dutch Emission Registration, for years 2022-2024. These total particle number emissions include both solid and volatile particles. Solid particles are typically measured as part of type approval standards such as for road transport, but the volatile particles are an important part of the contribution to ambient particles. Furthermore, a distinction has been made between the total emitted number of particles $TPN_{10\text{-}325}$ (number of particles up to 325 nm) and the part that is defined as ultrafine particles ($TPN_{10\text{-}100}$). An upper threshold of 325 nm is used, above which the total number of particles is negligible. The lower limit of 10 nm has been chosen because this will be the new lower limit for ambient air quality measurements (e.g. in relation to the EU Ambient Air Quality Directive), but also because it is increasingly difficult to measure emissions and concentrations of particles smaller than 10 nm. In addition their contribution to exposure is likely limited.

In this study we have improved the initial inventory for TPN for the Netherlands which TNO prepared for the year 2022 (van Mil, et al., 2024). Besides the coverage of 3 years instead of a single year, key updates compared to that initial version are the improvement of the methodologies for road transport and aviation, in both cases leading to a significant increase in assumed emissions for these sources. These increases are significant, yet in line with latest scientific insights with regard to emissions for these sources. Similar to the initial results for 2022, Dutch TPN emissions for 2022-2024 are dominated by traffic and transport, representing over 90% of the total emissions. Within the transport sector, aviation and sea shipping are the most significant contributors, followed by road transport and inland shipping. Compared to the earlier study, the increase in aviation emissions caused them to be of similar size as sea shipping emissions for 2022. For 2024, aviation emissions grow to the largest contributing sector due to the increase in flight movements in recent years. Furthermore, more than 90% of the national total TPN emitted is estimated to be smaller than 100 nm, hence within the definition of ultrafine particles.

The emission estimates in this report should be used with caution, as uncertainties for TPN are large. Future research is needed to improve emission estimates and decrease uncertainties. Next steps could include improving the understanding of the relation between solid and volatile particles, as well as improving insights of how these particles evolve and how to best quantify TPN emissions. Furthermore, the focus should be on improving

emission estimates for major sources where emissions are obtained using generic methods, such as industry and non-road mobile machinery leading to relatively high uncertainties. It is advised to perform a more in-depth analysis on a case-by-case basis to cover the potential variation in emissions throughout a wide range of processes (in industry) and vehicle types (in non-road mobile machinery). Another important next step would be to spatially distribute the emissions, as this is essential for use in atmospheric models and for comparisons to measurements of UFP in ambient air.

To improve the accuracy and robustness of the emission factors, we recommend incorporating measurements of TPN (including the volatile component) in the regular measurement programs that have been running for many years to quantify real-world emissions from various sectors in the Netherlands, including mobile sources. To this end, it first needs to be investigated how this can be done, while addressing the relatively high uncertainty of TPN measurements, which is related to missing methodological standardization. Once TPN measurements are robustly integrated into these measurement programs, targeted policy interventions can be prepared to reduce exposure of the Dutch population to ultrafine particles. Finally, we also recommend to explicitly study the relationships between TPN and other regulated pollutants.

Samenvatting

Blootstelling aan fijnstof heeft negatieve gevolgen voor de gezondheid. Recent is ook de aandacht voor gezondheidseffecten van ultrafijne deeltjes (UFP) toegenomen. Om beter inzicht te krijgen in deze ultrafijne deeltjes en hun mogelijke invloed op gezondheid, adviseerde de Gezondheidsraad om verschillende aspecten van UFP in kaart te brengen, waaronder de bronnen. UFP is gedefinieerd als deeltjes met een diameter kleiner dan 100 nanometer (nm), oftewel $PM_{0.1}$[1]. Doordat ze zo klein zijn, dragen ze weinig bij aan de totale massa. De beste manier om het vrijkomen van deze extreem kleine deeltjes te schatten, is door het aantal geëmitteerde deeltjes te tellen. Deeltjes groter dan 100 nm, die dus niet onder UFP vallen, dragen echter ook bij aan deeltjes aantallen en massaconcentraties. Ze zijn daarom ook relevant om mee te nemen in de inventarisatie, zeker aangezien maat en compositie van deeltjes veranderen na het vrijkomen in de atmosfeer.

Dit rapport beschrijft de methodologie en resultaten van de emissie-inventaris voor totale deeltjesaantallen (TPN, total particle number) in Nederland, opgesteld door TNO in nauwe samenwerking met het RIVM en de Nederlandse Emissieregistratie, voor emissiejaren 2022–2024. Deze deeltjesaantallen (TPN) emissies omvatten zowel vaste als vluchtige deeltjes. Vaste deeltjes worden vaak gemeten in het kader van wetgeving en typegoedkeuring, bijvoorbeeld bij wegverkeer, maar vluchtige deeltjes dragen eveneens belangrijk bij aan de omgevingsconcentraties. Daarnaast is ook onderscheid gemaakt tussen het totale aantal geëmitteerde deeltjes ($TPN_{10\text{-}325}$: aantal deeltjes beneden 325 nm) en het deel wat binnen de definitie van ultrafijne deeltjes valt ($TPN_{10\text{-}100}$). De bovengrens van 325 nm is gekozen omdat daarboven deeltjesaantallen te verwaarlozen zijn. Voor de ondergrens is 10 nm gekozen omdat dit de nieuwe standaard is voor metingen in de buitenlucht (bijv. in relatie tot de EU-luchtkwaliteitsrichtlijn (EU Ambient Air Quality Directive)), maar ook omdat het heel lastig is om voor de allerkleinste deeltjes emissies en concentraties te meten. Bovendien is hun bijdrage aan blootstelling waarschijnlijk beperkt.

In deze studie hebben we de initiële emissie-inventaris voor TPN voor Nederland verbeterd, die TNO heeft opgesteld voor het jaar 2022 (van Mil, et al., 2024). Naast de dekking van 3 jaar in plaats van één jaar, zijn de belangrijkste aanpassingen de verbeteringen in methodologieën voor wegverkeer en luchtvaart. In beide gevallen leiden deze verbeteringen tot een aanzienlijke toename in de geschatte emissies voor deze bronnen. Deze toenames zijn substantieel, maar in lijn met de meest recente wetenschappelijke inzichten. Net als in de oorspronkelijke resultaten voor 2022 worden de Nederlandse TPN-emissies voor 2022–2024 gedomineerd door verkeer en transport, goed voor meer dan 90% van de totale emissies. Binnen deze sector zijn luchtvaart en zeescheepvaart de grootste bijdragers, gevolgd door wegverkeer en binnenvaart. Door de toename in luchtvaartemissies zijn deze in 2022 vergelijkbaar groot geworden als die van de zeescheepvaart. Voor 2024 groeit luchtvaart uit tot de grootste sector door de stijging in het aantal vluchtbewegingen over de afgelopen jaren. Verder is meer dan 90% van de totale nationale TPN kleiner dan 100 nm, en valt daarmee onder UFP.

De emissieschattingen in dit rapport moeten met voorzichtigheid worden gebruikt, aangezien de onzekerheden voor TPN groot zijn. Toekomstig onderzoek is nodig om

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[1] $PM_{0.1}$ refereert aan deeltjes grootte uitgedrukt in µm (micrometer). 0.1 µm is gelijk aan 100 nm (nanometer).

emissieschattingen te verbeteren en onzekerheden te verminderen. Volgende stappen zijn bijvoorbeeld het verbeteren van het begrip van de relatie tussen vaste en vluchtige deeltjes, evenals het verbeteren van inzichten in hoe deze deeltjes evolueren en hoe TPN-emissies het beste gekwantificeerd kunnen worden. Daarnaast is het aan te bevelen de methodiek voor grote bronnen waar emissies momenteel voor worden verkregen via generieke methoden tegen het licht te houden, zoals voor de industrie en mobiele werktuigen. Deze generieke aanpak leidt tot relatief hoge onzekerheden. Het wordt daarom geadviseerd om meer specifieke analyses per type proces (in de industrie) en type voertuig (voor mobiele machines) uit te voeren om de variatie in emissies hiertussen in beeld te krijgen. Een andere belangrijke volgende stap zou zijn om de emissies ruimtelijk te verdelen, aangezien dit essentieel is voor gebruik in atmosferische modellen en voor vergelijkingen met metingen van UFP in omgevingslucht.

Om de nauwkeurigheid en robuustheid van de emissiefactoren te verbeteren, raden we aan om TPN-metingen (inclusief de vluchtige component) op te nemen in de reguliere meetprogramma's die al vele jaren lopen om emissies onder praktijkomstandigheden uit verschillende sectoren in Nederland, waaronder mobiele bronnen, te kwantificeren. Hiervoor moet eerst onderzocht worden hoe dit te doen, waarbij de relatief hoge onzekerheid van TPN-metingen, die samenhangt met het ontbreken van methodologische standaardisatie, worden aangepakt. Wanneer TPN-metingen op een robuuste wijze zijn geïntegreerd in deze meetprogramma's, kunnen gerichte beleidsinterventies worden voorbereid om de blootstelling van de Nederlandse bevolking aan ultrafijne deeltjes te verminderen. Tot slot bevelen we ook aan om expliciet de relaties tussen TPN en andere gereguleerde verontreinigende stoffen te onderzoeken.

1 Introduction

1.1 Ultrafine particles and particle numbers

Ultrafine particles (UFP) are particulates in the atmosphere with a diameter below 100 nm. These particles are likely to have a more significant negative impact on human health compared to average particulate matter. This has triggered a lot of research into ultrafine particles in recent years. Since ultrafine particles are very small, their contribution to the particulate mass is typically negligible, but these particles may exist in large numbers. Therefore, UFPs are typically expressed in number of particles.
To get a better insight into ultrafine particles and their possible impact on human health, the Dutch Health Council ('Gezondheidsraad') advised[2] to get a better understanding of UFP in a broad sense, which includes getting a better understanding of exposure to and health impacts of UFP, but also to reduce UFP emissions and where possible increase distance to sources. A key prerequisite for the latter is to get a good overview of the sources of UFP, hence the Health Council advised to start monitoring sources of UFP emissions in the Netherlands in a similar way as this is done for many other air pollutants. This will facilitate a good understanding of the main sources of UFP, to quantify the sources with highest emissions and uncertainties and prioritize improvements, but also to monitor trends in UFP emissions over time.

This document describes the most recent methodology for the inventory and the latest results, building on the methodology and results of the first emission inventory for particle numbers for the Netherlands, which is described in detail in (van Mil, et al., 2024).

