Deliverable D18 (D3.3)

High resolution annual sectoral emissions for main pollutants, nanoparticles and non-exhaust contributors

RI-URBANS

Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial Areas (GA n. 101036245)

By TNO

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RI-URBANS (www.RIURBANS.eu) is supported by the European Commission under the Horizon 2020 – Research and Innovation Framework Programme, H2020-GD-2020, Grant Agreement number: 101036245

Deliverable D18 (D3.3): High resolution annual sectoral emissions for main pollutants, nanoparticles and non-exhaust contributors

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Comments	This document offers a description of the final gridded dataset of anthropogenic emissions (CH_4, CO, NH_3, NMVOC, NO_X, SO_2, PM_{10}, $PM_{2.5}$ and TPN) from a wide-range of sources with a focus on road transport including non-exhaust, made available to users within the RI-URBANS project. The dataset provides emission data at a spatial resolution of 6x6km² across the European domain, encompassing the 10 RI-URBANS pilot cities. It is an updated version of the first emission inventory presented in milestone M3.2 which was submitted in September 2022.

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Summary

The RI-URBANS project aims to enhance air quality information, particularly in urban areas, with a focus on providing accurate data for comparison and modelling. To support this objective, a high-resolution (6x6 km^2) anthropogenic emission inventory covering a wide range of sources was developed by TNO. This dataset provides specific improvements for emission inventories focusing on the transport sector (exhaust and non-exhaust) and on ultrafine particles. This dataset, of which an initial version was delivered earlier in the project, underwent updates due to inconsistencies discovered during comparisons with other datasets, as outlined in the M3.3 report.

The research within RI-URBANS focused on methodological changes in specific species, including PM data for small combustion sources to better incorporate condensables and total particle numbers (TPN) for road transport, with additional considerations for cold start emissions and diesel particulate filter (DPF) regeneration for vehicles equipped with DPFs.

New methodologies were applied to update the spatial distribution of traffic emissions, leveraging bottom-up inventories and open street data. The dataset, covering the year 2019 (due to the COVID-19 pandemic affecting more recent data availability) and focusing on Europe, will serve as crucial input for modelling air quality in the region.

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1. About this document

This document offers a description of the final gridded dataset of anthropogenic emissions (CH_4, CO, NH_3, NMVOC, NO_X, SO_2, PM_{10}, $PM_{2.5}$ and TPN-PNSD) from a wide-range of sources with a focus on road transport, including non-vehicle exhaust emissions, made available to users within the RI-URBANS project. The dataset provides emission data at a spatial resolution of 6x6km² across the European domain, encompassing the 10 RI-URBANS pilot cities. It is an updated version of the first emission inventory presented in milestone M3.2 which was submitted in September 2022.

This document is delivered to the European Commission as RI-URBANS deliverable D18 (D3.3) and shared with all RI-URBANS partners for their use. It will also be made available in the public domain, https://riurbans.eu/work-package-3/#deliverables-wp3. This includes the dataset that is accompanying this deliverable report.

2. Introduction

In support of the assessment of air quality and its impact on human health at European scale and specifically in urban areas, a good understanding of the sources of air pollution is needed in order to define cost-effective measures to reduce air pollution impacts. In RI-URBANS, the improvement of emission inventories is therefore included as a specific task, which will primarily support the modelling tools available to European countries.

The work in this deliverable build upon the conclusions drawn from milestones M3.2 and M3.3 which were delivered earlier in the RI-URBANS project. In Milestone M3.2, a first European emission inventory was created for the RI-URBANS consortium including an emission inventory for particle numbers and non-exhaust vehicle PM emissions that was subsequently shared with stakeholders, particularly the modelers in WP3 of RI-URBANS. As a next step, this inventory was downscaled to 1x1km^2 over specific cities of interest using the UrbEm methodology (described in deliverable report D3.2) and was later compared to local bottom-up emission inventories for a number of cities in Europe. In Milestone 3.3, our focus shifted to an emission intercomparison exercise, comparing the downscaled European inventory (CAMS-REG-UrbEm) against bottom-up urban-scale emission inventories sourced from 13 urban areas, including the 10-URBANS pilot cities. This comparative analysis unveiled disparities, notably in NOx, PM_{10}, and $PM_{2.5}$ road transport emissions, with the CAM-REG-UrbEm inventory consistently reporting lower values than local inventories. The root cause of this under-allocation was traced to the methodology employed within CAMS-REG, specifically in the allocation of emissions across different road types (urban, rural, and highway) and the subsequent spatial distribution approach. In addition, urban corridors, road rings, and city access roads were not distinctly represented within the downscaled CAMS-REG, highlighting uncertainties stemming from the spatial proxies utilized for distributing emissions at 6x6km at European scale as well as the downscaling of emissions to 1x1km^2.

To take stock of the findings of milestone M3.3, we have reviewed the road transport distribution in detail. All the steps involved in spatially distributing emissions from road transport have been updated based on the latest available information, described in detail in this report.

In addition, the emission estimates made at country level have been reviewed and updated, with a focus on ultrafine particles (UFP) and non-exhaust vehicle PM emission, and on road transport being a key contributor to urban air quality. This update was partly driven by new data being made available from national inventories, as well as improved characterization of UFP emission factors for the transport sector based on an extensive literature review.

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3. Methodology

3.1. Main air pollutants (based on previous work)

The CAMS-REG emission inventory (Kuenen et al., 2022) is widely used across Europe for modelling air pollutant concentrations. Updated versions are produced on an annual basis, the latest one being the CAMS-REG-v7 for the year 2021 which was released by the end of 2023. However, since 2020 and 2021 emissions were affected by the Covid-19 pandemic, it has been decided to use 2019 as the base year for emissions in this inventory. The basis is CAMS-REG-v6.1 which is based on the official inventory submissions from European countries in the year 2022. Building on the official reported data from countries has important advantages, such as the "official" status of these data but also the incorporation of specific local knowledge in each country. On the other hand, there exists some inconsistencies and gaps in these official data.

One of the inconsistencies that has received a lot of attention in recent years is related to the issue of condensables. This refers to the fact that emissions, which may be gaseous when exiting a stack or exhaust, can undergo cooling and dilution close to the emission, leading to the formation of additional particles. This happens within minutes after the release and is particularly relevant for small combustion (mostly consisting of household heating) where these additional particles may increase emissions 5-fold (Denier van der Gon et al., 2015). Official emission inventories provide an inconsistent picture in this respect, since some countries include these condensables in their PM emission inventories, and some exclude them. Due to the growing attention to this issue in recent years, more countries are moving towards including condensables in the inventories for small combustion, but in some countries this inconsistency remains. A recent study (Simpson et al., 2022) has provided an updated time series of consistent emissions of particulate matter (PM_{10} and $PM_{2.5}$) for small combustion for the whole of Europe for 2005-2019. For this RI-URBANS inventory, this consistency update is incorporated.

In RI-URBANS itself, we are further refining the CAMS-REG inventory (with the consistent condensables for small combustion included) by:

- Providing a comprehensive emission inventory for primary UFP in terms of total particle numbers (TPN), including particle number size distributions (PNSDs).
- Enhancing the consistency of road transport emissions by utilizing vehicle statistics and advanced emission estimation methods. This includes exhaust emissions but also specifically the non-exhaust emissions, implementing consistent methodologies for estimating emissions of both PM but also TPN where relevant.

