GUIDANCE DOCUMENTS ON MEASUREMENTS & MODELLING OF NOVEL AIR QUALITY POLLUTANTS:

EMISSION INVENTORIES FOR REGIONAL AND URBAN SCALE MODELLING APPLICATIONS

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

By

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ABBREVIATIONS

ACTRIS	Aerosols, Clouds and Trace gases Research InfraStructure
BC	Black carbon
CAMS	Copernicus Atmospheric Monitoring Service
EEA	European Environmental Agency
EMEP	European Monitoring and Evaluation Programme
EU	European Union
NMVOC	Non-methane volatile organic compounds
OSM	OpenStreetMap
OTM	OpenTransportMap
PM	Particulate matter
$PM_{0.3}$	Mass concentration of particles <0.3 µm
$PM_{2.5}$	Mass concentration of particles <2.5 µm
PM_{10}	Mass concentration of particles <10 µm
PNC	Particle number concentration
PNSD	Particle number size distribution
RF	Random forest
RI-URBANS	Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS EU-project
SPN	Solid particle number
TPN	Total particle number
UFP	Ultrafine particles
VOC	Volatile organic compound

CHEMICAL SPECIES

NH_3	Ammonia
NOx	Nitrogen oxides ($NO+NO_2$)
SOx	Sulfur oxides

1. ABOUT THIS DOCUMENT

This **Service Tool (ST)** guides on the steps needed to produce consistent emission inventories for regional and urban scale modelling applications. Estimates of anthropogenic primary emissions are key inputs to air quality models and for policy assessment. This guidance document describes the specific improvements that have been made to existing European emission inventories for RI-URBANS at a horizontal resolution of ~ 6x6 km^2 to better represent road transport emissions and include estimations of ultra fine particles, among others. While this is a sufficiently high resolution for modelling at European scale, for applications at urban level a higher resolution is necessary. Therefore, this document also describes a downscaling tool to detail the European emission dataset to a 1x1 km^2 resolution over urban areas in a consistent way. Finally, for the applications to urban areas this ST describes a number of comparisons that were made between the downscaled European emission products and independent emission inventories prepared for a number of urban areas in Europe, in particular including the RI-URBANS pilot cities. As a result of these benchmarking exercise, improvements of the European emission inventory and downscaling approach were performed, highlighting the importance of integrating quality assurance and quality control procedures in this work chain to produce consistent city level emission datasets for modelling applications.

The specific RI-URBANS emission inventories are elaborated for:

- Ultrafine particles-particle size distribution (UPF-PNSD).
- Non-exhaust PM.
- Other anthropogenic sources of PM and its components including BC
- PM precursor gases, including NOx, SOx, NH_3 and VOCs

The European wide emission inventories can be obtained directly through access to a FTP repository, or by requesting them via email (Jeroen.Kuenen@tno.nl or Marya.ElMalki@tno.nl), for more details see section 5 in this document. Urban (1x1 km^2) emission datasets for Amsterdam, Athens, Birmingham and Helsinki can be obtained by the same FTP repository or by requesting them via email (eathana@noa.gr). Requests for the other RI-URBAN cities are also welcome.

This is a RI-URBANS/ACTRIS guidance for this specific service tool that is part of the RI-URBANS deliverable D46 (D6.1, containing guidance for all service tools provided in the project) with the support for publication from AXA Research Fund to build up the final dissemination D55 (D7.6). Any dissemination of results must indicate that it reflects only the author's view and that the European Commission is not responsible for any use that may be made of the information it contains.

2. EUROPEAN EMISSION INVENTORIES FOR CRITERIA POLLUTANTS AND ULTRAFINE PARTICLES

Assessment of air quality at European scale relies on the availability of accurate emission inventories, which describe the sources of emissions in a spatially explicit manner. The most used dataset for such assessments is the CAMS-REG emission inventory (Kuenen et al., 2022) which provides updated emission inventories at 6x6 km^2 for the pan-European domain on an annual basis from the Copernicus Atmospheric Monitoring Service (CAMS). In this case, the "Ref2" version of CAMS-REG-v6.1 (base year 2019) was used, which includes a specific bottom-up inventory for PM emissions from small combustion which consistently includes condensables (Denier van der Gon et al., 2015, Simpson et al., 2022). Specifically, for RI-URBANS, improvements to this inventory were made for two specific topics:

- Providing an updated emission inventory for transport, with a focus on increasing the comparability and consistency of estimated emission for exhaust emissions and specific focus on non-exhaust particles.

- Providing an updated emission inventory for UFPnumbers, in the size range between 10 and 325 nm.

Both elements are described below in more detail.

2.1 Road transport emissions

A bottom-up model for road transport for all of Europe was constructed using the "COPERT data" dataset which provides annual vehicle stock and mileages per country, distinguishing more than 500 different vehicle types, consisting of main vehicle categories, engine capacities, fuel types and environmental standards. The dataset was obtained in 2021, covering the vehicle fleet information for the years 1990-2019 for 33 different European countries. European countries not covered in the COPERT dataset (all non-EU) were gapfilled using information from other sources on the fleet distribution at aggregated level, further detailed by making assumptions on similarities to other countries. The resulting vehicle kilometer dataset was subsequently combined with emission factors for each of the detailed vehicle types, both for the main air pollutants (e.g. NO_X, $PM_{2.5}$, etc.) and for particle numbers (see next section). Emission factors for the bottom-up model were taken from the Dutch emission inventory (Geilenkirchen et al., 2023) which provides emission factors for all relevant species. A crosswalk table was made linking the vehicle types in the Dutch inventory to the types used in the COPERT dataset, in order to select for each activity, the most appropriate emission factor. The emission factors only include the emissions when driving with a hot engine, and a specific novelty in this work was the application of specific cold start emissions, using emission factors expressed in mass emitted per cold start as suggested in Geilenkirchen et al. (2023).

For non-exhaust PM emissions, a consistent calculation of brake, tyre and road wear was made building on information on number of vehicles and mileages in the COPERT data for each country. For estimating emissions, the Tier 2 methodologies from the EMEP/EEA Guidebook (EEA, 2019) were utilised, considering speed dependencies and vehicle weight for trucks.

In terms of spatial distribution, initial comparisons made in this project revealed that road transport emissions in urban areas were underestimated (see Section 4). Hence, the spatial distribution of road transport emissions was revisited based on a European-wide traffic model (OpenTransportMap (OTM); Jedlička et al., 2016) which can be linked with OpenStreetMap (OSM) data via a common key. OTM provides traffic volumes for a large fraction of roads for EU-countries, but especially for smaller roads a large portion of the roads has missing traffic volume data. A gapfilling method based on a random forest (RF) machine learning model approach based on multiple predictors (Ishwaran et al., 2022), including a.o. land use information, administrative units (NUTS regions), and road characteristics included in OTM. The model was able to predict traffic volumes reasonably well, which was tested by predicting traffic volumes for roads where it was also reported.

Figure 1 shows the contribution of the different subsources in road transport to total emissions in 2019 according to this inventory. It shows that - depending on the pollutant - cold start emissions vary between 3% and 18%, whereas for PM_{10} the non-exhaust accounts for 60% of total emissions, while for $PM_{2.5}$ this share is around 45%.