It should be emphasized that with regard to emissions of ultrafine particles, there are major uncertainties, which are significantly higher than for typical air pollutants like NO_x or $PM_{2.5}$. This relates largely to the nature of ultrafine particles. These are small particles which may be emitted by sources, but immediately after emission chemical reaction and physical transformation processes start which strongly affect concentrations of UFP on the short time scales. These processes make the description of emissions difficult, hence working together with users of this inventory (e.g. atmospheric modellers, as in (Bohte & Manders, 2026)) is needed to interpret the resulting emissions in the correct way.
UFP is an overarching term for particles smaller than 100 nm. In practice, the emission of these particles consist of both solid and volatile particles. Solid particles, typically expressed as SPN (solid particle number) consist of the small particles already present in solid form in the exhaust gas at the time the hot flue gases exit the chimney or exhaust. After exiting the chimney or exhaust, however, the plume starts diluting and cools down, which typically triggers the generation of potentially many more particles, which are known as the volatile part. This part is especially difficult to quantify, since the actual processes creating volatile particles are in part dependent on the circumstances and hence measurements of such emissions are more difficult to reproduce. The solid particle number on the other hand is a more stable parameter, which is therefore typically used in the type approval or testing procedures of new engines or vehicles. It is, however, important to stress that the population

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[2] Risico's van Ultrafijnstof in de buitenlucht, Gezondheidsraad Advies Nr. 2021/38, https://www.gezondheidsraad.nl/documenten/adviezen/2021/09/15/risicos-van-ultrafijnstof-in-de-buitenlucht

is exposed to the sum of both solid and volatile particles. While some of the volatile particles will have limited lifetime their contribution to total emissions is such that they cannot be neglected when modelling concentrations of these particles, followed by exposure and health impact assessment.

The sum of the solid and volatile part is known as total particle number (TPN). We define TPN as the emission at the point of release into the atmosphere, but including the cooling and dilution until reaching ambient temperature conditions. Processes that occur here are condensation (hot exhaust gases cool and condensate to form additional particles) and nucleation (formation of new particles through gas-to-particle conversion). Especially the latter happens specifically for very small particles (~10nm), which is then quickly followed by coagulation where these agglomerate together to form larger particles. Inevitably, these processes are expected to be partly included in the emission inventory, hence close collaboration with users of this inventory (i.e. modelling teams) is needed to align approaches and further refine those where needed.

Since TPN is the parameter that is in the end relevant for air quality and exposure, this is what we aim to estimate with this study, despite the uncertainties associated with this. This study is, therefore, clearly aimed to be a starting point, and TPN emission estimates provided in this study should be improved in the years to come. For clarity, in the remainder of this report we will therefore refer to TPN as the relevant substance instead of the more generic term of UFP. We further detail TPN in the following way:

- TPN_{10-100}: total number of particles in the size range 10-100 nm;
- TPN_{10-325}: total number of particles in the size range 10-325 nm

While the total size range covered by this emission inventory is 10-325 nm, it should be noted that also particles smaller than 10 nm are emitted, in some cases in large quantities. These smaller particles are also recorded in UFP concentration measurements in ambient air. These ranges are chosen as such mainly for practical reasons, since the smaller the particles become the more difficult they are typically to measure. The 10 nm cut-off is in line with the latest ambient air quality measurement standards, and the latest motor vehicle standards (Euro-7/VII), that are currently being agreed upon at European level. This supports our decision to consider 10 nm as the lower limit in this study. On the other side, the 325 nm upper limit is chosen because above this limit, the contribution of emitted particles to the total particle numbers is typically negligible (Harni, et al., 2023). Most of the mass of particles is typically above this size, but the number is not relevant anymore for these few large particles. TPN_{10-100} best matches with the definition of UFP, but for completeness as well as the interpretation of observations, TPN_{10-325} is a valuable complementary source of information as it is considered to represent TPN as a whole.

1.2 About this document

This document describes the methodology and results for the emission inventory of particle numbers in the Netherlands which has been prepared by TNO in close collaboration with RIVM and the Dutch Emission Registration. It is set up to serve as a methodological background document similar to the “Methodology reports” annually produced for different emission sectors for regular pollutants, to record the details of the current methodologies used to estimate emissions of particle numbers for each relevant sector (Chapter 2).
In addition, Chapter 3 of this document also presents the resulting particle number emissions, including a comparison to earlier versions and how methodological changes affected the resulting emissions. Chapter 4 provides the main findings, discussion of the results and key next steps for future updates of the particle number inventory.

2 Methodology for the emission inventory

The methodology for obtaining TPN emission estimates for the Netherlands is kept close to the approach common in the Dutch Emission Inventory. This way, easy uptake can be enabled and the format is kept similar. Furthermore, with high uncertainties of TPN emissions and ample improvements to be made, the focus of this study is to implement knowledge from previous studies. We aim to obtain best estimates for sources identified in earlier work as having high emissions, whereas more standard approaches are used for emission sources with lower TPN emissions.

In contrast to emissions of most other species in the Dutch national Pollutant Release and Transfer Register (PRTR) (hereafter referred to as the Dutch Emission Inventory), the TPN-emissions are not defined in mass, but as particle numbers. Both TPN_{10-100} and TPN_{10-325} are given in 10^{21} (Z, Zetta) particles per year.

Our emission estimate results are gathered and combined in a work field (“werkveld”), similar to all other Dutch Emission Inventory numbers. In this work field, which consists of an MS Access database, the table ‘TPN_EMISSIES’ contains all emission estimates. This contains emission estimates for TPN compounds ‘TPN100’ and ‘TPN325’, which are referred to as TPN_{10-100} and TPN_{10-325} in this report, respectively. It also contains the compound definitions, dataset information, and fuel use per emission source and fuel type. Fuel use comes from the existing Emission Registration reporting and are in this study used as input for activity data when needed.

To align this inventory with the other Emission Registration work, an emission is obtained for each distinguished emission source (“emissie-oorzaak”) and fuel type (“emissie verklarende variabele”) for which there are relevant particle number emissions. In practice this means that emissions are obtained for each emission source (“emissie-oorzaak”) for which particulate matter (PM) emissions are included in the Emission Registration.

Table EA.2 in the Electronic Appendix lists all emission sources considered in this study, together with the related sectors (“doelgroep”). These sectors are a way to group emission sources based on their origin. Each emission source is already assigned to a sector in the Emission Registration. As transport related sources are known for their key contributions to TPN emissions, we have split this sector into subgroups, e.g. for road transport, aviation, shipping. See Table EA.1 in the Electronic Appendix for the full split.

Methodologies for obtaining emission estimates may differ for various source groups. For sectors known to lead to high TPN emissions, more detailed methodologies were used to obtain emission estimates. For others, more general approaches using a set of emission factors and different types of activity data are used. In total, 8 different methodologies were used to obtain emission estimates. Table 2.1 shows which methodologies were used for which sector. Table EA.2 in the Electronic Appendix indicates the methodology used for each emission source and fuel type. For each sector, the related methodologies are explained in more detail below.

For most sectors, we apply methodologies and emission factors developed in previous studies, resulting from literature studies and measurement campaigns. In this study (the update of the previous emission inventory (van Mil, et al., 2024)), we developed an updated methodology for aviation and improved it for road transport based on the latest insights. **Section** 2.1.5 gives a detailed explanation of the new methodology for aviation, including background information and how it was developed.

Table 2.1: Methodologies used to obtain emissions, for each sector group.

Sector group	Methodologies used
Transport	1 – Road transport exhaust 2 – Road transport brake wear 3 - Mobile machinery 4 – Inland shipping 5 – Railway 6 - Aviation 7 – Fuel based EF 8 - $PM_{0.95}$ based EF
Consumers	7 – Fuel based EF 8 – $PM_{0.95}$ based EF
Energy and industry	7 – Fuel based EF 8 – $PM_{0.95}$ based EF
Other	7 – Fuel based EF 8 – $PM_{0.95}$ based EF
Agriculture	Combustion emissions estimated using 7 – Fuel based EF Other emissions not estimated

For a number of emission sources, no TPN emission estimates were made. The nature of these emission sources is such that minimal to no TPN emissions are expected. This is the case for all sectors related to non-combustion sources in agriculture, as well as for example building fires, burning of candles, etc. Also, for some emission sources related to aviation, rail traffic, or road transport, no emissions were obtained. These are described in more details in the relevant sectors below.

2.1 Transport

2.1.1 Road transport

Emissions for road transport in the Netherlands are calculated bottom-up (Ligterink, Geilenkirchen, van Eijk, & de Ruiter, 2021). This means that the basis for the calculations is each individual vehicle that is registered. The emissions are calculated by multiplying the yearly activity of the vehicle (mileage or number of cold starts) with specific emission factors (emissions per km or per start). Activity data and Implied Emission Factors (IEF used for the calculation of wear emissions), aggregated per VERSIT+ vehicle category from the bottom-up calculation are used as input for the calculation of UFP emissions.

Particle emissions from road transport originate from four sources, i.e. tailpipe emissions, tire wear, brake wear and road wear. Tailpipe emissions are further subdivided in cold start emissions and emissions with a warm engine (Witt, et al., 2025).

PN[3] tailpipe emission factors for road transport are based on the current emission factors used for the calculation of SRM[4] emission factors (van Eijk, Ligterink, Geilenkirchen, de Ruiter, & Hoen, 2023). As exhaust emissions vary for different vehicles (ages, types, etc), the emissions are obtained on a more detailed level than per emission source and fuel type. These more detailed emissions are then later aggregated to obtain one $TPN_{10\text{-}100}$ and one $TPN_{10\text{-}325}$ emission for each emission source. The method used to obtain exhaust emissions, is referred to as *Method 1 – Road transport exhaust*. Cooling units of heavy duty vehicles are also considered, following this same method for road transport exhaust.

Emission factors are used from prior analyses (Keuken, et al., 2016), as well as new PN analysis (de Ruiter, Stelwagen, van Gijlswijk, & van Mensch, 2024) and measurement results. TPN emission factors for road traffic are based on existing (and regularly measured and updated) emission factors for solid particle number (PN), particle mass (PM), elemental carbon (EC) and total hydrocarbons (THC). The solid particles are estimated by the (measured and regulated) PN_{23} count, increased by the estimated share of particles up to 23 nm and a correction of solid soot to total solid mass. The number of volatile particles are estimated by the (measured and regulated) THC mass emission factor multiplied with a number-to-mass scaling factor based on the solid particles. In formula, TPN_{100} is approximated by

$$\begin{aligned} TPN_{100/325} &= PN_{10}(\sim PN_{23}) + PN_{volatiles} \\ &= (1 + f_{<23nm})\left(\frac{PM}{EC}\right)PN_{23} + \left(\frac{PN_{23}}{PM}\right)THC \end{aligned}$$

where PM, EC, THC the relevant VERSIT+ road-type dependent emission factors in g/km, PN_{23} the particle number larger than 23 nm as currently measured for vehicle legislation, and $f_{<23nm}$ the estimated increase with respect to PN_{23}: 0.3 for diesel and 0.5 petrol (European Commission: Directorate-General for Internal Market, 2022; Samaras, et al., 2020). With the pending transition from the lower limit for automotive measurements in Euro-7 from 23 nm to 10 nm, there has been a number of underlying comparative studies. Only for the highest particulate matter mass emissions, e.g., PM > 300 mg/kWh, there is a substantial part of the particles in accumulation mode, resulting in a difference between $TPN_{10\text{-}100}$ and $TPN_{10\text{-}325}$.

Cold start emission factors are calculated by multiplying the cold start PM emission factor with the PN_{23}/PM fraction per VERSIT+ class.