This updated inventory will cover main air pollutants from CAMS-REG (CH_4, CO, NH_3, NMVOC, NO_X, SO_2, PM_{10}, and $PM_{2.5}$), TPN, with detailed size distribution parameters. The base year for this data is 2019, and further details on the inventory components follow in the next sections.

3.2. Total particle numbers

Ultrafine particles, characterized by a diameter less than 100 nm, have been of particular interest in this version of the emission inventory, given the growing body of literature highlighting adverse health effects upon exposure (Schraufnagel, 2020). Due to the trivial mass of UFPs, they are quantified in terms of number of particles per unit of activity. While current EU regulations establish thresholds for solid particle number (SPN) emissions in certain sectors, notably in road transport, little regulatory attention is given to total particle numbers (TPN), encompassing both solid and volatile particles. This inventory adopts a TPN perspective for UFP emissions due to the prevalence of semi-volatile particles, which can substantially influence emissions and necessitate distinct emission control strategies compared to SPN (Gieschaskiel et al., 2022).

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3.2.1. TPN emission inventory

TNO has been developing and maintaining methods to estimate size-differentiated emission of primary particle numbers (PN) for several years. Particle diameter range covered is 10 to 300 nm and the methods explicitly include the (semi-) volatile fraction, hence representing the total particle number, hereafter referred to as TPN. Particle size distributions are statistically parameterized from literature data as mono- or multi-modal lognormal size distributions, described by a mode and geometric standard deviation. The developed methodology has been used to compile TPN emission inventories for Europe that aim to cover all known major anthropogenic sources, including both stationary and mobile.

The first European TPN inventory was the Eucaari inventory in 2009 (Kulmala et al. 2011), followed by the TNO Transphorm (see e.g. Beddows et al. 2014) inventory in 2015. A version of this TPN inventory was also implemented in the IIASA GAINS model in 2013 (Paasonen et al. 2016). In 2021/2022 part of the methodology was again updated in an inventory for the Rotterdam harbour and industrial area, focusing on sea shipping and several industrial sources (Visschedijk et al. 2022).

Recently further major development has taken place within the RI-URBANS project, resulting in an updated TPN inventory for 2019. Besides building on the latest estimation methods, the RI-URBANS work included a full revision of the emission factors for road transport, as described elsewhere in this deliverable report.

Generally, two types of estimation methods are used, depending on the type of source. Mobile sources are usually estimated by direct TPN emission factors related to the source activity rate. This generally gives the most reliable results compared to other methods, provided that TPN emission factors are available. Stationary sources are however often estimated by a mass-based approach, which entails estimating $PM_{0.3}$ mass emissions and assuming a source-specific PNSD, density and morphology to estimate number emissions. This approach gives reasonable results for sources which are governed by particulate matter control equipment, of which efficiencies may vary widely. Secondly, for the mass-based approach to work, PNSD maximum should not be too far removed from 300 nm, a condition often met for industrial sources.

The outcome of the TPN inventories show that $PM_{2.5}$ and TPN emissions may not always correlate. In this respect aerial transport can be mentioned, which may result in very high particle number emissions but only very little $PM_{2.5}$ mass. This contrary to residential wood combustion, which is a dominating source of $PM_{2.5}$ emission but only of secondary importance to TPN (because of the relatively large particles formed). Results furthermore highlight transport-related sources (e.g. road, sea and aerial transport) to be of particular importance to TPN emission. The lower cutoff particle size (10 nm in this case) is of great importance to aerial transport, for which TPN emissions in fact peak between 5 and 10 nm, so outside of the inventory scope, also from the emission standards. This is something that could possibly be addressed in the future by including particles down to 5 nm. Furthermore, the importance of (semi-)volatile particles is stressed, for most sources far exceeding the contribution by solid particles (SPN) only. It is important to note that Dayamanti et al. (2023) and Carcia-Marlès, et al. (2024) showed that while there is a generalised trend to decrease ambient TPN, in urban and traffic sites of Europe, in the range 25-800 nm due to the effect of the implementation of diesel particulate filters (DPFs) by Euro 5/V. However, the trends of the <25 nm are inconsistent, and this is in part due to the nucleation of SVOCs scaping to the DPFs. In many cases the urban ambient concentration of the nucleated UFPs are as relevant as the primary UFP.

3.2.2. Updates to the road transport sector

TPN emissions for road transport were updated based on both previous developments and new available data. Emission factors for older vehicles (i.e., Pre-Euro to Euro 4/IV) were derived from a previous inventory developed by TNO. As for newer models, we conducted an extensive literature review for Euro 5/V and 6/VI passenger cars,

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light-duty commercial vehicles (LCV), buses and heavy-duty vehicles (HDV), as well as Euro 4 and 5 L-Category vehicles. Working in collaboration with the EASVOLEE research project, we gathered available emission factors from diverse sources, primarily research papers, and meticulously selected appropriate factors for each vehicle type.

The literature review began by pinpointing relevant papers using specific keywords and author references. Data from these sources was meticulously recorded in a standardized template. Subsequently, the collected data underwent thorough processing. Outliers were identified and excluded, and where applicable, and median values were selected to calculate emission factors. When little information was available, average values were used instead. Regeneration effects were integrated into the TPN emission factors for diesel vehicles equipped with DPFs based on regeneration emission values and descriptions of the frequency and duration of regeneration events extracted from literature (Giechaskiel, 2020). Given the importance of DPFs in newer diesel vehicles, focusing on regeneration was relevant, as such an occurrence can increase TPN emissions considerably. Additionally, cold start TPN values were computed whenever feasible, as they are expected to play an important role with the rollout of hybrid vehicles. Moreover, data originating from the US and Asia was also collected and converted to align with European standards.

For HDVs, the newly derived TPN emission factors (Euro 5 and Euro 6) were converted from particles per kilowatt-hour (kWh) to particles per vehicle-kilometer (vkm). Values per kilogram of fuel were also recalculated to a per vkm basis to ensure consistency. The compiled emission factors were then aggregated according to vehicle types and technologies (Euro 5 and 6 classes), with specific considerations for petrol vehicles (direct injection/port fuel injection, and gasoline particle filter) and diesel vehicles (with/without DPF). Subsequently, any gaps in the dataset were filled using information from earlier studies where new emission factors could not be derived from literature. As for two-wheelers (L-Category vehicles), emission factors were calculated for Euro 2 to Euro 5 vehicles, with an important distinction being made between 2 and 4-stroke vehicles, given the considerably larger TPN emissions emitted by the former.

While the primary focus was on on-road measurements, some laboratory measurements were also incorporated. Although on-road measurements are inherently less stable compared to lab measurements, they are more pertinent to assessing air quality, hence their inclusion is crucial. Moreover, the various literature sources utilized different methodologies for measurements, including different driving protocols, driving cycles, and instrumentation. These methodological disparities pose potential sources of uncertainty or inconsistency. However, by meticulously examining available literature, we attempted to gather as much methodological detail as possible, aiming to comprehend the underlying factors influencing the data and pinpoint the primary causes of deviations in the emission factors. With this analytical approach we aim to get robust emission factors at a more aggregate level, instead of compromising quality for additional detail. These limitations will inform our future endeavours to refine these emission factors further.