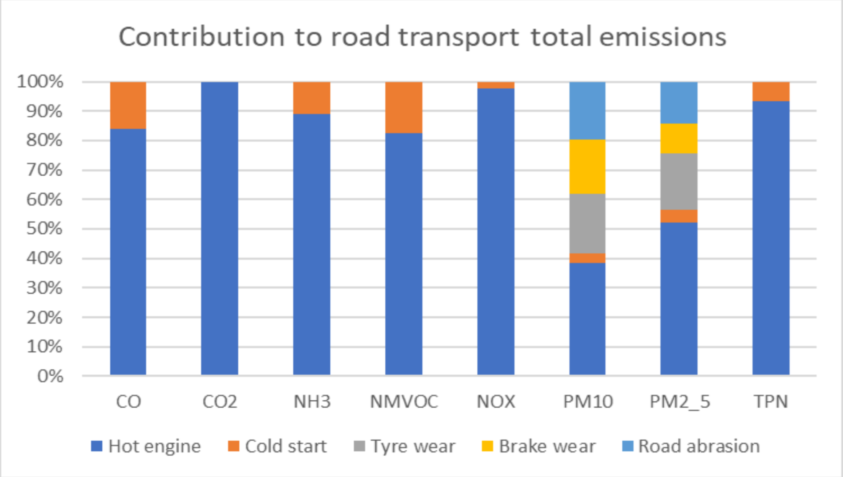


***Figure 1**. Contribution of different sources in road transport to total emissions for relevant pollutants. Exhaust emissions are split between hot engines and cold start contribution.*

2.2 Particle numbers

Ultrafine particles are particles with a diameter below 100nm. In order to characterize these particles correctly, these are typically expressed as number of particles instead of mass. At the same time, when it comes to emissions it is crucial to distinguish the solid particle numbers (SPN) which are used to characterize vehicles or appliances, for example in type approval or certification tests, and TPN (total particle number) which encompasses both solid and volatile particles, the latter being formed upon cooling and dilution of the exhaust gases. TPN is therefore the relevant metric in relation to air quality. The relation between SPN and TPN is source specific, but in the majority of cases the volatile part is more important than the solid particles, and hence this fraction is crucial to consider.

The particle number inventory described in this section is an updated of earlier inventories prepared in the EU FP6 EUCAARI (Kulmala et al., 2011) and FP7 TRANSPHORM (see e.g. Beddows et al., 2014) projects, and a recent inventory made for the Rotterdam harbour area (Visschedijk et al., 2022). 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 from $PM_{2.5}$ and subsequently 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.

Improvements of TPN emission estimates based on road transport have been made by conducting an extensive literature search, with a focus on the newer vehicles (Euro 4 and newer) and including explicitly the effects of cold starts and regeneration events, which were found to significantly impact TPN emissions. Also, specific emphasis was put on two-wheelers, which are considered an important contributor to ultrafine particles. Compiled emission factors from the literature search were grouped per vehicle type and technology and gapfilled with information from earlier work where necessary. Emission factors were expressed as number per vkm and subsequently combined with the activity data (see Section 2.1) to calculate total TPN emissions for road transport.

Figure 2 compares resulting TPN emissions and $PM_{2.5}$ emissions.

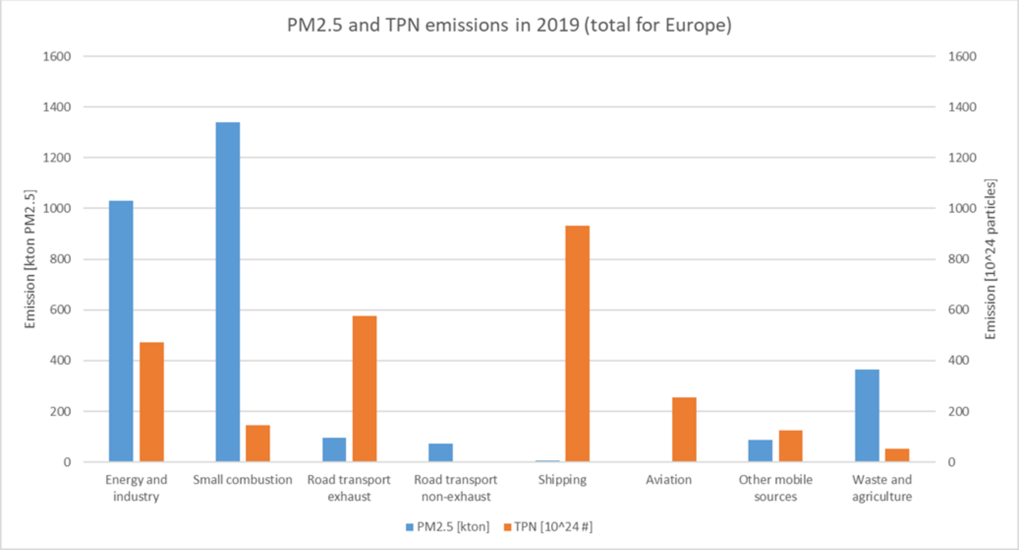


***Figure 2**. Comparison between $PM_{2.5}$ (in ktons) and TPN emissions (in 10^{24} #) across different sectors.*

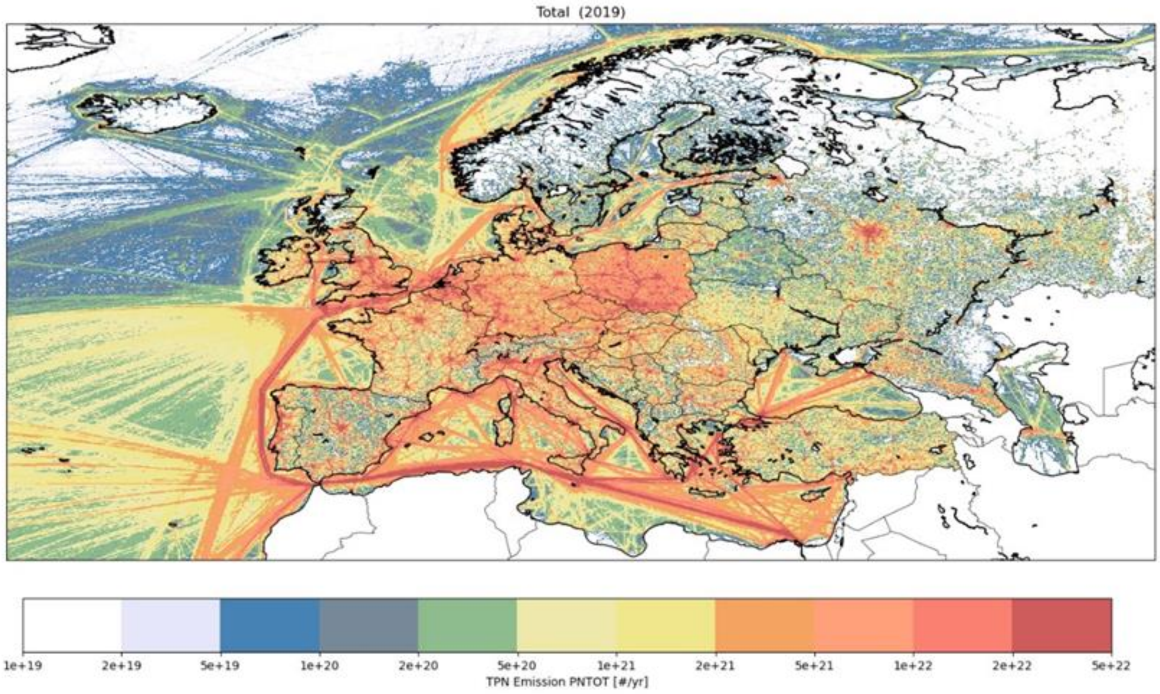


***Figure 3**. Emissions of TPN (in #/year) for 2019 distributed in space at 6x6 km2 resolution.*

The RI-URBANS European emission inventories are available publicly to support modelling studies. These are available in support of modelling activities through a FTP repository (see Section 5 of this document for details).