For petrol vehicles the $TPN_{10\text{-}325}$ emission factor is assumed to be equal to the $TPN_{10\text{-}100}$ emission factor as nearly all particles are <100 nm. For diesel, over half of the emissions are found in the nucleation mode (~10nm) and a fraction of the accumulation mode (~70nm) above 100 nm (as can be seen in the size distribution in Figure 2.1) (Eastwood, 2008). Therefore, only for diesel, $TPN_{10\text{-}325}$ emissions are assumed to be 15% higher than $TPN_{10\text{-}100}$ emissions.

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[3] For road traffic PN (particle number) refers to solid particles larger than 23 nm, in line with European emission standards (up to Euro 6/VI).

[4] SRM: Standaard Reken Methode, official procedure to model air quality in the Netherlands, with definition for vehicle categories and driving behavior.

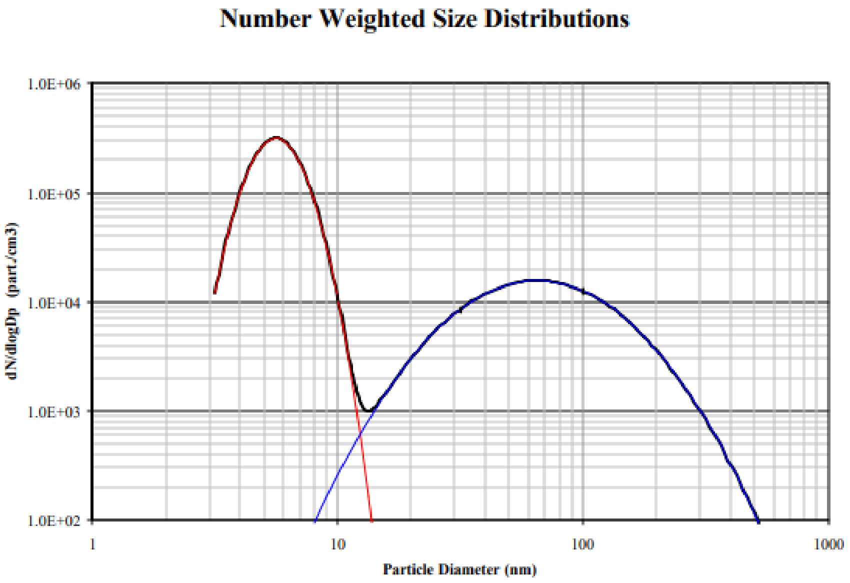

Figure 2.1: Size distribution diesel particles (Kittelson, Watts, Johnson, Baltensperger, & Burtscher, 2003)

Volatile particle emissions for vehicles on CNG, LNG and LPG are assumed to be zero as these fuels are gaseous in outside air and do not form particles, based on the vapour pressures. Such engines have particle emissions mainly associated with the burning of lubrication oil, and thus dependent on the type of oil, which follows the same trend as other engines, which all have the burning of lubrication oil (Samaras, et al., 2020).

Table 2.2 shows the fleet-average $TPN_{10\text{-}100}$ emission factors for road traffic.

Table 2.2: Implied emission factors per vehicle and fuel type ($TPN_{10\text{-}100}$ in #/km)

Vehicle	Fuel type	2022	2023	2024
Light duty vehicles	Petrol	1E+19	1E+19	1E+19
	CNG	7E+17	7E+17	7E+17
	Diesel	5E+19	5E+19	4E+19
	LPG	5E+19	5E+19	5E+19
Heavy duty vehicles (and busses)	Petrol	6E+21	6E+21	6E+21
	CNG	3E+18	3E+18	3E+18
	Diesel	1E+20	1E+20	1E+20
	LPG	2E+20	2E+20	1E+20
L-category vehicles	Petrol	4E+20	3E+20	3E+20
	Diesel	1E+20	1E+20	9E+19

Tire wear and road wear from road transport are not estimated in this study. Both mainly contribute to emissions of coarser particles and therefore TPN emissions of tires and road are expected to be of minor importance. TPN is in the extreme tail of their size distributions.

Brake wear emissions are a complex problem with far more and smaller particles, especially when the brakes warm up. At lower temperatures about 5x10^{9} particles are measured per 1 mg of particulate matter (Wahlström, Olander, & Olofsson, 2010). At higher temperatures this can increase to a factor 100 higher particle numbers per mg (we experience this in our own measurements as well). Assuming that about 2% of the mass is generated in higher temperatures, that leads to a conversion factor of 0.98 x 5x10^{9} + 0.02 x 5 x 10^{11} = 1.5 x 10^{10} #/mg based on the $PM_{2.5}$ wear emission factors for $TPN_{10\text{-}325}$. For $TPN_{10\text{-}100}$ a factor of 1.2 x 10^{10} #/mg is assumed based on the particle size distribution. This method is referred to as *Method 2– Brake wear*.

2.1.2 Mobile machinery

TPN emissions for Non Road Mobile Machinery (NRMM) largely depend on the presence of a particulate filter. Especially smaller NRMM have no PN_{23} limit values which implies that from legislation perspective, there is no incentive to install a particulate filter.

For diesel engines without particulate filter we typically see maximal values of 10^{7} #/cm3 or 10^{10} #/l (ambient conditions), regardless of the source (road or NRMM). This is caused by the fact that particles clump together based on the square of the given concentration (Smoluchowsk equation) (Eastwood, 2008). The residence time of gases in the exhaust line determines the concentration. (Hinds, 1999). For higher mass ($PM_{2.5}$), the particle size, or the fraction in accumulation mode around 100 nm, increases. Basically, more particles are produced in the diesel engine itself, but they are coagulated, condensed and accumulated in larger particles.
Diesel engines typically have a range of a factor two in engine speed between the lowest and highest engine load, and thus in mass flow. Depending on turbo and EGR, that means that there is a factor 2-3 in volume flow between the lowest and highest engine power.

Lots of diesel engines without particulate filter (especially smaller NRMM) are oversized for the power they need to deliver (1.6-2 litre engines for 20kW are not uncommon). For larger engines the engine size increases slower with the engine power (typically 40kW per litre). Therefore, the engine size in litres is estimated by 1+0.025 x P_{rated}[kw].

Particle numbers for engines with high particulate matter emissions are mainly a function of exhaust volume flow, thus proportional engine size times engine speed. With higher particulate mass, the particles are larger, not so much higher in number. Hence, the determination below, is based on this principle.

Diesel engine speed is typically between RPM = 800 and 2400 [min^{-1}], and the filling degree, i.e., the amount of inlet air related to the engine volume, is 90%. Volume flow can thus be calculated as:

$$Q\left[\frac{liters}{hour}\right] = \left[\frac{min}{h}\right] * [filling\ degree] * [engine\ size\ (l)] * [average\ engine\ load]$$
$$= 60\ * 0.9\ * (1 + 0.025 * P_{rated}) * \frac{RPM}{2} = (27 + 0.067 * P_{rated}) * RPM$$

This lead to a TPN emission factor, depending on the requested power, for “land based” mobile sources without particulate filter of:

$$TPN_{100}\left[\frac{\#}{hour}\right] = 10^{10}\left[\frac{\#}{liter}\right] * Q\left[\frac{liters}{hour}\right] = 2.7 * 10^{11} * RPM + 6.75 * 10^{9} * P_{rated} * RPM$$

RPM does not directly correlate with requested power, for example during accelerations and hydraulics where engine torque can very strongly, but by approximation:

$$TPN_{100}\left[\frac{\#}{hour}\right] = 2 * 10^{14} + 4 * 10^{14} * \frac{P_{demand}[kW]}{P_{rated}[kw]} + 5 * 10^{12} * P_{rated}[kW] + 10^{13} * P_{demand}[kW]$$

Where $0 < P_{demand}[kW]/P_{rated}[kW] < 1$ is the fraction requested engine load.

Many of the smaller diesel engines have a large engine volume compared to the power they supply, and, therefore, a relatively high exhaust gas rate. For larger engines, the engine volume is about 40 kW per litre engine. Therefore, the equation $Engine_{litres} = 1 + 0.025 * P_{rated}[kW]$ is used. Moreover, larger engines run slower, thus have a more limited increase in exhaust mass flow, compared to the rated power (P_{rated}) and power demand. See above.

For larger engines (>56kW) an approximation in the following form suffices:

$$TPN_{100}\left[\frac{\#}{hour}\right] = (5 * 10^{12} + 10^{13} * Load[\%]) * P_{rated}\ [kW]$$

The EMMA model (Dellaert, Ligterink, Hulskotte, & van Eijk, 2023) uses engine maps to calculate emissions for different NRMM types (Dellaert, Ligterink, Hulskotte, & van Eijk, 2023). Based on the formulas given above, $TPN_{10\text{-}100}$ emission factors have been estimated for the requested fields. They are summarized in table below (Table 2.3).

Table 2.3: The emission maps of a NRMM engine, with emission rates for different engine loads, proportional to the rated power.

Engine size	Load	0%	10%	20%	30%	40%	50%
>56 kW	#/s*P_{rated}	1.39E+09	1.67E+09	1.94E+09	2.22E+09	2.50E+09	2.78E+09
<56kW	#/s*P_{rated}	2.78E+09	3.33E+09	3.89E+09	4.44E+09	5.00E+09	5.56E+09
		60%	70%	80%	90%	100%	
>56 kW	#/s*P_{rated}	3.06E+09	3.33E+09	3.61E+09	3.89E+09	4.17E+09	
<56kW	#/s*P_{rated}	6.11E+09	6.67E+09	7.22E+09	7.78E+09	8.33E+09	

Diesel engines with particulate filter emit around 100.000 #/s*P_{rated}. (de Ruiter & van Mensch, 2022). These are typical values from Dutch Periodic Technical Inspection (PTI or ‘APK’)) and PEMS-PN testing of diesel engines under load. (Kadijk, Elstgeest, van der Mark, & Ligterink, 2020) If the engine is idling, the values are lower, however, more regenerations with associated particle emissions may occur when the engines are operated much at low engine loads. However, given the insignificant values, these distinctions are irrelevant.

As for road traffic, $TPN_{10\text{-}325}$ are assumed to be 15% higher than $TPN_{10\text{-}100}$ emissions.

Since these diesel engines, with high air-fuel ratios emit mainly EC, and little OC or VOC, the formulas should be used without modifications for volatiles.

The method to obtain TPN emission estimates for mobile machinery as described here is referred to as *Method 3 – Mobile machinery.*

2.1.3 Inland shipping

For inland shipping and sea vessels, the formulae from Section 2.1.2 can be used with a factor 5 increase for high-speed engine and a factor 10 for low-speed (two-stroke) engines, due to a shorter residence time of the engine gas in the tailpipe itself. This only holds for engines with PM emission limits above 0.3 g/kWh and NO_X > 8 g/kWh, or no aftertreatment. With aftertreatment the formulae can be used directly.

With the lack of detailed information on engines and engine loads the current ratio of CO2 (424 kton) and $PM_{2.5}$ (146 ton), and the typical CO2 concentration of 5% in exhaust gas, it translates to 0.34 g/kg CO2. In one litre exhaust gas for CCR0 and CRR2 , with little aftertreatment and residence time in the exhaust line, is 10^{11}. For newer CCR2 the value is 10^{10}. It is expected that CCR0 and CCR1 are dominant for UFP of inland shipping, and this yields with typical exhaust gas composition a ratio of **$TPN/PM_{2.5} = 3 \times 10^{15}$ [#/g]**. Particles are fine and therefore $TPN_{10\text{-}100} = TPN_{10\text{-}325}$.