3.3. Road transport model

3.3.1. Bottom-up emission inventory

A bottom-up emission inventory for road transport was constructed based on the European vehicle statistics from the “COPERT data” dataset. This dataset includes information on vehicle stock and annual mileages for each year (1990-2019) for 33 European countries, distinguishing more than 500 different combinations of vehicle category, engine capacity, fuel type and environmental standard. In addition, a split for the mileages over urban, rural and highway road types is also available. This is important since different emission factors are applied to the different situations.

While for TPNs we use emission factors introduced in Section **Error! Reference source not found.**, for the other (regular) pollutants we make use of the emission factors from the Dutch VERSIT+ model which are also applied in

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the Dutch emission inventory. The emission factors are based on the combination of many on-road measurements and really aimed to best mimic the actual emissions on the road. These emission factors are available in the public domain from the methodology report for Dutch emissions from traffic and transport (Geilenkirchen et al., 2023). The emission factors are provided in this report at a level of detail which is similar to the COPERT data. A crosswalk table was made to link the correct emission factors to each of the COPERT vehicle classes for the emission calculation. In most cases this was a relatively easy one-to-one match, but for some categories this was not possible. The latter applied mostly to specific vehicle types such as hybrids or quads/mini cars. In these cases, a replacement sector was chosen in the crosswalk table which is expected to have similar emission levels.

A novelty is that for the first time, cold start emissions are accounted for explicitly. Cold start emission factors are expressed as emissions per cold start event, also available from the Dutch emission inventory. The earlier referenced Dutch methodology report (Geilenkirchen et al., 2023) also provides a method to estimate the number of cold start events based on actual assessment of the situation in the Netherlands. For this study, we assumed this to be similar in other European countries as a first step. The number of cold start events is calculated using the following formula:

$$CS_y = f\,\frac{veh\_vkm_y}{(veh\_vkm_y + 500)}$$

Where:

- CS_y represents the number of cold start events per individual vehicle in year *y*,
- *f* is a multiplication factor equal to 600 for light duty vehicles (passenger cars and vans) and 250 for heavy duty vehicles (trucks and buses),
- veh_vkm_y is the annual mileage per individual vehicle in year *y*, which can be derived from the COPERT data as an average for each detailed vehicle type.

It is assumed that cold starts occur only on urban and rural roads (not on highways) and that 95% of all cold starts take place in urban areas.

3.3.2. Non-exhaust emissions

The regular CAMS-REG emission inventory utilizes the European reported emissions. Earlier analyses has shown that some of the methodologies for estimating non-exhaust differ per country, which may lead to inconsistencies when looking at the pan-European scale. To overcome this inconsistency, we have compiled a bottom-up methodology explicitly for the non-exhaust sources (brake wear, tyre wear and road abrasion), building on the information on vehicle numbers and other characteristics from the COPERT data. The methodologies for estimating the non-exhaust PM emissions are adapted from the EMEP/EEA Guidebook 2019 version Tier 2 methodologies (EEA, 2019), taking into account speed dependencies and vehicle weight for trucks.

The general equation used to estimate emissions from brake and tyre wear at the country scale is the following:

$$TE = \sum_j N_j \times M_j \times EF_{TSP,s,j} \times f_{s,i} \times S_s(V)$$

Where:

- TE represents the total emissions (per year per country),
- N_j is the number of vehicles in the country in category *j,*
- M_j is the average mileage (kilometers) driven by each vehicle in category *j* per year,
- $EF_{TSP,s,j,}$ is the emission of TSP for the vehicle in category *j*, expressed in g/km,

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- $F_{s,I}$ is the mass fraction of TSP that can be attributed to the particle size class *i* (e.g. when considering $PM_{2.5}$ this represents the fraction of $PM_{2.5}$ in TSP),
- $S_s(V)$ is a correction factor for the mean vehicle travelling speed *V.*

Since estimates are made on a country scale, averages for the speed had to be used for this inventory.

3.3.3. Spatial distribution revision

The spatial distribution of traffic emissions was based on a European-wide traffic model (OpenTransportMap (OTM); Jedlička et al., 2016). The traffic model provides traffic volumes for a large fraction of roads for EU-countries. In the model, traffic is generated by demographic data, and then scaled to absolute values using traffic count data. OTM data can be linked with OpenStreetMap (OSM) data via a common key. We downloaded a complete OSM dataset for the domain in July 2023, performed the linking and used OSM geometries for spatial calculation. For the use in this project, the traffic volume data provided by OTM has two major limitations.

Firstly, it is incomplete, and lacks information on a large fraction of roads. Whereas the share of missing data for 1st class roads is only around 10%, this share increases to almost 50% for 3rd class roads. Moreover, values for smaller roads are not reported (see Figure 1).

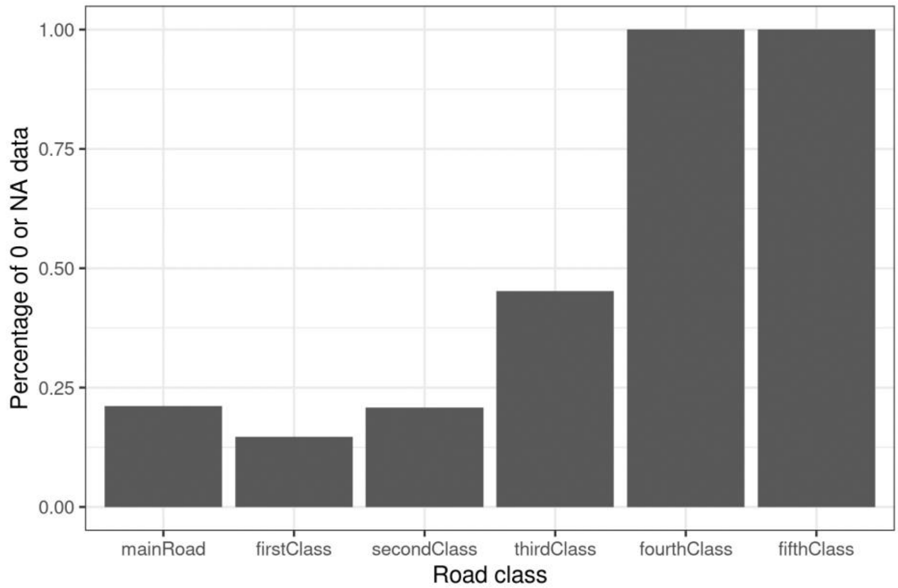

***Figure 1**. Share of missing data in the OpenTransportMap dataset.*

Secondly, the dataset is not spatially complete for the study area and lacks predictions for non-EU countries such as Russia, Ukraine or Serbia.

Due to these limitations, a gap filling methodology was applied. Initial analysis of the dataset showed a high variance in traffic volume per road type, with standard deviations multiple time the mean traffic volume per road type (see Figure 2).