Pending further evaluation, the improvements described in this chapter will be integrated in a future version of the CAMS emission inventories.

3. METHODOLOGY TO DOWSCALE EMISSION FOR URBAN MODELLING PURPOSES

Estimates of urban air pollution require timely and spatially resolved emission inventories. Investment upon regional datasets is an accountable option for cities that lack bottom–up emission inventories and/or when homogeneity between different cities is pursued. The UrbEm method and tool (Ramacher et al., 2021) supports the downscaling of regional emission inventories, such as the CAMS-REG dataset (Sect. 2). In particular, the spatial disaggregation of emission rates per 6x6 km^2 can be performed using high-resolution, source-specific, open-access spatial proxies. High resolution -per 1x1 km^2 area- emission data, consistent to the CAMS-REG structure and contents are then created, with the flexibility for point and/or line data, if asked.

Specifically, for RI-URBANS, in addition to the improvements incorporated in the “Ref2” version of CAMS-REG-v6.1 emission inventory (Sect. 2), the UrbEm tool provides an improved fine-scale spatial allocation for the coarse emissions by

- On-road vehicles
- Off-road activities
- Industries
- Ships

Changes are described below in more detail.

A less impactful but necessary improvement of the method has been the incorporation of a backup proxy (population density) for all source sectors.

3.1 Road transport emissions

The spatial disaggregation of road transport emissions is now performed though the direct use of road network, rather than the support of population density. In particular, CAMS-REG data are downscaled to 1x1 km^2 using the OpenStreetMaps (OSM) road links tagged as motorway, trunk, primary, secondary and tertiary roads. The spatial attribution of emissions per road type has been updated with the use of the weight factors considered by uEMEP (Mu et al., 2022). This update followed a series of sensitivity tests, towards the harmonization with the available bottom-up datasets (Sect. 4), which have indicated pronounced emissions from motorways in comparison to residential streets.

Figure 4 shows the original and spatially refined CAMS-REG road transport emissions of NOx for two of the pilot cities. Emission totals for the urban domains are also given as a proof of mass consistency between datasets, while the high-resolution proxy (here road network) is overlaid to the 6x6km2 dataset, as a means of visualization of the applied method. As expected, coarse vehicle emissions are allocated at the fine cells hosting road surfaces, while the weighing procedure described above is visualized as peak emissions from the road rings and national roads.

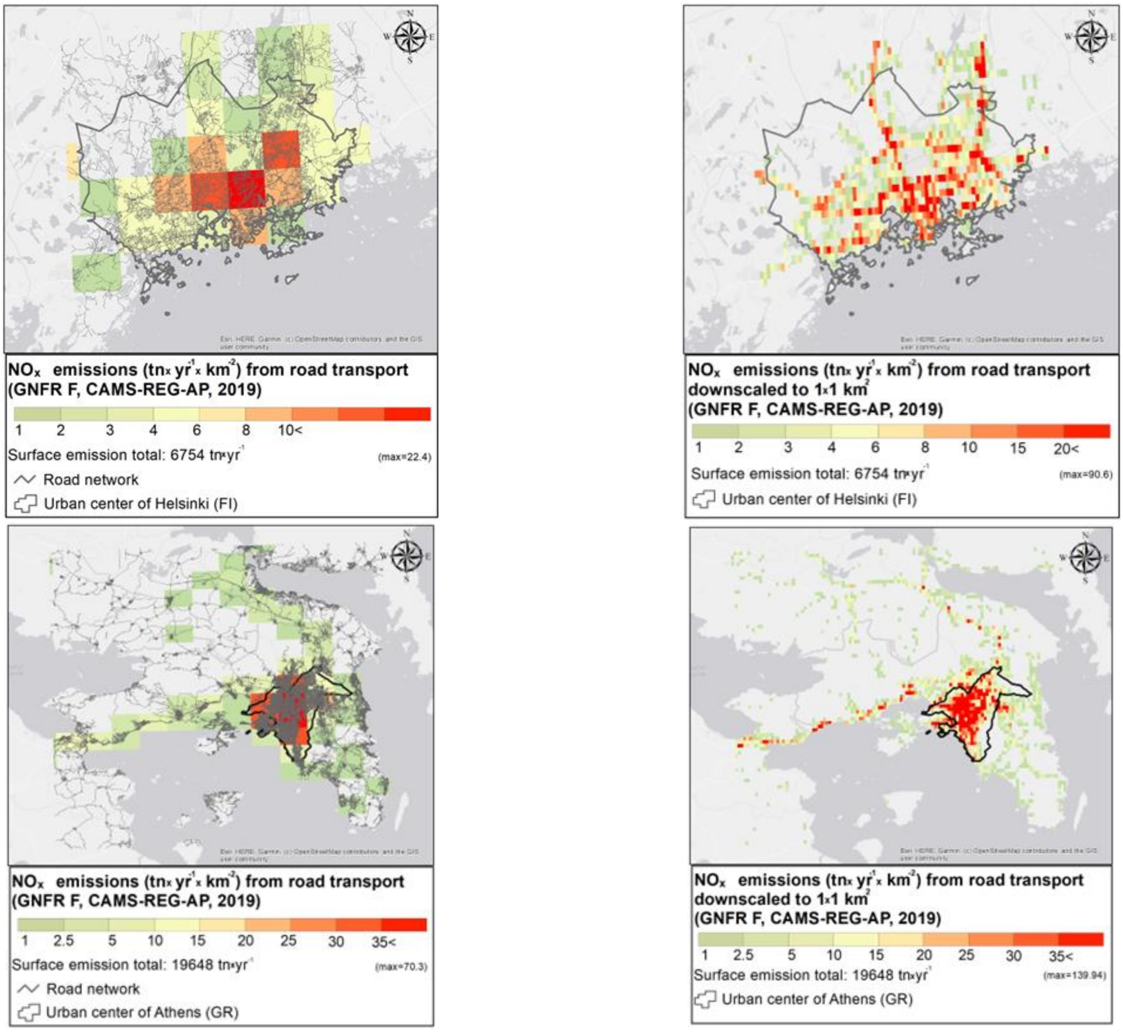


Figure 4. *The spatial distribution of annual (2019) NOx emissions (tn y^{-1}) from road transport (GNFR F) derived from the "Ref2" version of CAMS-REG-v6.1 emission database (left) and after their spatial refinement (right). Indicative results are shown for the urban areas of Helsinki (top) and Athens (bottom).*

3.2 Off road emissions

The spatial disaggregation of off-road emissions was enriched with multiple proxies per sub-sector. In specific:

- Emissions from the mobile machinery for industrial activities are attributed to industrial areas.
- Emissions from the mobile machinery for agricultural activities are attributed to agricultural areas.
- Railway emissions are attributed to the railway network (using the OSM information).
- Emissions from all other types of machinery are distributed using population density.

It should be noted that the option to enrich the UrbEm tool and method with more spatial disaggregation proxies was thoroughly examined for all source sectors, but found effective only for this specific source category, due to the inhomogeneity of its sub-categories.

3.3 Industrial and ship emissions

The improvement in the spatial allocation for these two sectors has been performed through the following changes:

- The 6x6km^2 industrial emissions are spatially disaggregated using the coordinates of industrial sites.
- Shipping emissions are allocated at the 1x1 km^2 cells hosting ship lanes (retrieved from the OSM database).