The use of this $PM_{2.5}$ based emission factor to obtain emissions is referred to as *Method 4 – Inland shipping*.

2.1.4 Railways

Emissions for railways were first estimated for emission year 2022. For this year, the following methodology holds.
There are about 80 diesel-fuelled trains in use for passenger transport in the Netherlands and a similar amount of diesel locomotives. Passenger trains have some sort of aftertreatment and emit 10^{10} #/liter in exhaust gas, diesel locs do not and emit 10^{11} #/liter. Passenger trains have 2 x 15 = 30 liter engine and diesel locs 100 liter engines. They operate typically 10 hours per day and 250 days per year. This leads to:

- Passenger trains: 1.8×10^{21} #/year
- Diesel locomotives: 6×10^{22} #/year

These numbers represent total #/year for 2022, aligning with $TPN_{10\text{-}325}$. 62% of this is considered to be $TPN_{10\text{-}100}$. For years 2023 and 2024, the TPN emissions were scaled using PM emissions, for each emission source.
This methodology is referred to as *Method 5 – Railway*.
Diesel locomotives are represented by emission source 0200100 ‘Exhaust gas, rail traffic – cargo’. Passenger trains are represented by emission source 0200300 ‘Exhaust gas, rail traffic – passengers’.
For all other rail related emission sources, such as wear and wheel dust, no PN emissions are estimated.

2.1.5 Aviation

Introduction to UFP from aviation
UFP emissions from aerial transport have gained increasing scientific attention in recent years, despite the sector’s relatively small contribution to particulate mass emissions. Since

the late 1960s and 1970s, commercial jet engines have been progressively optimized to reduce visible smoke, resulting in substantially lower black carbon mass emissions. Consequently, aviation contributes only a minor fraction to total $PM_{2.5}$ mass emissions—for example, approximately 0.2% of total national $PM_{2.5}$ emissions in the Netherlands in 2024. However, reductions in visible soot have not necessarily translated into lower particle number emissions. In fact, several combustion modifications aimed at minimizing optical smoke have unintentionally increased TPN emissions.

Jet engine particle emissions consist of both non-volatile (solid) and volatile fractions. While regulations currently limit non-volatile particle number (nvPN) emissions, the volatile fraction (vPN)—often constituting the dominant share—remains largely unregulated. The formation of ultrafine particles is promoted by characteristic jet engine operating conditions, including high-temperature combustion with intense flame turbulence, rapid exhaust dilution, and strong cooling immediately downstream of the engine. In addition, the relatively high sulphur content of conventional jet fuel (typically 400–800 ppm) enhances the formation of sulphuric acid. During exhaust cooling, this leads to nucleation of large numbers of ultrafine particles (initially largely consisting of sulphuric acid nuclei). Together, these processes make aerial transport a highly significant source of ultrafine particle emissions, with TPN emission factors (in PN/kg fuel) exceeding those of diesel engines by orders of magnitude.

Methodology
The methodology to calculate TPN emissions from aviation (only below an altitude of 914m or 3000ft), consistent with the Emission Registration framework, is based on a comprehensive literature review of scientific publications and technical reports from the early 2000s through 2025, with emphasis on work published between 2015 and 2025. The review focused on emission indices, particle size distributions, and the chemical composition of aircraft exhaust particles as observed under ambient conditions, thereby including the volatile particle fraction relevant to airport environments. Although non-volatile particle number emissions are more extensively documented in the literature, they were considered primarily for contextual comparison rather than as the main focus.

Before presenting and discussing the updated emission factors, several methodological considerations related to measuring TPN emissions from aircraft at airports should be noted. Particle concentrations in the immediate vicinity of engine exhaust can be extremely high, sometimes exceeding 10^8 particles cm^{-3} prior to dilution, requiring measurement systems capable of operating accurately under heavily diluted sampling conditions. In the near-field plume, nucleation and coagulation processes occur at very high rates and continue for several seconds after exhaust release. To allow the particle size distribution to stabilize, sampling is therefore preferably conducted at some distance from the aircraft—typically on the order of 100 m or more. The formation of volatile and semi-volatile particles is strongly temperature dependent, implying that emission factors for these fractions ideally account for ambient temperature conditions, such as differences between ground-level and cruise environments. Next, particle losses within sampling lines and instruments can be substantial, particularly for ultrafine particles below 10 nm. Unless dedicated correction procedures are implemented to quantify actual penetration efficiency down to approximately 2.5 nm, TPN measurements generally represent particles larger than about 10 nm. These factors should be considered when interpreting reported TPN emission data.

Literature emission indices
Real-world TPN emission factors for commercial jet aircraft were compiled from six published studies, primarily representing measurements during landing and take-off (LTO) operations, with two studies additionally covering cruise conditions (Tran, 2020); (Mahnke, et al., 2024). The dataset includes original measurement campaigns (Moore, et al., 2017); (Takegawa, et al., 2021), as well as literature syntheses spanning earlier and more recent operational periods (1980s/1990s: (Schumann, et al., 2002); 2005-2019: (Zhang, Karl, Zhang, & Wang, 2020)). Each study specifies the lower particle size detection limit imposed by its

measurement configuration, with reported cut-off diameters ranging down to 2.5 nm. The emission factor dataset has been visualized by Figure 2.2, with the lower particle size cut-off boundary plotted on the X-axis and the emission factors (in number of particles per kg of fuel) on the Y-axis.

Figure 2.2 shows the dependence of reported emission factors on the minimum detectable particle size: inclusion of smaller particles leads to higher total particle counts. Several studies (Moore, et al., 2017); (Zhang, Karl, Zhang, & Wang, 2020); (Schumann, et al., 2002) adopt a lower size boundary near 4 nm, resulting in data series overlapping for this particle size in Figure 2.2. The work with the most explicit treatment of small-particle sampling efficiency (Takegawa, et al., 2021) demonstrates that extending measurements to include particles between 2.5 and 10 nm can approximately double the reported TPN emission factor (compare Takegawa series 2.5 nm (solid orange squares) with series 10 nm (solid green triangles) in Figure 2.2). Takegawa et al. (2021) argue that many of the earlier measurements, including the work by Moore et al. (2017), were likely influenced by a reduced capturing efficiency for particles below 10 nm, and therefore may have underestimated TPN emission. They use a corrective approach that explicitly accounts for size-dependent sampling losses when reporting representative real world emission factors.

Particle size distribution and origin of particle numbers
Analysis of particle number size distribution spectra reveals that TPN from commercial jet engines usually show a bi-modal particle size distribution (e.g. (Takegawa, et al., 2021); (Moore, et al., 2017); (Stacey, Harrison, & Pope, 2023)). The number size distribution peaks on average at 11 nm (8 – 15 nm, 98.2% of N_{total}, geometric standard deviation (GSD) 1.56), with a second peak at approximately 60 nm (1.8% of N_{total}, GSD 1.48). The nucleation mode peak appears to be composed of a sulphuric acid nucleus with an organic (semi)volatile coating consisting of engine lubrication oil (Fushimi, et al., 2025), This particle mode forms after the engine, when the exhaust gases rapidly cool. The second mode at 60 nm is primarily composed of soot (mainly refractory elemental carbon with, or without an organic coating) and forms in (not after) the engine, as a result of incomplete combustion of fuel. In case the soot mode particles would be bigger in size (e.g. > 100 nm), these particles would be responsible for a visible dark exhaust plume.

Factors affecting TPN emission factors
In reviewing literature on aircraft TPN emissions it became apparent that the formation of ultrafine particles from jet aircraft is primarily influenced by the following factors:

- Jet fuel sulphur and aromatics content
- The type/design, operational age and maintenance state of the engine
- Engine thrust setting
- Aircraft load
- Ambient temperature during the measurements

A very important parameter governing the TPN emission from jet engines is fuel sulphur content. Schumann et al. (2002) reported an order of magnitude difference in emission indices between low (e.g. <50 ppm) and high (>800 ppm) sulphur Jet A fuel. Tests with low-sulphur biofuels seem to confirm this dependence (e.g. Tran, 2020). Often the actual fuel sulphur content of the used fuel by aircraft in airport-based emission measurements is unknown (and highly variable between different fuel batches). That is also the case for the aromatics content, which may influence TPN emissions as well. In addition to the exact fuel specs, the exact age or state of maintenance of the engine and the airplane loading is also generally not known, when multiple aircraft are measured in real world conditions.

None of the reviewed literature found a consistent generally applicable relation between the engine power/thrust setting and the TPN emission factor. There are differences found between light phases (e.g. idle/taxiing, take-off and/or approach) but it seems this can go either way, with often seemingly contradicting results.

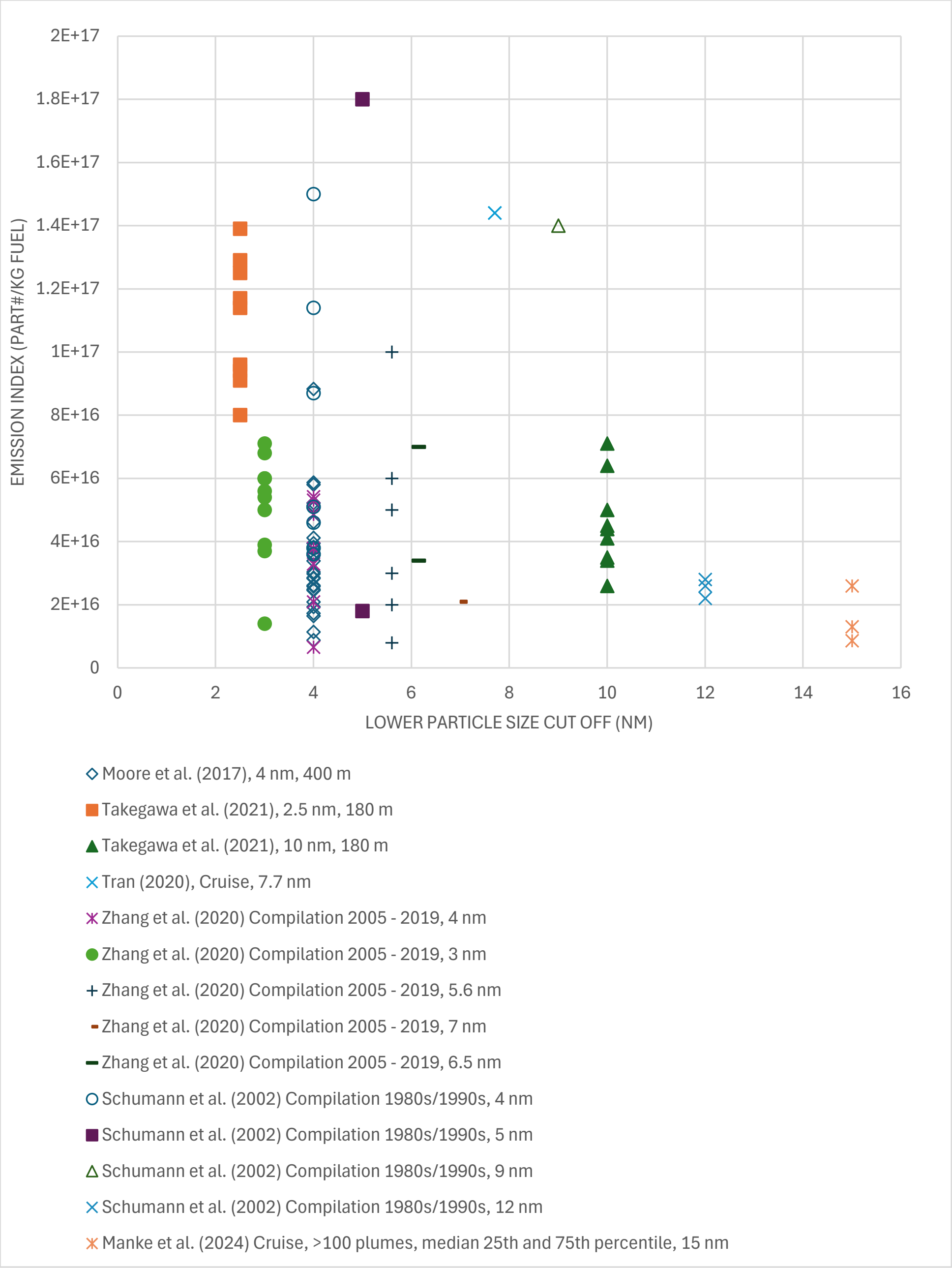

Figure 2.2: Real-world TPN emission factors for commercial jet aircraft, compiled from six published studies