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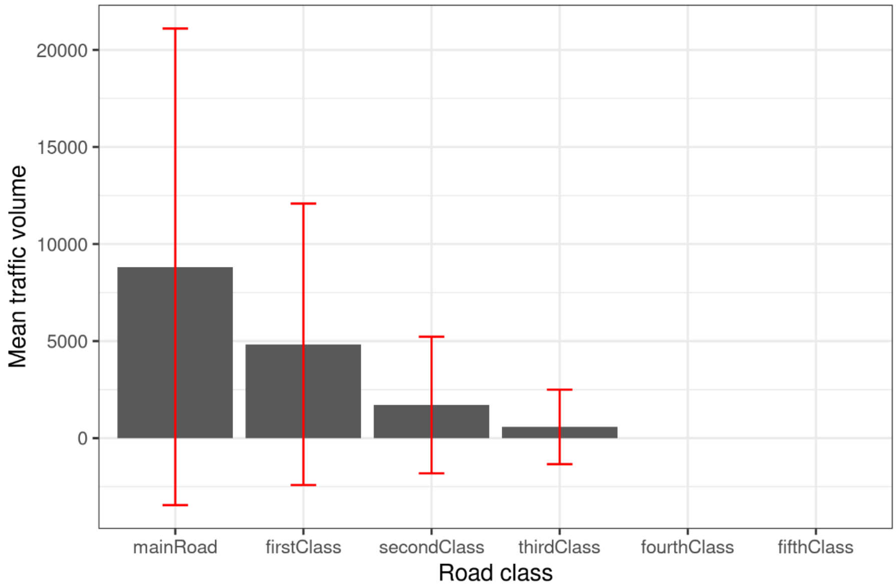

Figure 2. *Standard deviation (red) in comparison to mean traffic volume per road type.*

To capture a large amount of this variation when doing gap filling, two random forest (RF) machine learning models were trained based on multiple predictors (Ishwaran et al., 2022).

The first model was used to gap fill traffic volumes outside the EU domain. This model was based on population data from landscan, OSM keys road type, road surface, road lanes, as well as calculated road length. The second model was used to gap fill traffic volumes inside the EU domain and was additionally trained on Corine land-use information, administrative units (NUTS), and OTM keys road capacity, direction, form of way and road function.

Overall model success was high, with an R^2 of 0.63 for model 1 and 0.74 for model 2. In general, model success was higher for motorways and trunk roads compared to secondary or tertiary roads (see Figure 3). The most important independent variables for predicting traffic volume were road type, population density and land-use type.

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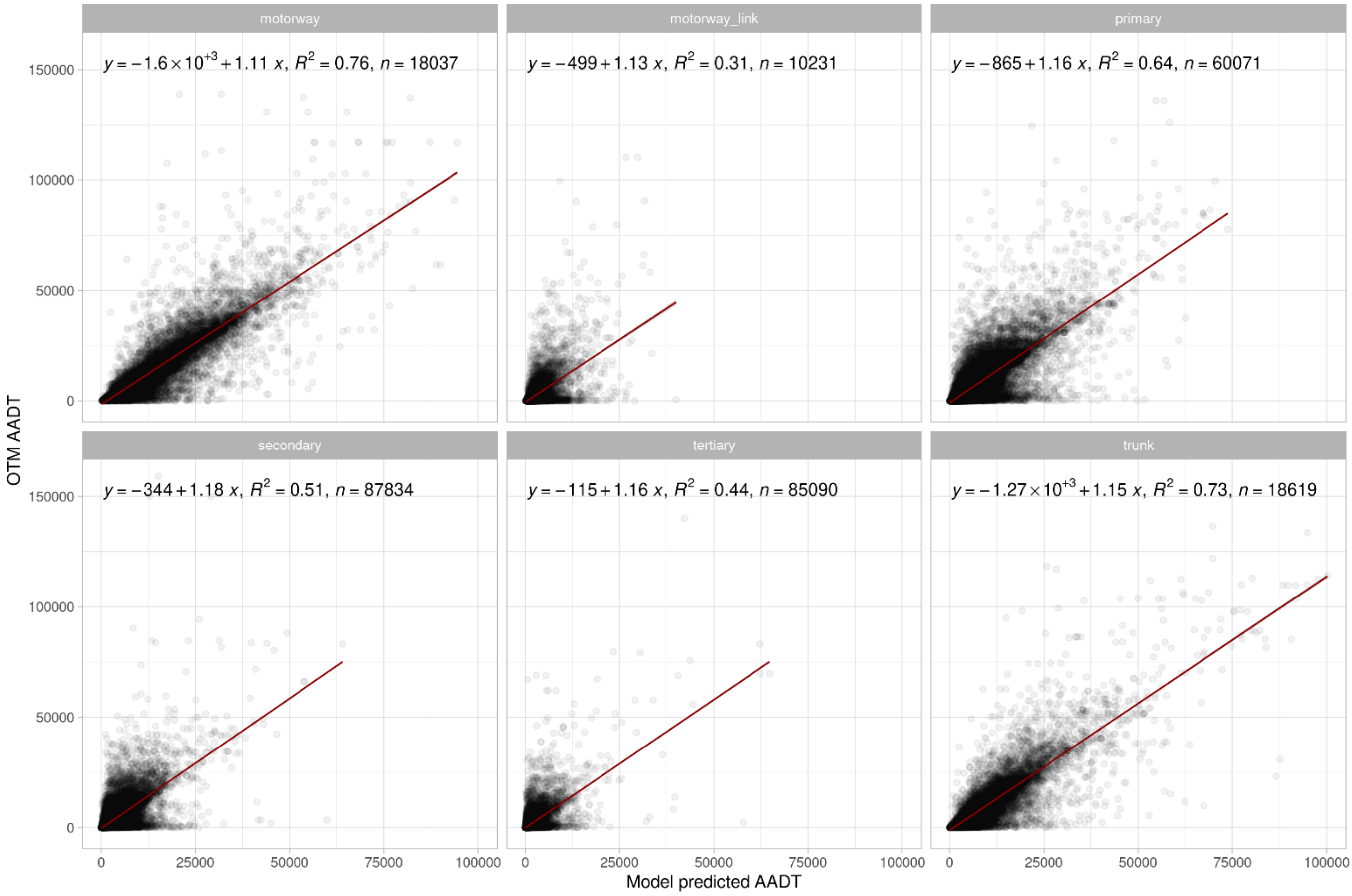

Figure 3. *Model success for model 2 used in the EU domain.*

Additional gap filling for 4th and 5th class roads was performed using expert judgement. Based on the average traffic volume of 3rd class roads within a 5km pixel, we estimated the traffic volume of 4th and 5th class roads as 30% and 15%, respectively.

Finally, vector-based results were gridded, assigned to urban, rural or highway fractions based on Corine land-use type, and scaled for each country from 0 to 1.

4. Results and Discussion

This section presents the results derived from the above-mentioned methodologies, covering the overall resulting emissions across different sectors with a focus on road transport. The outcomes of the updated spatial distribution will be discussed, as well as particle size differentiated TPN emission, geospatially distributed based on the CAMS-REG methodology (Kuenen et al., 2022).