4. INTERCOMPARISONS AGAINST INDEPENDENT LOCAL EMISSION INVENTORIES

An emission intercomparison exercise was performed between the 1x1 km^2 downscaled European-wide inventories developed as described in the previous two sections (hereafter referred to as CAMS-REG-UrbEm) and independent bottom-up emission inventories for a total of 13 urban areas, including 10 RI-URBANS pilot cities. The comparison assesses the consistency between local city and regional NOx, NMVOC, PM_{10} and $PM_{2.5}$ emission estimates for the road transport and residential/commercial combustion sectors, both in terms of total annual emissions and their spatial distribution. These two sectors are the main contributors to total NO_x and $PM_{2.5}$ European emissions, respectively. Additionally, we also considered the 1x1 km^2 downscaled uEMEP emission inventory for 2018, developed by MetNo using as a basis the official data submission to the EMEP Centre on Emission Inventories and Projections and sector-specific spatial emission proxy data, as described in Mu et al. (2022). For this inventory we only considered emissions for the road transport sector, as the original EMEP PM emissions from the residential/commercial combustion sector (GNFR_C) are replaced by the same TNO bottom-up estimates considered in the RI-URBANS European inventory.

4.1 Local bottom-up inventories

Figure 5 and Table 1 indicate the location and main characteristics of the local bottom-up emission inventories compiled for the intercomparison exercise. The collected dataset allows covering all the RI-URBANS pilot cities except for Bucharest (for which no bottom-up inventory is available), as well as Madrid, London and Hamburg.

The local emission inventories were either downloaded from the corresponding open data repository or made available to BSC by the research centres and institutions responsible for their development. Note that for some cities (i.e., Milan, Bologna, Paris, Madrid) the local inventories were only available at the municipality level and therefore comparisons at the grid level could not be made. Note that the local inventories that are reported at a spatial resolution finer than 1x1 km^2 (i.e., Helsinki, Zurich) where aggregated to a 0.01x0.01º regular lat-lon WGS84 grid for compatibility. For the majority of local inventories, the base year is equal (2018) or very close (2019, 2017) to the one considered in the European-wide inventories.

For some cities and sectors, certain species had to be removed from the intercomparison as the emissions were not reflecting the same activities and sources considered in the CAMS-REG-UrbEm GNFR_F (road transport) and GNFR_C (other stationary combustion activities) categories, as detailed in Table 1.

Table 1. *Summary of local bottom-up emission inventories considered.*

Pilot city	Year	Spatial resolution	Sectors & pollutants	Provider
Amsterdam	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC[(1)], PM10, PM2.5)	RIVM
Central Athens area	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	NOA
Barcelona	2019	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	BSC
Birmingham	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Defra & BEIS
Bologna	2017	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Arpa Emilia-Romagna
Hamburg	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Helmholtz-Zentrum Hereon
Helsinki	2019	0.25x0.25km^2 & road link	Road transport (NOx, PM2.5) Residential (PM2.5)	FMI
London	2018	1x1km^2	Road transport (NOx, PM10, PM2.5) Residential (NOx[(2)], PM10, PM2.5)	Greater London Authority

Madrid	2019	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Madrid City Council
Milan	2019	Municipality level	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC, PM10, PM2.5)	Arpa Lombardia
Paris	2018	Paris city, metropolis, Ile-de-France	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC(3), PM10, PM2.5)	Airparif
Rotterdam	2018	1x1km^2	Road transport (NOx, NMVOC, PM10, PM2.5) Residential (NOx, NMVOC(1), PM10, PM2.5)	RIVM
Zurich	2015	0.01x0.01km^2	Road transport (NOx, NMVOC, PM10) Residential (NOx, NMVOC, PM10)	UGZ

(1) Excluded since emissions from non-residential/commercial facilities are included

(2) Excluded since commercial combustion emissions are reported in another sector (industrial combustion emissions)

(3) Excluded since residential use of solvent emissions are included in the same sector

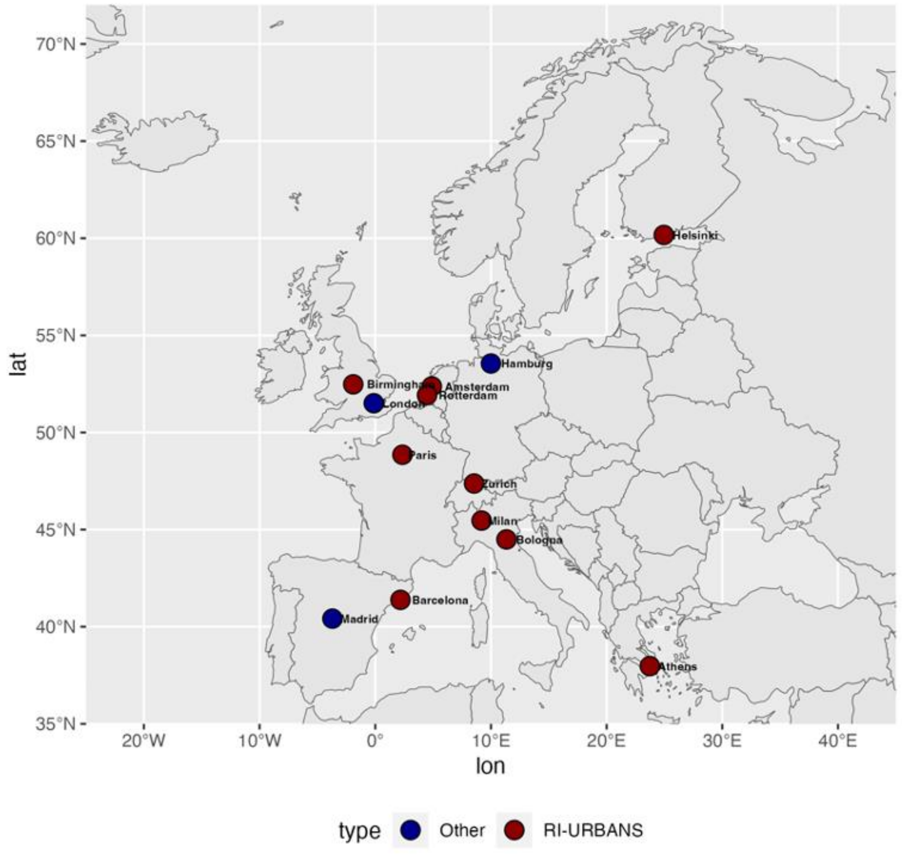


***Figure 5**. Cities for which bottom-up emission inventories were collected. Red dots indicate RI-URBANS pilot cities while blue dots indicate additional cities that were added to the comparison.*

4.2 Road transport

Figure 6 to Figure 8 show the results of the intercomparisons performed between road transport gridded emission inventories for the cities of Amsterdam, Birmingham and Helsinki. All three figures follow the same scheme: the top part presents a comparison between total annual road transport NOx, NMVOC, PM_{10} and $PM_{2.5}$ emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and the corresponding local emission inventory (referred to with the name of the provider), while the bottom part shows the spatial distribution of the road transport NO_x emissions [t/year·cell] reported by each inventory as well as the administrative borders considered for the comparisons. Summary scatter plots showing the relationship between local bottom-up and CAMS-REG-UrbEm NO_x and $PM_{2.5}$ road transport emission estimates for each individual city are shown in Figure 9.