Average TPN emission indices
Both Takegawa et al. (2021) and Moore et al. (2017) specify TPN emission indices by engine type. There were however no clear correlations found between these two studies, in the sense that a certain engine type consistently showed higher or lower emissions in both studies. Both the fuels specs as well as the ambient temperature differed between the two.

Because there are still too many unknowns in the annual aircraft movements in the Netherlands (primarily the fuel sulphur content) it was decided to use only one average emission

factor for TPN from jet engines. These are based on the Takegawa $N_{2.5}$ and N_{10} (all particle numbers above 2.5 and 10 nm) measurement results, as this study is most complete in taking account particles from 2.5 nm lower bound and considering both volatile and non-volatile particles. The emission factors for $TPN_{2.5-100}$ and TPN_{10-100} that average out into 1.09 x 10^{17} and **4.56 x 10^{16} part#/kg fuel**, respectively. As particles emitted from aviation are very small, we assume that the emission factor for TPN_{10-325} is equal to that for TPN_{10-100}. Fuel sulphur content during take-off varied between 30.4 and 440 ppm in the study by Takegawa et al. (2021), which may be considered to be somewhat on the lower end of the spectrum.
Note that in the previous Dutch UFP emission inventory the TPN_{10-100} emission factor used for jet engines was 1.24 x 10^{16}, so considerably lower. About 50% of the particle number appears to be below 10 nm in size. The same emission factor has been used for auxiliary power units (APUs).

Aviation gasoline-fueled piston engines
Smaller aircraft (both fixed wing and helicopters) may be equipped with piston engines. These represent a small fraction of the aircraft fleet. For these smaller aircrafts, emission factors from Rindlisbacher (2007) and Rindlisbacher & Chabbey (2015) were applied. This type of engines is fueled by leaded aviation gasoline, while their technology more resembles automotive engines. There is only little information available on TPN emission factors by this type of engines, particularly regarding volatile particle contribution. A key aspect is that leaded gasoline is used. Tetra ethyl lead decomposition products provide a strong nucleation pathway, which leads to much more particles than unleaded gasoline. These particles are also far less volatile than particles from a regular automotive PFI vehicle using lead-free gasoline. The notion arises from this that TPN will likely be much closer to nvPN for engines fueled with leaded fuel, and until better information becomes, TPN is assumed to be equal to nvPN for this source. Engine-specific nvPN emission indices are available by flight phase from Rindlisbacher (2007) and Rindlisbacher & Chabbey (2015).

The methodology presented here is used to obtain TPN emissions from all emission sources for aviation and is referred to as *Method 6 – Aviation*.

2.1.6 Sea shipping

Emissions from sea shipping are a major source of TPN emissions. A recent European research project (SCIPPER) provided a set of emission factors for main pollutants and also TPN for shipping in Europe based on an extensive literature review (Grigoriadis, Mamarikas, Ntziachristos, Majamäki, & Jalkanen, 2021). An emission factor of 3.58 x 10^{15} #/kWh is provided as base emission factor for TPN at European scale for liquid fuels (diesel-like). Assuming an efficiency of ~30% this would imply an emission factor of 3.0 x 10^{14} #/MJ. Similarly, for LNG an emission factor is provided at 2.3 x 10^{12} #/kWh, which would be equivalent to 1.9 x 10^{11} #/MJ when assuming the same 30% efficiency.

As means of a cross-check, these are compared to other estimates which were made in earlier EU research projects. Here, the emission factors were estimated dependent on the sulphur content of the fuel. This is important, since the sulphur content of the fuel is an important factor with a strong correlation to the amount of particles formed. The range provided here for shipping EFs (all liquid fuels) is between 16 and 50 x 10^{13} #/MJ (Visschedijk & Denier van der Gon, 2022). Here, the lowest value is representative for fuels with a sulphur content < 0.1%, which would be the most representative for the North Sea which – together with the Baltic Sea – has the most strict limit values with regard to sulphur in Europe. This EF is around half the EF quoted from the SCIPPER study, which might be explained by the fact that this is from a European project which also included the Mediterranean region where a less strict sulphur regime applies. Hence, the lower emission factor is believed to be more

representative for the Netherlands and North Sea at this point and this is the EF used for liquid fuels.
In addition, a measurement campaign conducted by TNO in the Rotterdam harbour (around Hoek van Holland) quantified TPN emissions from ships based on measurements at locations on both side of the Nieuwe Waterweg for a range of ships, where the average emission factor that was calculated from these measurements was similar as the emission factors used for this inventory, hence confirming the emission factors to be in the correct range.
For LNG, the SCIPPER emission factor quoted earlier in this section is used in the absence of an alternative emission factor.

For sea shipping, for all fuels, a direct emission factor based on fuel use is used to obtain emission estimates. This method is referred to as *Method 7 – Fuel based EF*. This methodology is described in more detail below, in 2.2 Other Sources.

2.2 Other sources

For other sectors, relatively straight-forward methods were used to obtain emission estimates. As shown in Table 2.1, these consist of *Methodology 7 – Fuel based EF* and *Methodology 8 – $PM_{0.95}$ based EF*. For both cases, an emission factor approach is used, where an emission factor is multiplied with relevant activity data in order to get to a yearly total emission estimate. For these two methods, different types of activity data and corresponding emission factors are used.

The emission factors used in this study all originate from literature review. Earlier EU projects EUCAARI (Kulmala, et al., 2011) and TRANSPHORM (Denier van der Gon, et al., 2014) first European-wide emission inventories for TPN were made on this basis. This work originates from ~10 years ago and given technological developments these may therefore be on the high end of the range for a number of sources. Emission factors were collected for main sources, but it was quickly found that TPN emission factors are generally scarcely available. Therefore, an alternative method was developed by looking at $PM_{2.5}$ mass, estimating the smaller fraction therein (first $PM_{0.95}$ and then down $PM_{0.3}$, representing the PM mass below 0.95 µm and 0.3 µm, respectively) and then estimating the number of particles therein by means of a literature-based or assumed size distribution. A range of these size distributions were collected from various literature sources as part of the EU Horizon Europe project “RI-URBANS” where TNO built a European-wide inventory for particle numbers (El Malki, Hohenberger, Visschedijk, & Kuenen, 2024). The latter approach is mainly used for small sources, where a simple method suffices, but also for industrial sources where different processes causing both mass and number emissions are happening at the same time. By applying specific knowledge of the processes in each industry, a decision is made on which size distribution is the most suitable.

Table EA.2 in the Electronic Appendix gives an overview of the emission sources for which these methodologies are considered to obtain TPN emission estimates. For relevant emission sources where an emission factor approach is used (*Methodology 7 – Fuel based EF* or *Methodology 8 – $PM_{0.95}$ based EF*), the emission factors are also included here. Emission sources are often more detailed than TPN emission factors. These emission factors represent more general processes. Therefore, emission factors often applied to multiple emission sources. To link these two, assumptions have been made on the main processes prescribed in an emission source. Table EA.3 in the Electronic Appendix gives an overview of the various emission factors considered in this study. It includes a more general description of the process captured by this emission factor. This gives more insight into why emission factors are used for certain emission sources. Each emission factor is given a short label, which is also referred to in Table EA.2, allowing to cross-check which emission factor is used for which emission source, and to see which assumptions have been made when linking an emission factor to each emission source. Furthermore, Table EA.3 indicates in which project each emission factor was obtained; EUCAARI (Kulmala, et al., 2011), TRANSPHORM (Denier van der Gon, et al., 2014), RI-URBANS (Kuenen, Visschedijk, & Heslinga, 2022), or TNO study for UFP in the Rijnmond region (Visschedijk & Denier van der Gon, 2022).

Methodology 7 – Fuel based EF

For some emission sources, a direct emission factor is considered, with the fuel use *('Emissie verklarende variabele hoeveelheid')* as activity data.

$$TPN_x\ emission = EF_{direct,x} \cdot fuel\ use$$

Where

- TPN_x is TPN$_{10\text{-}100}$ or TPN$_{10\text{-}325}$ in Z (10^{21}) particles.
- $EF_{direct,x}$ is a direct emission factor for TPN$_{10\text{-}100}$ or TPN$_{10\text{-}325}$. Such an emission factor is considered for each fuel type and emission source combination. This emission factor is in 10^{16} particles/MJ fuel use.
- Fuel use is fuel use in MJ. This is also defined per emission source and fuel use in the Emission Registration. For this study, we have used the fuel use reported in the Dutch Emission Inventory for the years 2022-2024 based on the final figures (Dataset "ER 1990-2024 Definitief").

Methodology 8 – PM$_{0.95}$ based EF

In other cases, the particle number emissions are deduced from the PM emissions. An indirect emission factor is then used, for which activity data is often PM$_{0.95}$ emissions (total mass of emitted particles smaller than 0.95 µm). Both the emission factor and PM$_{0.95}$ emission are defined for each combination of emission source and fuel type.
Therefore, for each emission source and fuel type, a specific TPN emission estimate is obtained as follows:

$$TPN_x\ emission = EF_{indirect,x} \cdot PM_{0.95}\ emission$$

Or

$$TPN_x\ emission = EF_{indirect,x} \cdot PM_{10}\ emission\ \cdot fraction \frac{PM_{0.95}}{PM_{10}}$$

Where

- TPN_x is TPN$_{10\text{-}100}$ or TPN$_{10\text{-}325}$ in Z (10^{21}) particles.
- $EF_{indirect,x}$ is an indirect emission factor for TPN$_{10\text{-}100}$ or TPN$_{10\text{-}325}$. This is specific for a fuel type and emission source combination. This emission factor is in $10^{13}\ particles\ /\ kg\ PM_{0.95}$.
- $PM_{0.95}$ emission is the yearly total emission of PM$_{0.95}$. This can be obtained my multiplying the PM$_{10}$ emission from the emission registration by a fraction for PM$_{0.95}$/PM$_{10}$. The PM$_{10}$ emissions used are those reported in the Dutch Emission Inventory for the year 2022 based on the final figures (Dataset "ER 1990-2022 Definitief"). The fractions to obtain PM$_{0.95}$ can be found in Electronic Appendix Table EA.4. These are also based on existing fractions from the Dutch Emission Inventory.

$$PM_{0.95}\ emission =\ PM_{10}\ emission\ \cdot fraction \frac{PM_{0.95}}{PM_{10}}$$

2.3 **Industry –** ‘NACE’ (‘ERI’)

For industry, emission estimates in the Emission Registration are partly based on annual emission reports (AER) by individual facilities. These are included in the so-called ‘NACE’ (‘ERI’). Emission factors related to this are also treated separately.