4.1. Overall resulting emissions including non-exhaust contribution

$PM_{2.5}$ and TPN exhibit varied importance across different sectors. Figure 4 illustrates the $PM_{2.5}$ emissions and TPN emission totals for the year 2019 for aggregated sectors. Small combustion, and energy and industry are identified as the largest contributors to $PM_{2.5}$ emissions, followed by waste and agriculture. However, for TPN, the transport

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sectors (Road Transport exhaust, Shipping, Aviation, and Off-road mobile sources) emerge as the primary sources. While for $PM_{2.5}$ the contribution of non-exhaust sources to emissions is similar to exhaust, for TPN the exhaust is clearly the dominant source of the two. Additionally, a notable contribution from energy and industry is observed for TPN emissions. This is expected, as particles emitted from shipping and aviation for instance, are largely at nanoscale, whereas particle emission from residential heating are much coarser. It is relevant to note that the size distribution for TPN emissions from aviation was amended since the last version of the inventory because of an error encountered during the calculation, which allotted more emissions to larger size bins, despite TPN emission from aviation peaking at below 10 nm.

The result below highlights the importance of distinguishing between $PM_{2.5}$ and TPN emissions, as it enables targeted mitigation strategies to improve air quality and protect public health by understanding the specific contributions of different source sectors to overall particulate pollution.

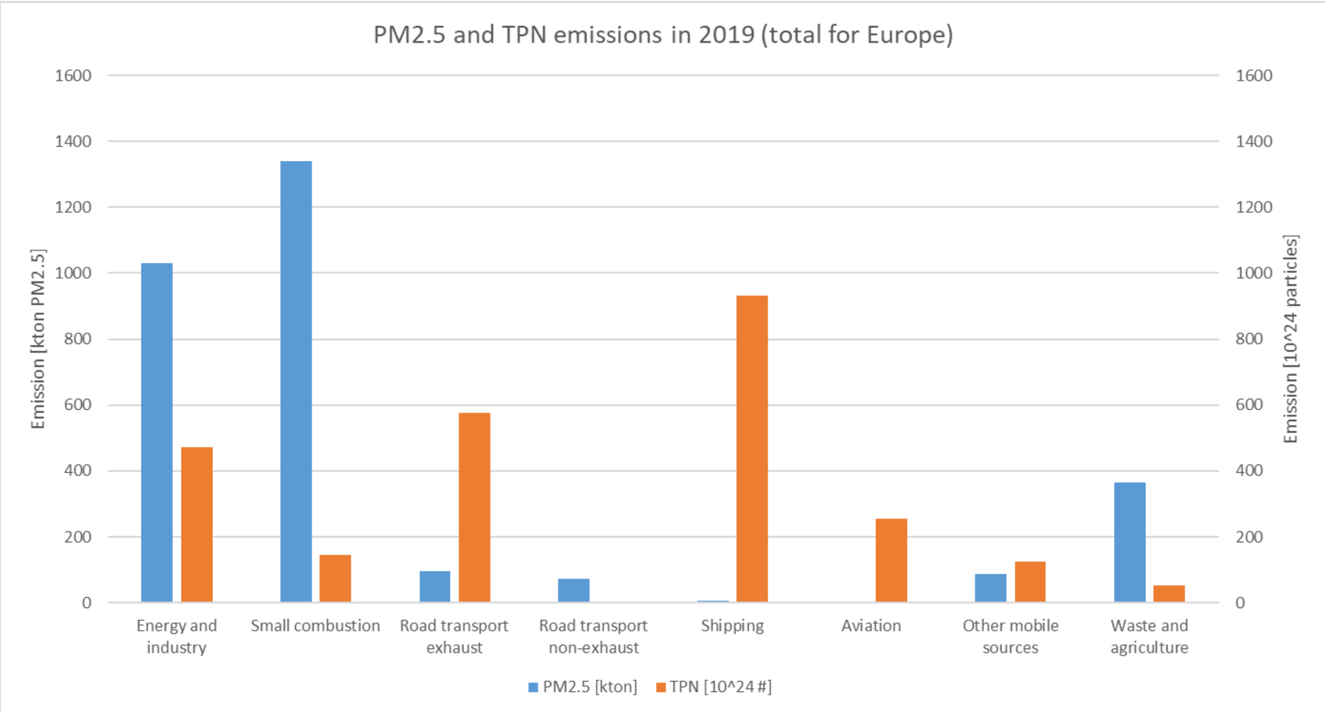

Figure 4. *Comparison between PM2.5 (in ktons) and TPN emissions (in 10^{24} #) across different sectors.*

Figure 5 and Figure 6 depict the spatially distributed emissions of $PM_{2.5}$ and TPN, respectively. $PM_{2.5}$ emissions primarily originate from small combustion activities (predominantly residential heating), transportation, and industrial sources, as highlighted in Figure 4. Conversely, for TPN, shipping emerges as a significant emission source, evident from the provided maps. Additionally, other transportation routes, notably main roads, are visible in the maps, nearby urban centres.

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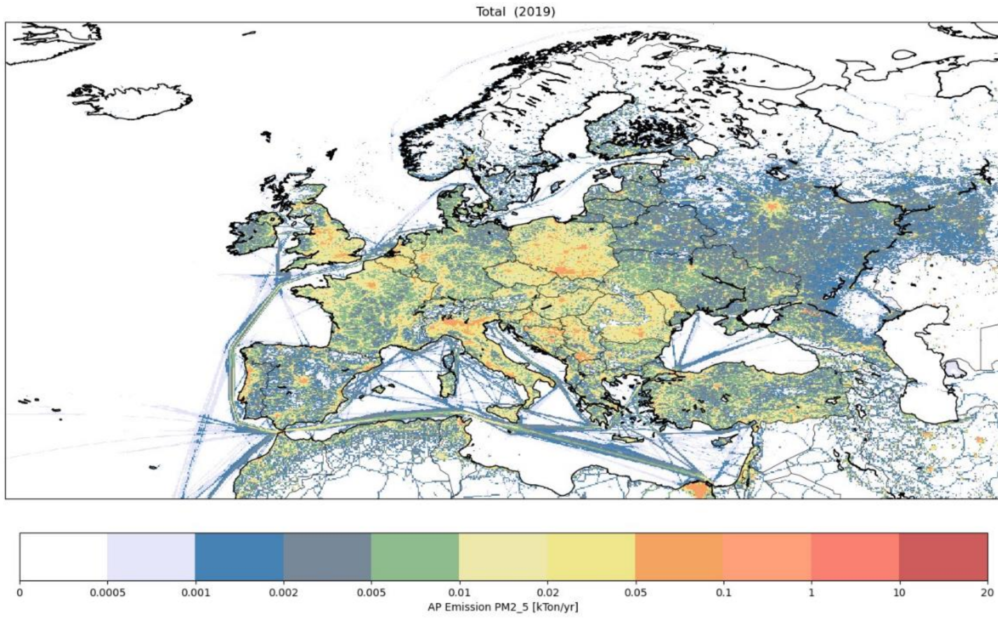

Figure 5. *Emissions of PM2.5 (in kton/year) for 2019 distributed in space at 6x6 km² resolution.*