The same pattern is observed in almost all cities when looking at NO_x results: CAMS-REG-UrbEm tends to report lower emissions than the local inventories, while uEMEP results are more in line with the bottom-up estimates. The large discrepancies between CAMS-REG-UrbEm and the local NO_x inventories could be related to the share of the road type split between highway and non-highway (i.e., urban and rural) emissions that is assumed in the CAMS-REG approach for spatially distributing national emissions to grid level (Kuenen et al., 2022). The method considers traffic intensity as a direct proxy but might not correctly consider detailed traffic parameters such as levels of congestion, which tend to be higher in urban areas.

For PM_{10} and $PM_{2.5}$, CAMS-REG-UrbEm tends to allocate less emissions when compared to the local bottom-up inventories, as seen for NOx. Largest discrepancies both in relative and absolute terms are observed in Hamburg, Barcelona and London (around -75% and between 500t/year and 2000t/year for PM_{10}), where the local estimates include resuspension emissions, a source that is not considered in the CAMS-REG-UrbEm inventory.

Regarding the spatial distribution of NO_x emissions, important differences are observed between CAMS-REG-UrbEm, uEMEP and the local emission inventories. In the CAMS-REG-UrbEm emission maps main urban corridors, road rings and city access roads are in general much less marked than in the results reported by uEMEP and the local inventories. The discrepancies observed between CAMS-REG-UrbEm and local estimates could be caused by a combination of three factors:

- The under-allocation of NOx emissions in urban areas in CAMS-REG.
- The spatial proxies used to distribute the original CAMS-REG emissions.
- The spatial proxies used in UrbEm to downscale the CAMS-REG emissions.

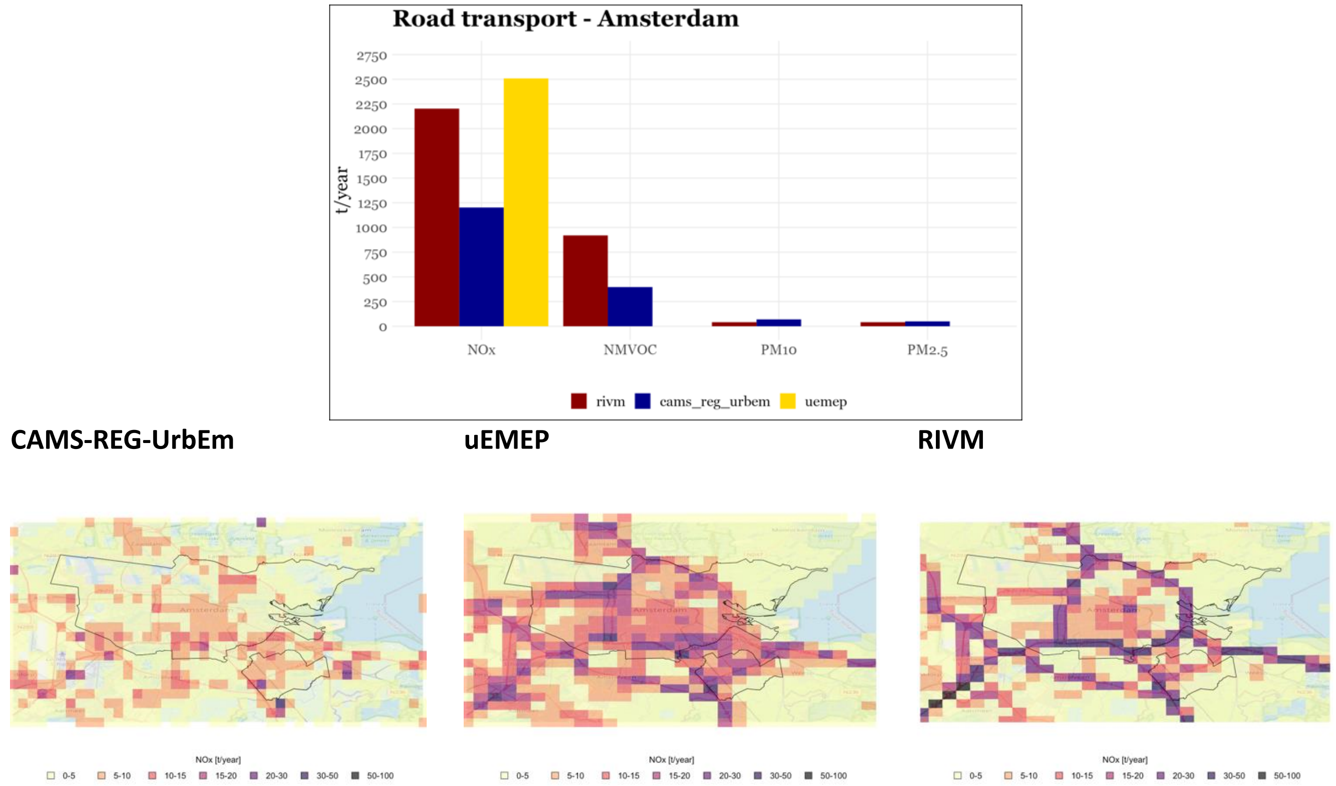
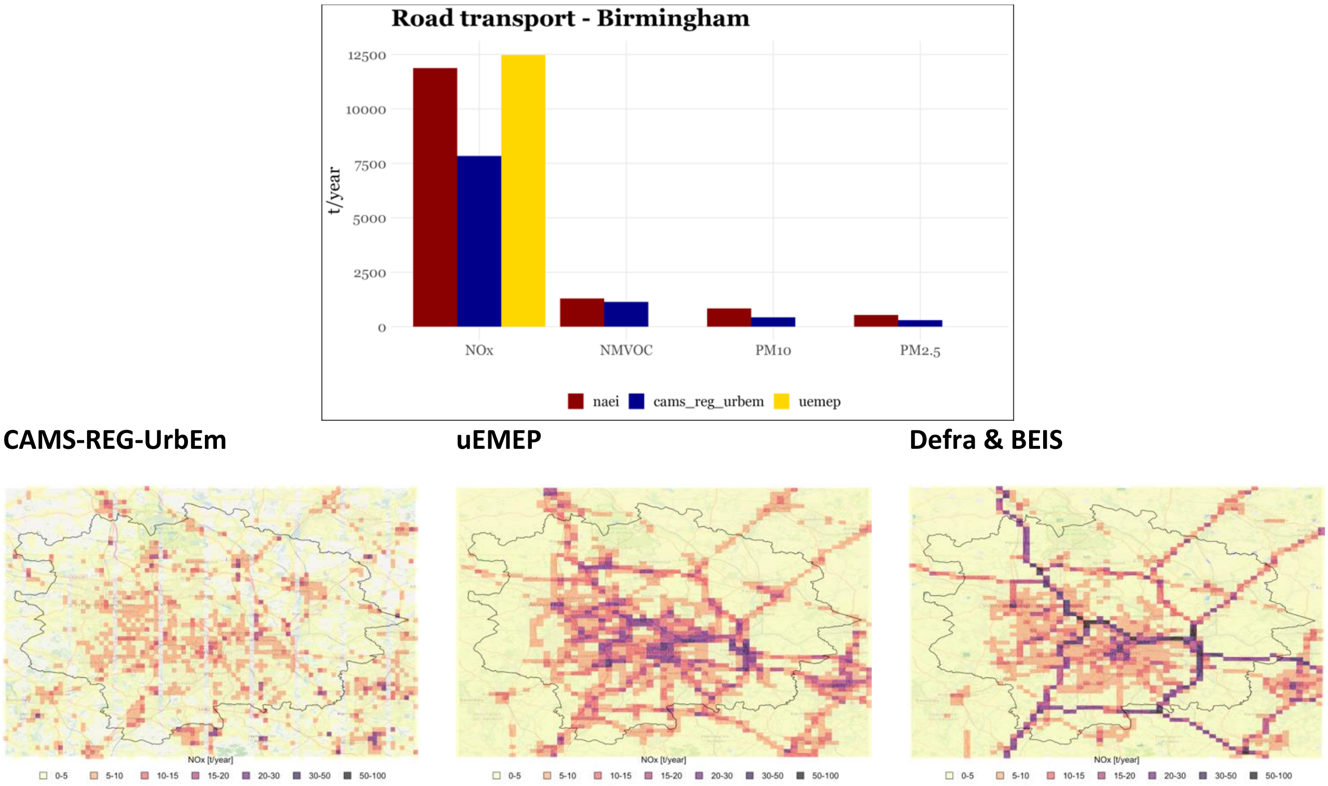
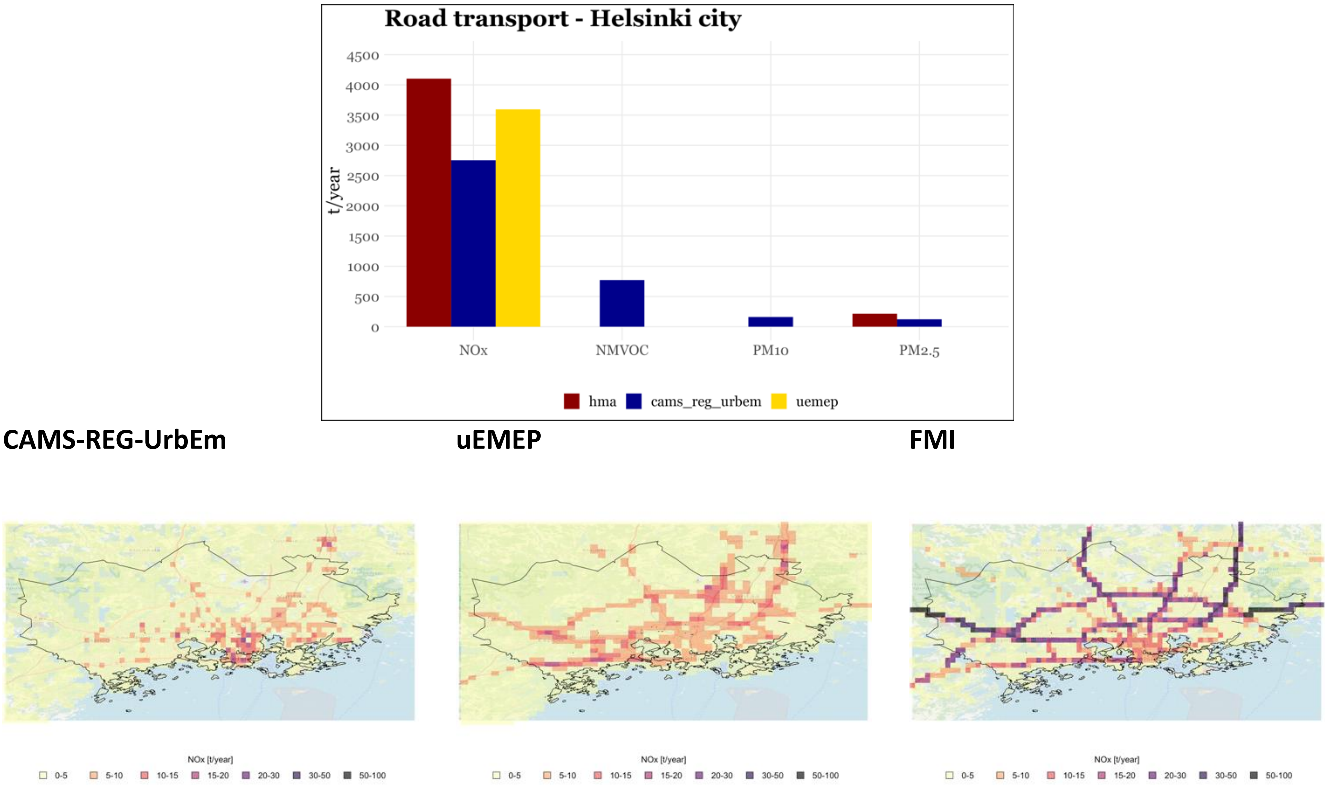