For the ERI emission sources, it was decided to obtain emissions on the level of the emission sources, and not obtain company specific emissions. Because of the high uncertainty of TPN emission estimates, it is more fitting to obtain estimates on an aggregated level (emission source) rather than per individual company. However, this does imply that spatial distribution of the emissions is not possible for now.

Also, for industrial emissions, there is often not a clear split between process or combustion emissions. For these emissions reported by companies, the emissions are labelled as combustion if there is fuel used by the installation from which the emissions occur. However, the emissions reported may actually represent a sum of process and combustion emissions. For many of these emission sources related to industry, we use indirect emission factors and therefore reported PM emissions as activity data. However, if the reported PM emissions also include a significant contribution from process-based emissions, application of a fuel-based emission factor will lead to erroneous PN emission estimates. To overcome this issue, an implied emission factor was obtained and used to judge whether the PM emissions are mainly combustion- or process-based. These implied emission factors were obtained for natural gas and PM_{10} emissions. When this check indicated that PM emissions were too high based on the natural gas consumption, it was assumed process-based emissions play a key role in this process and a process-based EF was chosen for this emission source. This was then done for all fuel types linked this emission source, as it was assumed that then process-based emissions were dominant for all fuel types. When PM emissions were in the expected range for natural gas combustion, it was assumed that this emission source mainly contained combustion emissions, and therefore the relevant TPN emission factor for the combustion process was used.

As was explained before, already existing emission registration fractions of $PM_{0.95}/PM_{10}$ per fuel type and emission source were used to obtain $PM_{0.95}$ emissions (for these fractions, see EA.4). For emission sources for which emission estimates were obtained using *Methodology 8 – $PM_{0.95}$ based EF*, these $PM_{0.95}$ emissions are needed as activity data. However, when industries report both PM_{10} and $PM_{2.5}$ emissions, both emissions are included in the ER. However, the $PM_{2.5}/PM_{10}$ fraction as follows from reported emissions may not align with the fractions in the ER. The fractions in the ER are more general and may vary per industry. In some cases, this leads to complications, as now using PM10 emissions to obtain $PM_{0.95}$ lead to occurrences where $PM_{0.95} > PM_{2.5}$. For these cases, $PM_{0.95}/PM_{2.5}$ fractions were obtained and $PM_{2.5}$ emissions were used to obtain $PM_{0.95}$. These fractions are also included in Table EA.4.

3 Results

3.1 Results current version

Table 3.1 shows TPN emissions for the different sectors (“Doelgroepen”). These sectors are a way to group emission sources based on their origin. Each emission source is already assigned to a sector in the Emission Registration. It becomes clear that for 2024 the main source of TPN emissions in the Netherlands is traffic and transport, which is found to account for 93% of the TPN emissions when considering the size range up to 325 nm. When zooming in only on particles below 100 nm, the share of traffic and transport in total TPN emissions increases to 98%, since especially for combustion, these small particles make up most of the TPN emissions.

Table 3.1: TPN emissions for all source groups ('Doelgroepen'), for 2024.

Doelgroep	$TPN_{10\text{-}100}$ (10^{21} #)	$TPN_{10\text{-}325}$ (10^{21} #)
Agriculture	92	309
Chemical industry	1.8	14
Construction	6.3	23
Consumers	195	1183
Drinking water supply	0.1	0.1
Energy sector	8.3	15
Other industry	264	413
Refineries	131	144
Sewage systems and waste water treatment plants	1.4	1.5
Trade, Services, and Government	64	255
Traffic and transport	30756	31240
Waste disposal	4.1	10
Total	**31530**	**33613**

The TPN emissions are shown again in Figure 3.1 but now also including $PM_{2.5}$ emissions from the Dutch Emission Inventory in the same plot, again for 2024. In these figures the traffic and transport sector is split in the main subsectors, while some smaller source groups are lumped together. It shows that the main contributors are aviation and sea shipping[5] , which account for 41% and 29% of $TPN_{10\text{-}325}$ emissions, respectively. The other main contributors are road transport (16%) and inland shipping (8%).

Figure 3.1 also shows the corresponding $PM_{2.5}$ emissions as reported in the Dutch Emission Inventory for the year 2024 (based on Dataset “ER 1990-2024 Definitief”). Here it can be clearly observed that the main sources of particle number emissions are different from the

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[5] Sea shipping includes all shipping activities happening on the Dutch Continental Shelf (or “Nederlands Continentaal Plat”), so also including ships that do not depart from or arrive in the Netherlands

main sources contributing to the PM mass. For PM mass, the main contribution is from consumers (incl. wood combustion) and energy and industry sectors which together represent more than half of the Dutch $PM_{2.5}$ emissions, however for TPN_{10-325} their combined contribution is only 5%. For mobile sources on the other hand, the contribution to total $PM_{2.5}$ emissions is 35% while for TPN_{10-325} the transport sectors contribute more than 90%.

The uncertainties of the estimated emissions have not been estimated at this point. However, as mentioned earlier in this report uncertainties for TPN are higher than for main air pollutants like PM. Since in many cases available measurements are scarce, there is little information to base uncertainty estimates on.

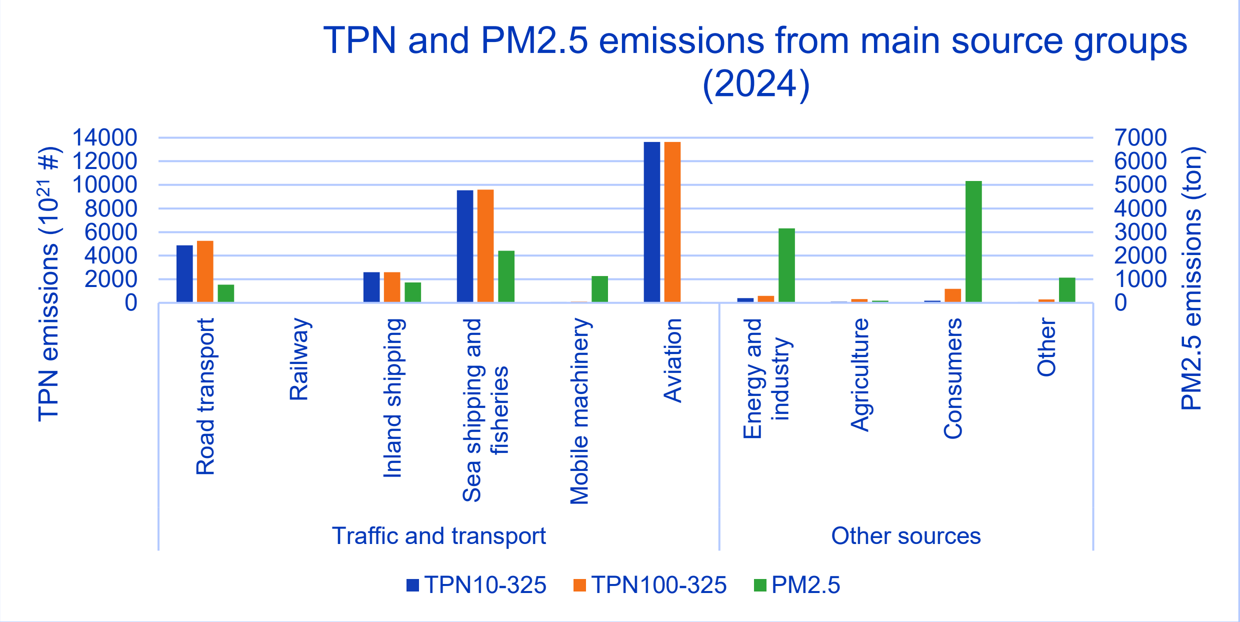

Figure 3.1: Annual TPN emissions (10-100 and 10-325 nm, respectively) and $PM_{2.5}$ emissions as reported in the Dutch Emission Inventory for the main contributing sectors to TPN emissions, for 2024.

Road transport

Figure 3.2 partially shows the effect of particulate filters in TPN emissions of diesel passenger cars. The figure shows that diesel passenger cars without particulate filter (the 4 left most vehicle types) accounted for 7% of the total mileage of diesel passenger cars in 2024 but 71% of the TPN emissions of these vehicles. On the other hand, vehicles with a particulate filter have a smaller contribution to the total TPN emissions, but a significantly higher share in the vehicle kilometres. Note that the TPN emissions for vehicles with a particulate filter consist almost exclusively of volatile particles, as emissions of solid particles are negligible.

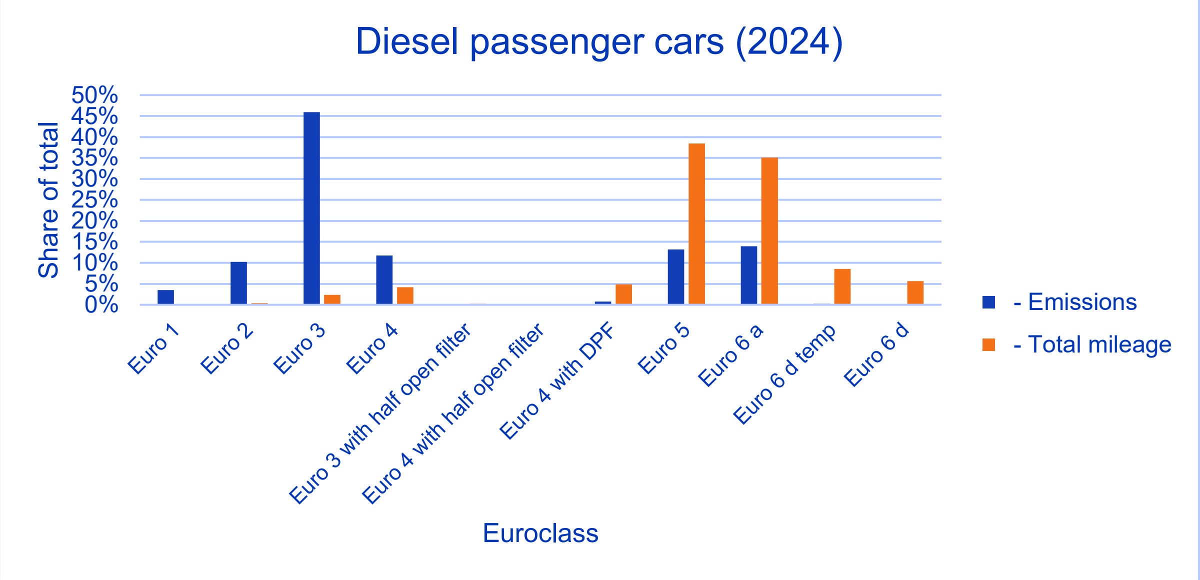

Figure 3.2: Share in mileage and TPN_{10-100} emissions of diesel passenger cars

Aviation

In this study, we focus on TPN emissions of particles larger than 10 nm (TPN_{10-100} and TPN_{10-325}). However, for aviation, emissions of particles smaller than 10 nm play an important role, related to the presence of sulphur in jet fuel which leads to generation of a significant amount of particles with a diameter below 10nm, see also (Bohte & Manders, 2026). For most other sources, these very small particles are not very relevant, but for aviation the inclusion of particles between 2.5-10nm may increase emissions by more than a factor 2, as depicted in Figure 3.3 below. The figure shows $TPN_{2.5–100}$ (total particle numbers ranging from 2.5 to 100 nm) split in the range 2.5-10nm and 10-100nm. It shows that the particles in the size range 2.5-10 nm are constituting more than 50% of the total particles, thus confirming the important role of these very small particles.