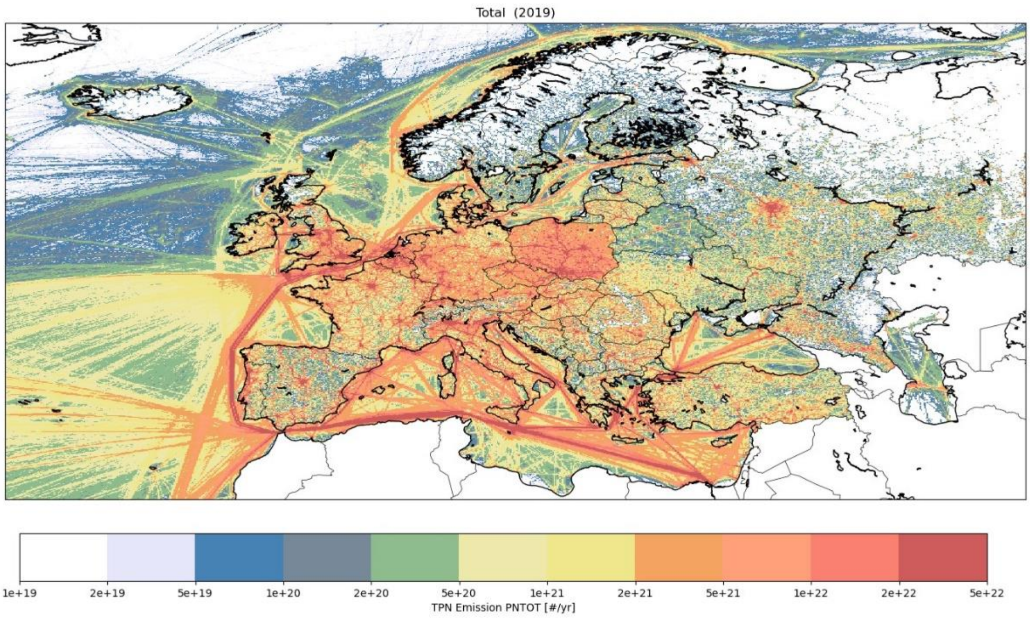

Figure 6. *Emissions of TPN (in #/year) for 2019 distributed in space at 6x6 km² resolution.*

As outlined in this report, the different non-exhaust contributors as well as cold starts are now accounted for as a distinct source of emissions, whereas previously the latter were included within the average emission factors. Explicitly considering cold starts enhances the accuracy of spatial emission representations, particularly since they predominantly occur in urban areas. Although the proportion of emissions attributable to cold starts varies by pollutant, it typically constitutes around 10% of total emissions. For TPN, this contribution is slightly lower, potentially due to incomplete cold start calculations for certain vehicle types, such as HDVs, buses, and L-category vehicles, owing to insufficient data availability. Referring to Figure 7, notable disparities between $PM_{2.5}$ and TPN

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emissions are evident, notably the significantly greater contribution of non-exhaust sources like tire and brake wear and road abrasion to $PM_{2.5}$, compared to TPN, where it is negligible. This trend aligns with existing literature, as non-exhaust emissions predominantly comprise larger particles.

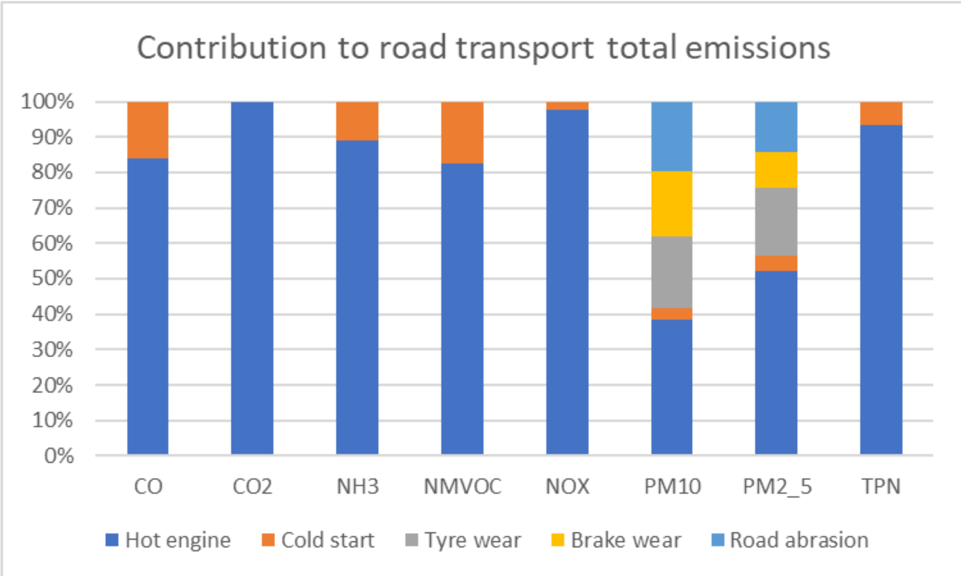

Figure 7*. Contribution of different sources in road transport to total emissions for relevant pollutants. Exhaust emissions are split between hot engines and cold start contribution.*

Non-exhaust emissions

Figure 7 shows the overall contribution of the non-exhaust sources to emission levels for different pollutants including PM_{10} and $PM_{2.5}$. It is shown that on average the non-exhaust contribution to PM_{10} emissions in 2019 is almost 60%, while for $PM_{2.5}$ it is around 45%. The contributions of tyre wear, brake wear and road abrasion in PM_{10} are in the same range, but for $PM_{2.5}$ the tyre wear is found to be somewhat larger contributor than the other two sources. The non-exhaust emissions are important to account for explicitly, since these have a very different composition compared to particles from the exhaust. Such differences should be taken into account when using these emission inventories, therefore specific PM composition profiles are provided along with this inventory for exhaust and non-exhaust contributors.

It should be noted here that the non-exhaust emissions here do not include resuspension. Since resuspension emissions largely depend on local circumstances (meteorology including wind and rain) it is difficult to calculate these using a traditional bottom-up emission inventory since calculations are first made on a per country and per year basis, whereafter they are spatially and temporally distributed. Resuspension is also not included in any of the official country emission inventories which are the basis for the CAMS-REG inventory. As a future step, it would make more sense to calculate these in a specific model which also includes specific meteorological circumstances in a specific region and time of the year so that emissions can be modelled. This could be considered in the future by expanding the transport model described in this report by including meteorological information, but this has not been implemented yet.

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4.2. Total particle numbers in road transport

As outlined in this report, we have undertaken a thorough update of the initial emission inventory within RI-URBANS. A key focus of our research has been refining TPN estimates originating from road transport. Figure 8 provides a comparative view of the initial and revised estimates. Here we focus on exhaust since as depicted in Figure 7 the contribution of TPN to non-exhaust emissions is marginal.

In contrast to the initial 2018 figures, our updated dataset for 2019 reflects a notable 19% increase in total TPN emissions from road transport. This surge primarily stems from heightened emissions from petrol-fuelled vehicles, encompassing both passenger cars and two-wheelers (L-Category). This trend aligns with current changes in the vehicle fleet, particularly the prevalence of newer petrol-fuelled vehicles equipped with Direct Injection (DI) engines. Unlike Port Fuel Injection (PFI) counterparts, DI engines directly inject petrol into the combustion chamber at high pressure, enhancing engine efficiency. Despite these efficiency gains, DI vehicles have been observed to emit greater TPN than PFI vehicles. This phenomenon is attributed to the direct injection process, which can amplify the formation of particulate matter, including finer particles that contribute to TPN emissions. Moreover, given that gasoline particle filters (GPF) remain scarce within the vehicle fleet, no considerable abatement of TPN for more recent petrol-fuelled passenger cars has been observed.