Figure 6. *Comparison between annual NO_x, NMVOC, PM_{10} and $PM_{2.5}$ (top) and gridded NO_x (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and RIVM for Amsterdam.*



CAMS-REG-UrbEm **uEMEP** **Defra & BEIS**

Figure 7. *Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded NO$_x$ (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and Defra/BEIS for Birmingham.*



CAMS-REG-UrbEm **uEMEP** **FMI**

Figure 8. *Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded NO$_x$ (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm, uEMEP and FMI for Helsinki.*

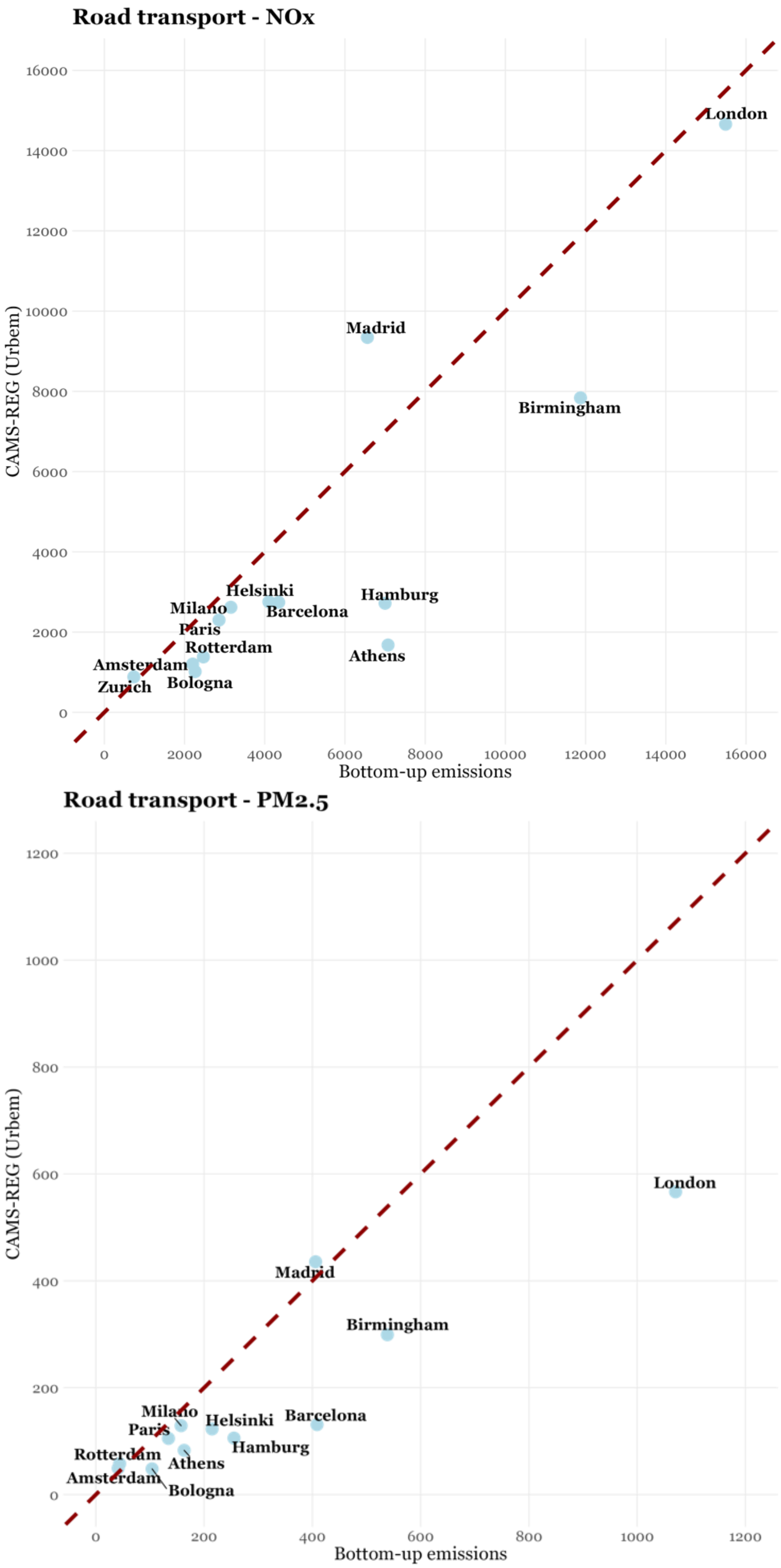


***Figure 9**. Scatterplots showing the relationship between local bottom-up (X-axis) and CAMS-REG-UrbEm (Y-axis) NO_x (top) and $PM_{2.5}$ (bottom) road transport emission estimates per city (light-blue dots). Lines of equalities are represented with the dashed dark red lines.*

4.3 Road transport - revision

As indicated in Sections 2 and 3, and as result of the intercomparion results showed in the previous section (4.2), the spatial distribution of the 6x6 km^2 CAMS-based European road transport emissions and associated UrbEm downscaling methodology to finer resolutions were reviewed. The new 1x1 km^2 downscaled emission product (referred to as CAMS-REG-UrbEm_v2 hereinafter) were intercompared against the independent bottom-up inventories to assess the impact of the revisions on the final results.

Figure 10 to Figure 12 show the results of the new comparisons for the cities of Helsinki, Amsterdam and Brimingham. For the three cases, it is observed how the emissions reported by CAMS-REG-UrbEm_v2 have substantially increased when compared to the previous version, the final NO$_x$ emissions being much closer to the local bottom-up estimates. For instance, in the case of Birmingham CAMS-REG-UrbEm NO$_x$ road transport emissions have almost doubled between version 1 and version 2 (increase of 75%). In terms of spatial distribution, it is also observed that in the new CAMS-REG-UrbEm_v2 downscaled emissions the main roads are more marked, the inconsistencies with the bottom-up emission maps being lower although still present.

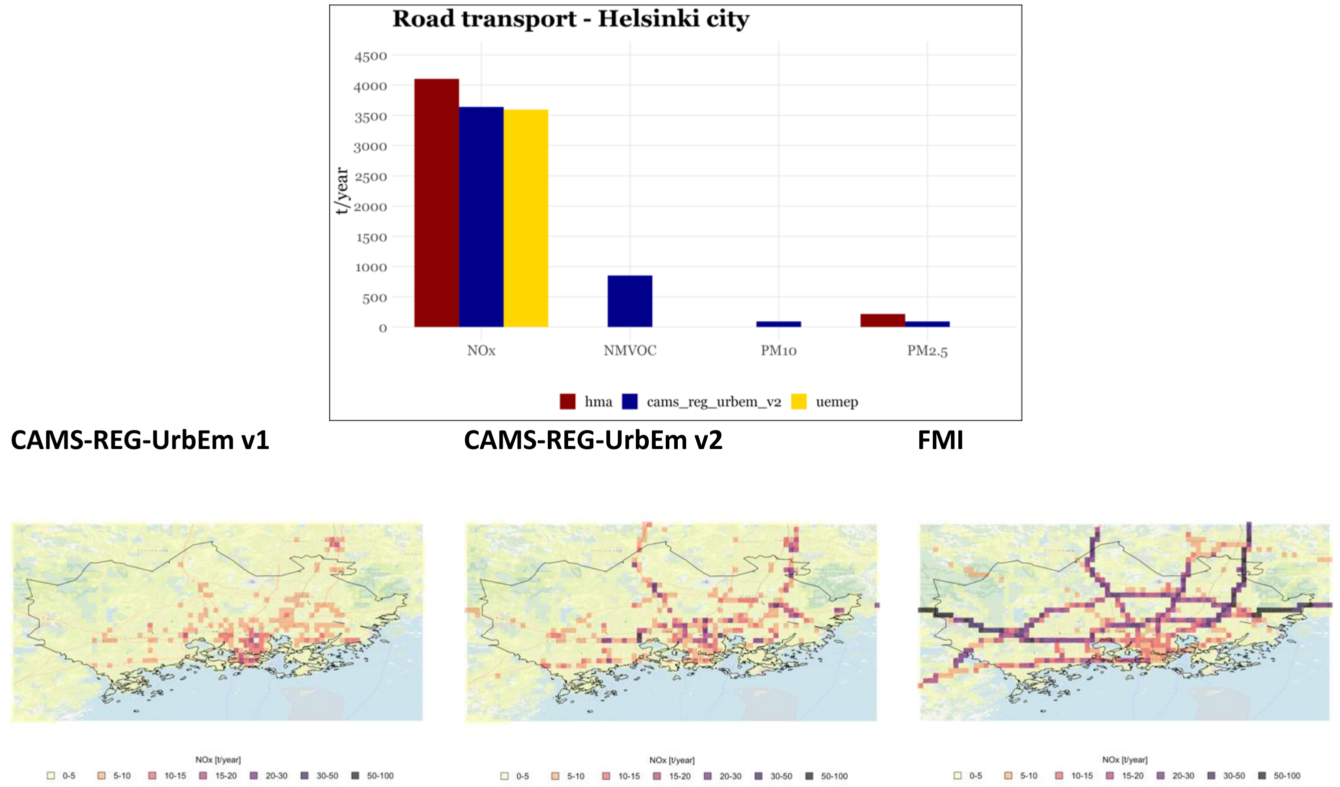


***Figure 10**. Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded NO$_x$ (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm (version 1 and 2), uEMEP and FMI for Helsinki.*