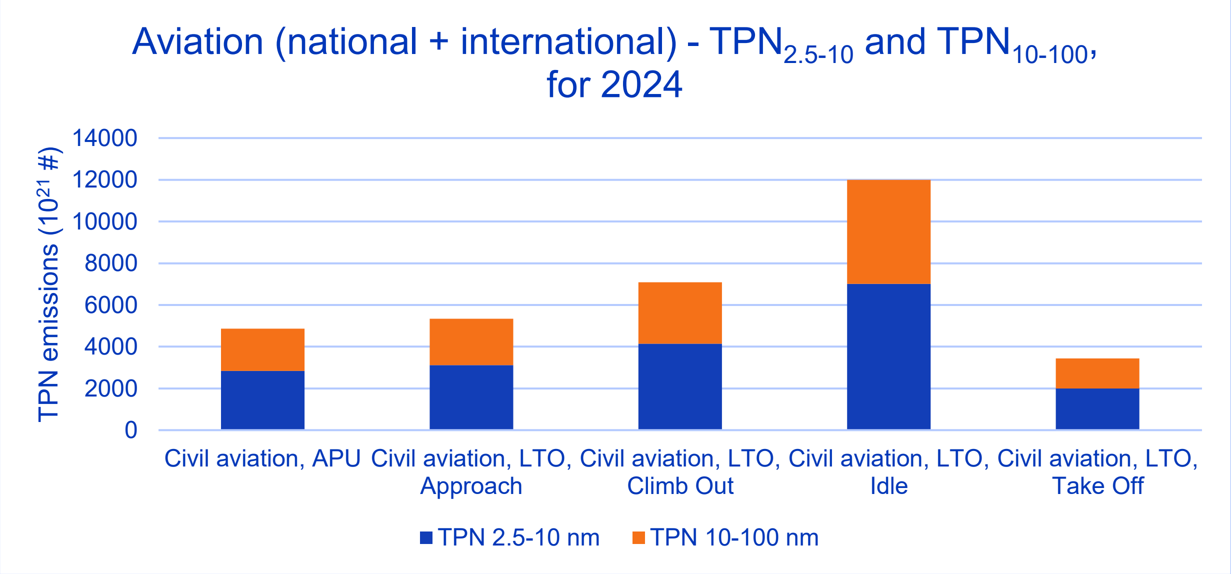

Figure 3.3: $TPN_{2.5-10}$ nm and TPN_{10-100} nm emissions for aviation, showing the high emissions of very small particles (excluded in this study).

Trend (2022-2024)

Figure 3.4 shows $TPN_{10\text{-}325}$ emissions for 2022, 2023 and 2024. It is again clear that aviation, sea shipping, and road transport contribute most to the total emissions. These three most emitting sectors also show the strongest variations between years. The other sectors are relatively constant.

For aviation, there is a strong upward trend in TPN emissions from 2022 to 2024. This is related to the strong effect of COVID-19 travel restrictions on the number of flights in the period 2020-2023 in the Netherlands. Compared to 2019, 2020 saw an almost 50% decline in total Maximum Take Off Weight of all flights, with a 58% reduction in number of flights with typical wide-body commercial aircraft. In 2022, the activity level was still ~20% lower than in 2019, and it further increased in 2023 and 2024 to a level that is close to the activity in 2019.

Sea shipping emissions decrease from 2022 to 2024. This is in line with the trend that in the last 15 to 20 years, sea shipping has shown a gradual decline in the amount of fuel consumed. This has to do with both a slightly decreasing amount of transport across the seas and the steady increase in the efficiency (and cleanliness) of the fleet.

For road transport, TPN emissions also decrease over time (about 10% per year), even though the total kilometres driven have increased by about 2.5% each year. This is caused by rejuvenation of the vehicle fleet. Older vehicles leave the fleet (or drive less kilometres per year) and newer vehicles, complying with strict emission limits, enter the fleet. Further, electric vehicles (with zero tailpipe emissions) have entered the fleet rapidly in recent years and the share of diesel passenger cars has declined quickly since diesel gate.

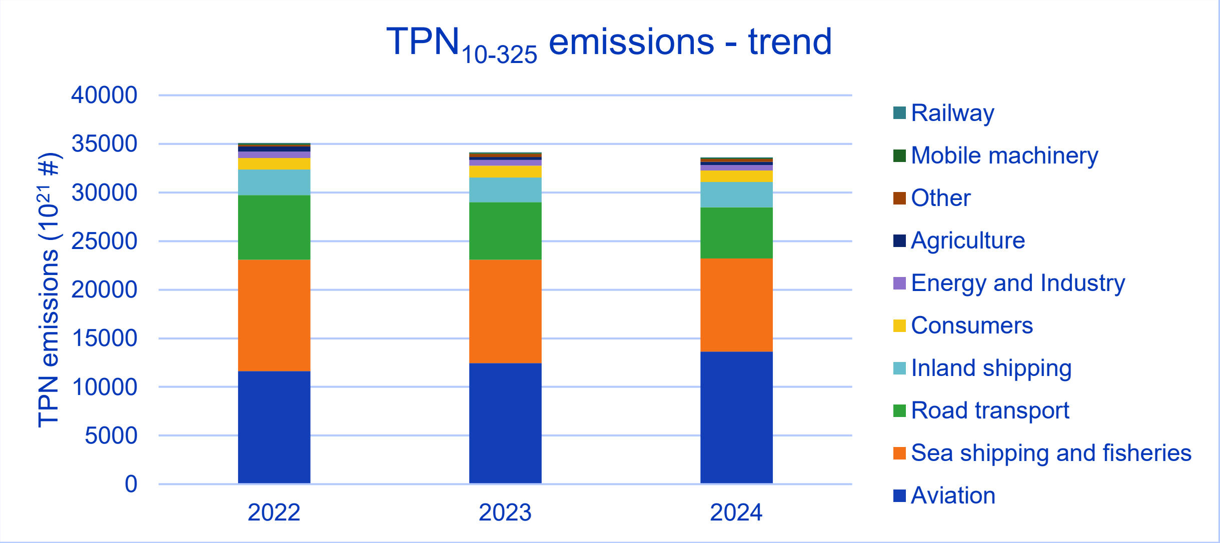

Figure 3.4: $TPN_{10\text{-}325}$ trend for 2022, 2023, and 2024, per sector group

3.2 Recalculation of emissions - Comparison to previous version(s)

In this study, some methodologies have been updated compared to the previous version (van Mil et al., 2024). These methodological changes and updates of emission factors result from new research and insights. Methodologies have been updated for road transport and aviation.

Furthermore, activity data and $PM_{2.5}$ emissions that are used as a starting point for our calculations originate from the most recent version on the emission registration dataset. In the previous version, this was based on Dataset “ER 1990-2022 Definitief”, whereas now they are based on “ER 1990-2024 Definitief”. Changes made in this dataset or the addition of new sources also result in changes in TPN emissions. These changes are small compared to the impact of the methodological changes made in this study.

Figure 3.5 shows a comparison for TPN_{10-325} in 2022 per source sector. TPN_{10-325} emissions for road transport increased from 3070 to 6637 x 10^{21} #. For aviation, the methodology change also results in a strong increase of TPN emissions, from 6499 to 11620 x 10^{21} #.

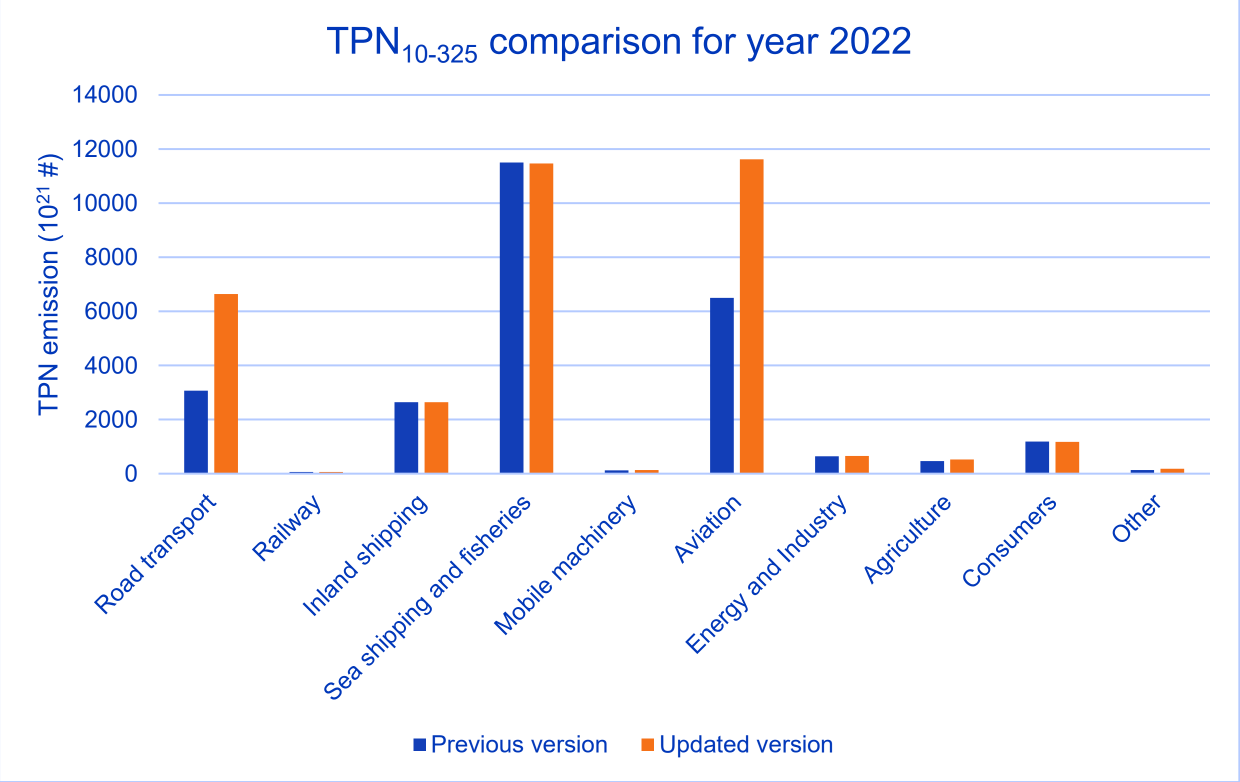

Figure 3.5: Comparison of TPN_{10-325} emissions for year 2022, comparing recalculated emissions with previous emissions.