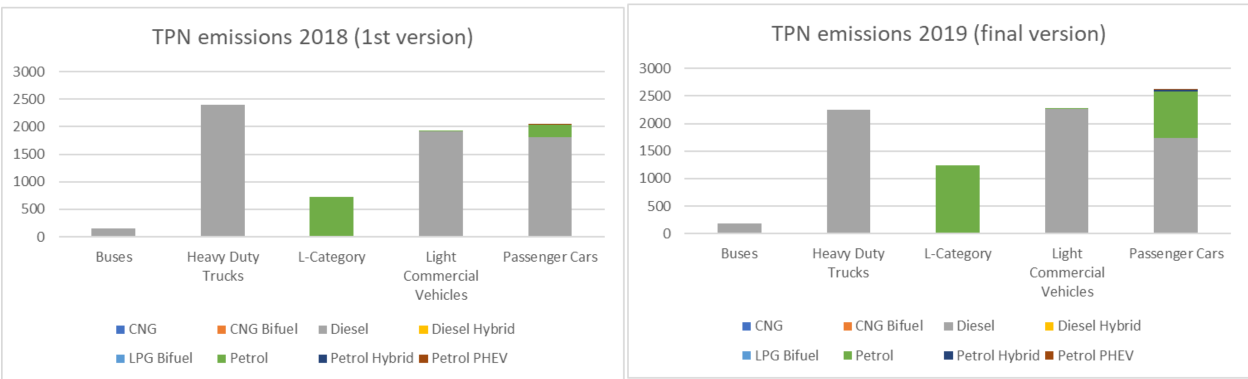

Figure 8. *TPN emissions (in 1021#) from road transport exhaust for the first version of the RI-URBANS inventory (year 2018) and the final version (year 2019).*

Figure 9 below presents the calculated number weighted particle size distribution for road transport emissions of TPN across continental Europe. Notably, it exhibits a bi-modal distribution, with the primary peak at 65 nm attributed largely to non-DPF diesel and non-GPF DI petrol vehicles. Conversely, the secondary peak at 20 nm results from PFI petrol and DPF-equipped diesel vehicles. It is essential to acknowledge that the reliability of the data diminishes progressively for particle sizes below 20 nm.

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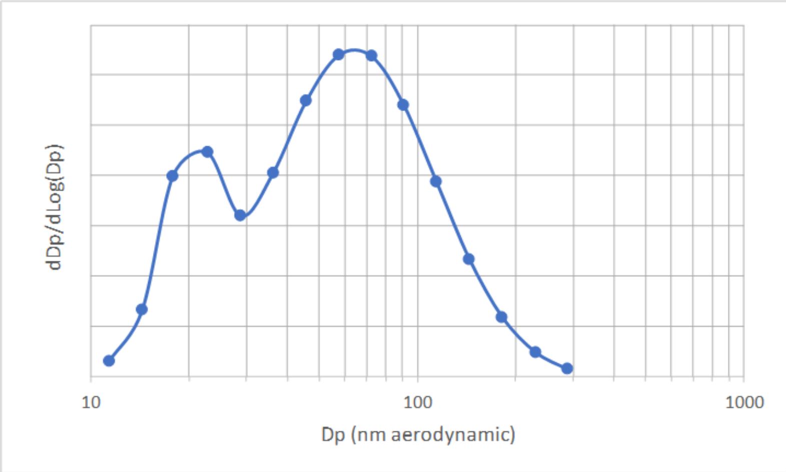

Figure 9. *Number weighted particle size distribution for road transport emissions of TPN in Europe.*

Figure 10 displays the mileage distribution across Euro classes in Europe for 2019, alongside TPN emissions. An analysis of the figure reveals that the highest mileages are observed in Euro 5 and Euro 6 vehicles for passenger cars, and Euro V for HDVs. However, TPN emissions are predominantly determined by older vehicles within the fleet. Looking ahead, these older vehicles will be phased-out and replaced by newer ones equipped with technologies like DPFs, potentially reducing the significance of the contribution of road transport to overall TPN emissions.

A similar trend could be anticipated for other mobile sources, though at a slower pace. However, it is crucial to acknowledge that certain transport sectors such as shipping and aviation are likely to persist as significant contributors to TPN emissions, necessitating targeted interventions and regulatory measures to address emissions reduction.

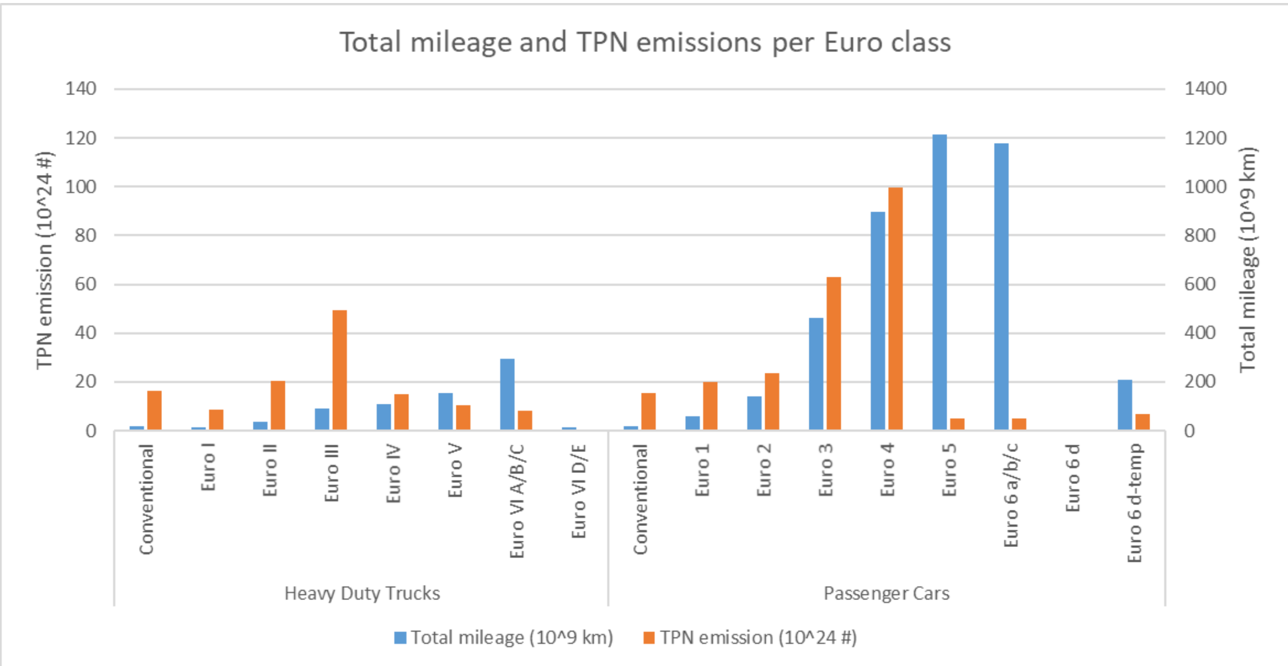

Figure 10. *Total mileage (in 109 km) and TPN emissions (in 1024 #) per Euro class for diesel-fuelled heavy-duty trucks and passenger cars.*

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4.3. Spatial distribution for traffic emissions

For the spatial distribution of traffic emissions, we drew comparisons with previous results. Table 1 shows a comparison between selected countries and cities with previous methodology for both absolute vkm and fraction of country totals. For most cities, the urban share increased by around 10-20%, denoting a higher importance of urban pollutions than previously calculated. This is in line with previous comparisons made from bottom-up city inventories. Country total vkms for non-EU countries such as Russia and Ukraine were not well captured by the previous approach and are now certainly more realistically depicted. The strong increase of Spain's total vkm has to be investigated further.