For road transport, emissions have increased by a factor 2 compared to the previous version. This results from an update in the emission factors and no longer capping these factors to a maximum value. To come to this new methodology, the emission factors as used in the previous version were compared to the emission factors found in another study (El Malki, Visschedijk, & Kuenen, 2025). The main difference between both sets of emission factors were caused by the capping (maximum value) used in the previous version of this study. Further analysis of measurement data showed that values higher than the capped values were found in measurement data. Therefore, the emission factors are now no longer capped to a maximum value. For some (older) vehicle categories, this resulted in unrealistically high emission factors. Further analysis showed that this was mainly caused by the underlying set of solid PN emission factors, where emission factors were too high. For older vehicle categories, there is a lack of proper measurement data. For these vehicle categories, that are rarely seen on the road, new estimations were made.

For aviation, emissions have increased by almost a factor 2 following the new methodology implemented and explained in Section 2.1.5. This is the result of three main changes.
First, a review of recent literature resulted in an emission factor for jet fuel of between 3 and 4 times larger than the previous EF used. This new EF is based on (Takegawa, et al., 2021) and is used as this study measured particles from 2.5 nm diameter and takes into account both volatile and non-volatile particles. It is therefore considered most complete and best suitable for our inventory. This updated emission factor is now directly applied to the amount of fuel used, whereas before we applied it to number of LTO, assuming an average of 1000 kg fuel/LTO. Applying it now directly to fuel used leads to more accurate and higher emissions. It shows that assuming 1000 kg fuel/LTO led to an overestimation of emissions, as now emissions from LTO increased by a factor 2.6, which is lower than the ratio between the new and old emission factor.
Second, the emissions for APU were previously overestimated, due to an error. This has now been corrected and the updated emission factor was applied, leading to an overall decrease in emissions from APU.
Third, also the emission factor for aviation gasoline has been updated, from a $PM_{0.95}$ based to a direct emission factor using fuel usages, leading to an increase of emissions.

Lastly, as TPN estimates are created for all emission sources (‘emissie-oorzaken’) in the Dutch emission inventory for which PM is reported, there are also new sources added to this version in comparison to the previous version. Table 3.2 shows an overview of additional and removed emission sources. There are also often new fuels added for existing emission sources. These are not summarized here, but all emission factors for each emission source – fuel combination can be found in Table EA.2 in the Electronic Appendix.

Table 3.2: New emission sources in this TPN inventory compared to the previous version

EMK_CODE	Emission Source	Explanation
0401101	Exhaust gas, mobile machinery - other	New emission source
0930007	Exhaust gas, civil aviation, LTO	Previously no TPN estimated, now added
T102000	Facilities NACE 16.23: manufacture of builders' carpentry and joinery	No PM emissions in 2022. There are PM emissions for 2023 and 2024.
T104300	Facilities NACE 23.32: manufacture of bricks and tiles	No PM emissions in 2022. There are PM emissions for 2024.

4 Conclusions and Next Steps

In this study, TPN emissions for the Netherlands were obtained for emission years 2022-2024. This built upon a previous study, where a first TPN emission inventory for 2022 was created for the Netherlands (van Mil, et al., 2024). Both studies closely follow the Dutch emission inventory methodology. In this update, two years (2023-2024) were added, activity data was updated to align with the newest Dutch emission inventory dataset, and methodologies for aviation and road transport were updated.

The revised methodologies for aviation and road transport lead to strong increases in TPN emissions (~ factor 2 for both sectors overall). While this seems like a large change, it should be noted that particle number emissions is a field that is strongly in development, hence new insights become available continuously, affecting emissions significantly. For road transport, this mainly results from the removal of the ‘capping’ of emission factors to a maximum level, which was included in the first inventory since some of the solid PN emission factors were considered to be too high. Road transport emissions and emission factors of our initial TPN inventory for the Netherlands have been compared with recent measurement data and other emission inventories, such as prepared for EASVOLEE based on international literature (El Malki, Visschedijk, & Kuenen, 2025). This led to new insights and the removal of the original ‘capping’ of emission factors to a maximum level. This caused an increase in emission factors for mainly the older vehicles, which emit much more particles compared to newer vehicles. These emission factors remain uncertain but, due to old age, the vehicles are leaving the fleet and their impact on total emissions decreases.
For aviation, particle numbers have gained a lot of attention in recent years, which resulted in a large amount of publications looking into emissions of particle numbers from aircraft, especially in the last decade. A synthesis of the available literature has resulted in updated emission factors for different aircraft types, also considering APUs, smaller aircraft and ground support equipment, which resulted in updated emission factors such that emissions from aviation have more than doubled.

The results of the update show that traffic and transport account for more than 90% of TPN emissions in the Netherlands. While in the initial inventory for 2022 shipping was the largest sector, aviation is now the largest source of anthropogenic TPN emissions in 2024 in the Netherlands, accounting for 41% of total particle numbers. The increased contribution of aviation is due to higher activity levels in 2024 compared to 2022, and the revised methodology with higher emission factors. Sea shipping accounts for 29%, while road transport accounts for 16%.

Aviation emissions are centred around airports, especially since only emissions below 914 meters are considered for this inventory. Therefore, these will be most pronounced at and around Schiphol airport near Amsterdam, which is by far the biggest airport in the Netherlands. The area around Schiphol is also highly populated, hence the potential impact of UFPs from aviation is significant. For the second biggest source, sea shipping, the situation is different. A significant part of these emissions take place at sea, where no people live, limiting exposure and as such potential health impact of these emissions.

For TPN, uncertainties in emissions are larger than for most other air pollutants, in part because of the lack of source-specific measurements to quantify TPN emissions. Given the variability and dependence of emissions on local circumstances, a larger number of measurements, spanning the different circumstances under which these emissions take place, would help making the emission estimates more robust. This would therewith decrease the uncertainty. One specific aspect here is the lower cut-off diameter for particles. In the current inventory, 10 nm is used as a lower limit across all sectors, as we want to maintain consistency across sectors for the size range of particles included in the inventory. For most sectors there is limited information available on smaller particles, given the difficulties to measure them accurately. For aviation however, particles below 10 nm are known to play an important role and in recent years a lot of research has been conducted. Therefore, we have estimated the contribution of these smallest particles for this sector specifically and included it in this report. Our findings show that particles smaller than 10 nm make a large contribution to the total number of particles from aviation and can therefore not be neglected. These are discussed in the results, but are not included in the delivered inventory, where we use 10 nm as the lower limit. Furthermore, it should also be taken into account that the lifetime of the smallest particles in the atmosphere is typically very short.

Continuous further refinement is needed to make the emission data more robust. Priorities for future updates of the inventory include:

- Industrial sources: review available information in the international literature from specific industry branches that are important in the Netherlands, such as iron and steel production and the chemical industry. In our current inventory, emissions from industry are relatively small. However, the emission numbers have high uncertainty as generic emission factors were applied to industry at a high level (per emission source, rather than for specific processes at an industrial complex). This could lead to an underestimation of emissions, as the large variability of industrial processes is not well captured and high-emitting processes for some industries are potentially missed, such as nucleation events which could potentially generate large amounts of small particles. However, every industrial facility is different and hence a more in-depth analysis is needed at facility level to identify a potential underestimation and to improve emission estimates on a case-by-case basis.
- Non-road mobile machinery: this sector comprises a lot of different sources of emissions which are difficult to capture in a single methodology. A first step for improving this methodology would to be to explore the availability of additional information on TPN emissions from non-road mobile machinery in literature and measurement studies. Incorporating whatever information is available would help to improve the robustness of the emission factors and reduce the associated uncertainties. Overall, this sector needs further attention to review the approach.
- Spatial distribution: Within the current study only national total emissions are obtained. We recommend that spatially distributed emissions for TPN are made as a next step, in a similar way as is currently being done for other substances in the Dutch emission inventory. This is essential for modelling purposes and comparison with measurements.

To improve the knowledge base for estimating TPN emissions in the medium to longer term, we recommend including TPN in existing measurement programs for mobile emission sources. These programs, such as those for road transport, currently only include solid particles since this is what is regulated in source specific policy (e.g. EU Directives) and hence relevant for approval of new vehicle types. Including also TPN in these programs would lead to a much more robust set of emission factors and hence reduce the current uncertainty ranges significantly. This could then be the basis for specific targeted policy interventions to reduce exposure of the Dutch population to ultrafine particles. However, TPN measurements are currently associated with relatively high uncertainty which is related to missing methodological standardization. Therefore, we recommend first studying how TPN measurements can be robustly included in these existing programs. In addition, we recommend to explicitly study the relationships between TPN and other regulated pollutants.

Furthermore, it could be explored to what extent measurements of UFPs in ambient air can help to verify the results of this inventory, and provide indications of which sources might be under- or overestimated. This can be done by using the emissions in modelling studies to predict concentrations of UFP, which can subsequently be compared to measured UFP concentrations. Also the long-term measurement data from stations such as Cabauw could be used to identify source contributions depending on wind directions.

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Ondertekening

TNO ⟩ Energy & Materials Transition ⟩ Utrecht, 1 april 2026

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Appendix A

Description of Electronic Appendices

This report contains several Electronic Appendices (EA), all combined in one Excel file. This consists of 4 tables:

- EA.1 – Sector and Doelgroep (NL, Emission Registration)
  - This table indicates the sectors referred to in this study and how these relate to the “Doelgroep” as in the Dutch Emission Inventory. The Dutch Emission Inventory already links every emission source to a “Doelgroep”.

- EA.2 - All emission causes and fuel types considered in this study, together with its source group and methodology. For Methodology 7 - Fuel based EF and Methodology 8 - $PM_{0.95}$ based EF, also emission factors are included.
  - This table provides information on the methodology for each emission cause and fuel type. For emission causes for which emissions are obtained using *Methodology 7 - Fuel based EF* and *Methodology 8 - $PM_{0.95}$ based EF*, also the emission factors and a EF short code are included. The EF short code indicates which emission factor is used.

- EA.3 – All emission factors used in analyses, including a brief description and project reference.
  - This gives an overview of the various emission factors considered in this study. It includes a more general description of the process captured by this emission factor. For *Methodology 7 - Fuel based EF* and *Methodology 8 - $PM_{0.95}$ based EF* , only a selection of emission is factor is used. Some emission factors are reused for multiple emission causes.
    In this table, each emission factor is assigned an EF short code, which is included in table EA.2 for referencing. Furthermore, this table also includes a brief description of the types of processes or sources that the emission factor represents. The emission factors used in this study originate from literature review in earlier projects. For each emission factor, the project reference is also included in this overview.

- EA.4 – Fractions used to obtain $PM_{0.95}$ estimates from PM_{10} or $PM_{2.5}$ reported emissions.
  - These fractions come from the Dutch Emission Inventory. However, this table is updated regularly by the Dutch Emission Inventory. Therefore, the fractions used for this study are also included here.

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