Table 1. *Comparison between absolute vkm and country fractions from old and new methodologies.*

Location	Absolute vkm (in millions)		Fraction of country total (in %)		
	Old	New	Old	New	Ratio
Germany	672029	939846	/	/	
France	581929	832949	/	/	
Italy	492415	449908	/	/	
Russia (western)	2410	469115	/	/	
UK	488348	637046	/	/	
Poland	167392	287019	/	/	
Ukraine	899	250047	/	/	
Spain	250047	723600	/	/	
Netherlands	133746	109579	/	/	
Rome	6738	7382	1.37	1.64	1.12
Munich	10499	16249	1.56	1.73	1.11
Athens	7689	9072	13.25	11.23	0.85
Rotterdam	4807	4247	3.59	3.88	1.09
Krakow	2311	1144	0.68	0.81	1.19
Paris	14510	28550	2.49	3.43	1.38
London	22113	23309	4.53	3.66	0.81
Zurich	2831	5367	4.26	4.78	1.12

Figure 11 shows an example of the new spatial distribution in the Marmara Sea region gridded to 1km detail, which shows main highways and urban areas (e.g. Istanbul).

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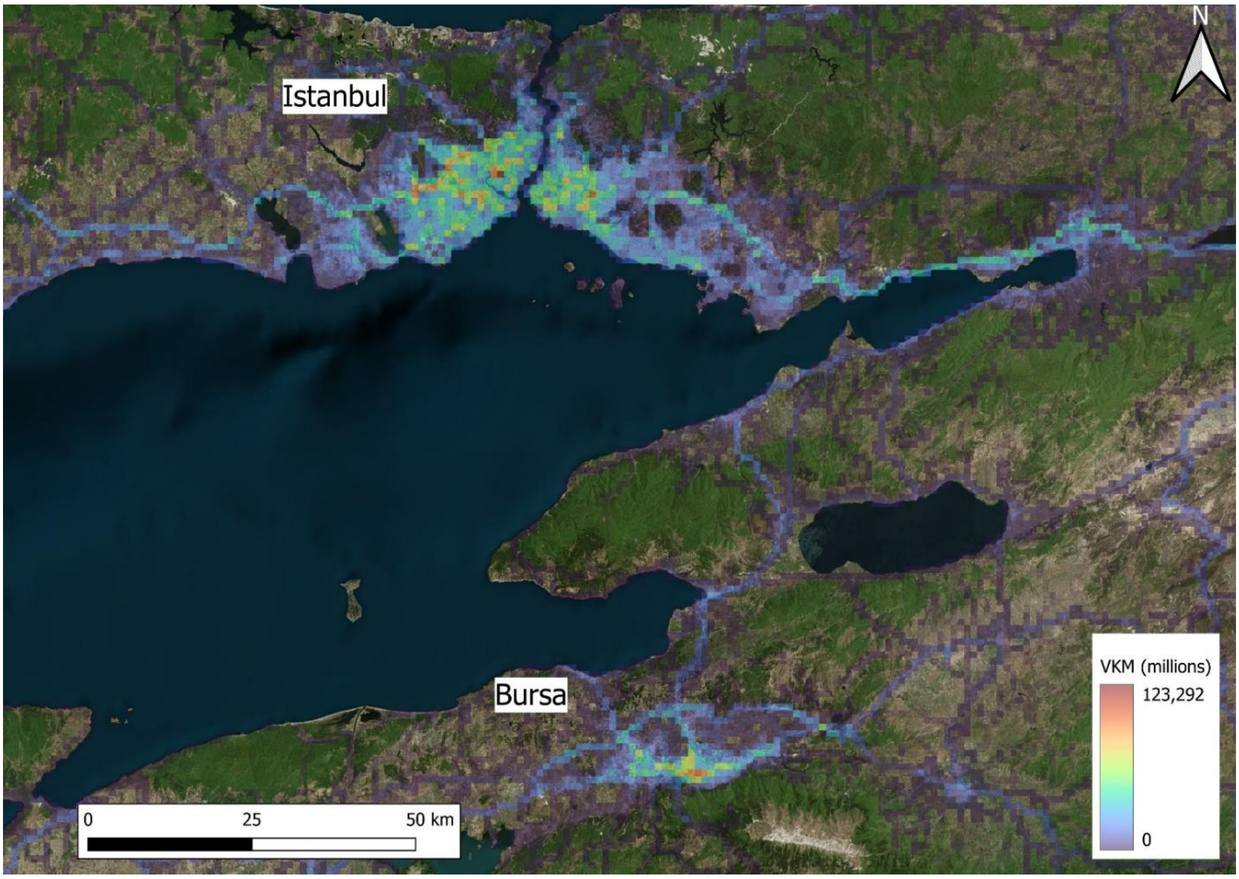

Figure 11. *VKM distribution for the Marmara Sea region in Turkey. Background satellite map used: Bing Satellite (2024).*

5. Conclusion and Outlook

This report presents a refined version of the high-resolution annual sectoral anthropogenic emission inventory introduced in milestone M3.2, with a particular focus on TPN emissions for road transport within Europe. By addressing discrepancies identified in previous milestones and incorporating updated methodologies, the dataset offers a more robust representation of emissions, supporting efforts to model emissions in urban areas under the RI-URBANS project.

Looking ahead, beyond the scope of the RI-URBANS project, we intend to refine the methodology for road transport by potentially updating the cold start methodology and incorporating more recent years for a more representative fleet. Additionally, we aim to broaden the inventory's scope by including finer particulate matter emissions for aviation below 10 nm. In the shorter term, we plan to conduct new comparisons with city-level inventories to assess the impact of our refinements, particularly the updated spatial distribution for road transport emissions. These steps reaffirm our commitment to enhancing the inventory's reliability and relevance for emissions modelling.

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6. Data Availability

Data are available on TNO's FTP site and can be made available upon request. Please contact Marya.elMalki@tno.nl or Jeroen.Kuenen@tno.nl to request the details.

The gridded dataset is structured using the same sectoral level of detail as the CAMS-REG inventories for most sources. Only for non-exhaust transport (GNFR category F4) a specific distinction is made between tyre wear, brake wear and road abrasion, based on requests from project partners in RI-URBANS.

The inventory comes with a specific PM speciation profile which breaks down emissions of PM (coarse and fine mode) into elemental carbon, organic carbon and other (non-carbonaceous) particles.

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