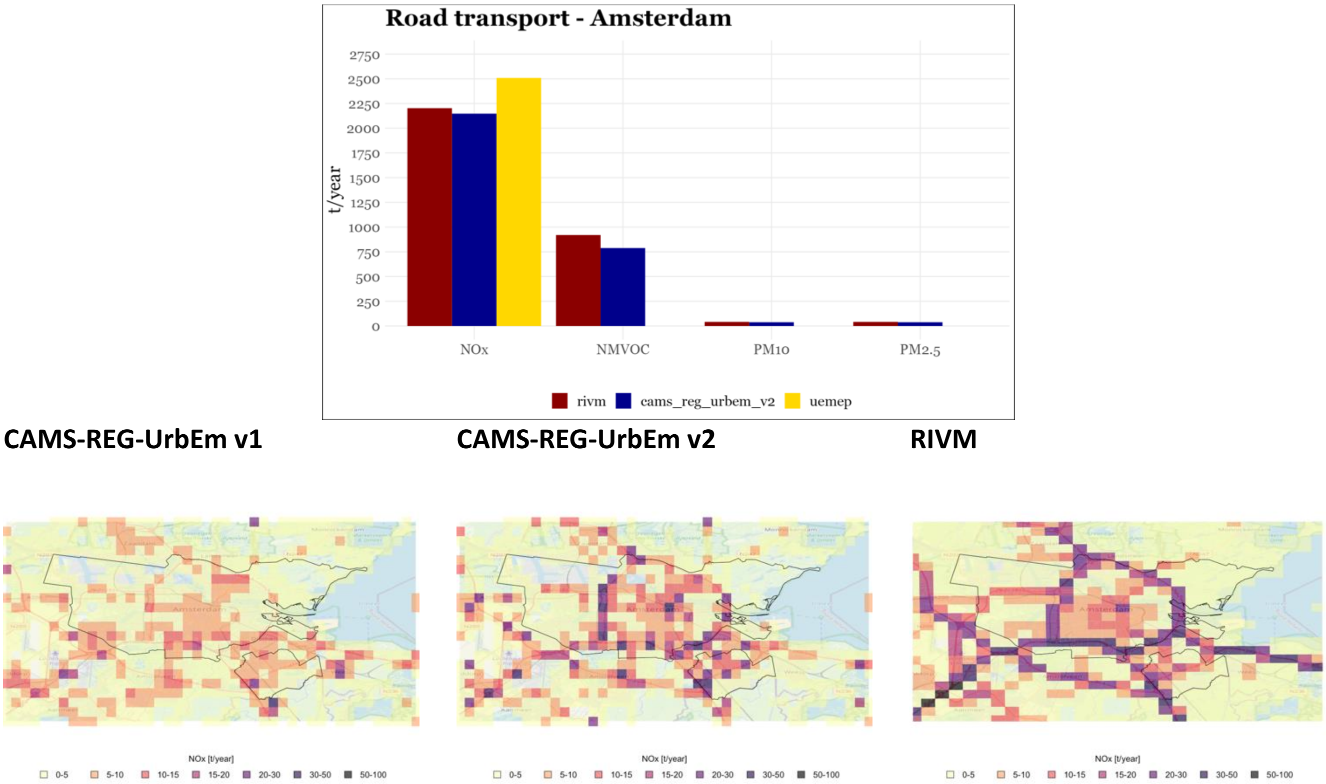


***Figure 11**. Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded NO$_x$ (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm (version 1 and 2), uEMEP and RIVM for Amsterdam.*

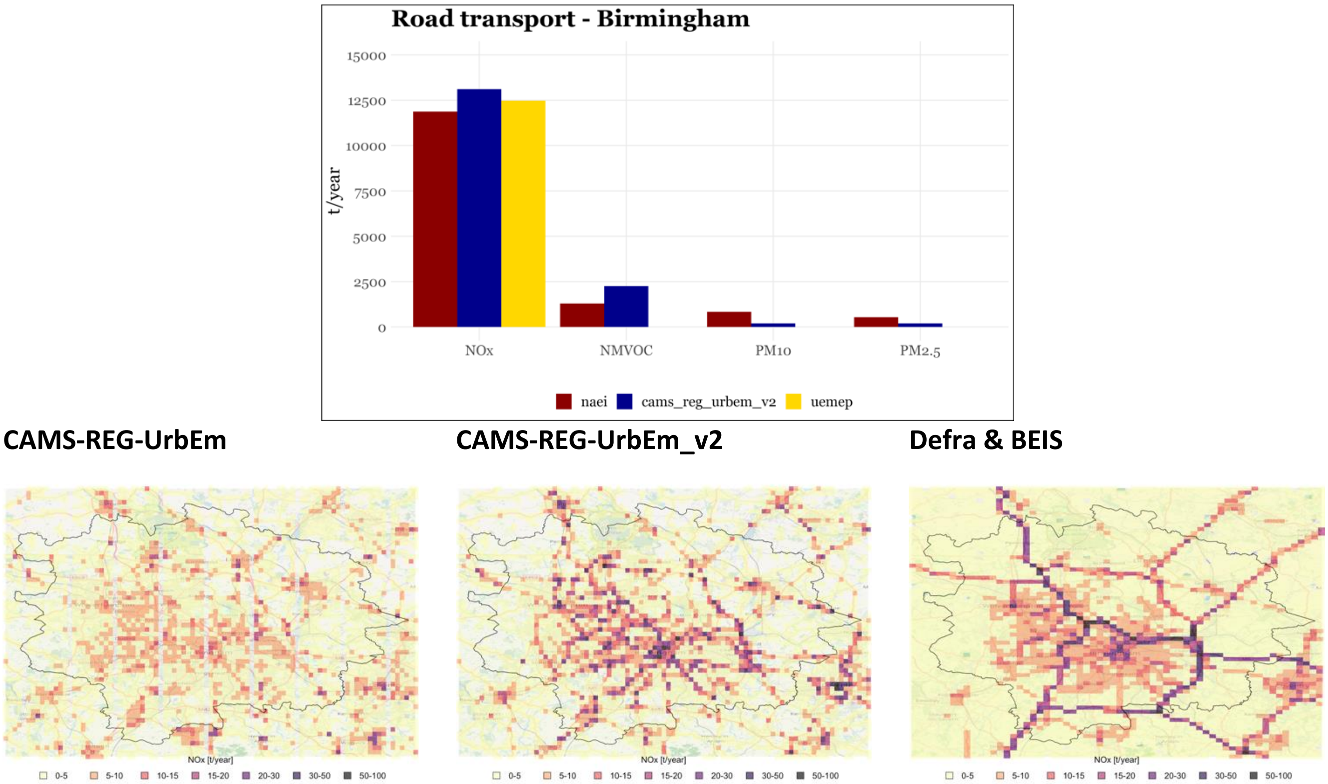


***Figure 12**. Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded NO$_x$ (bottom) road transport emissions [t/year] reported by CAMS-REG-UrbEm (version 1 and 2), uEMEP and Defra/BEIS for Birmingham.*

4.4 Residential and commercial combustion

Figure 13 to Figure 15 show the results of the intercomparisons performed between residential and commercial combustion, gridded emission inventories for the cities of Barcelona, Helsinki and Rotterdam. All three figures follow the same scheme: the top part presents a comparison between total annual residential and commercial NO_x, NMVOC, PM_{10} and $PM_{2.5}$ emissions [t/year] reported by CAMS-REG-UrbEm and the corresponding local emission inventory (referred to with the name of the provider), while the bottom part shows the spatial distribution of the residential and commercial combustion $PM_{2.5}$ emissions [t/year·cell] (PM_{10} in the case of Helsinki) reported by each inventory as well as the administrative borders considered for the comparisons. Summary scatterplots showing the relationship between local bottom-up and CAMS-REG-UrbEm NO_x and $PM_{2.5}$ emission estimates per city are shown in Figure 16.

Discrepancies between CAMS-REG-UrbEm and bottom-up NO_x emissions are in general much lower than the ones reported for road transport. Depending on the city, CAMS-REG-UrbEm reports higher or lower emissions. In contrast, significant discrepancies are observed when comparing $PM_{2.5}$ emissions. In Birmingham, London, Athens and Paris, CAMS-REG-UrbEm reports between -60% and -90% less emissions, while in Madrid, Helsinki and Barcelona, the emissions reported by the downscaled inventories are between 1.5 and 4.5 times larger than the bottom-up estimates. Residential and commercial $PM_{2.5}$ emissions are mainly driven by residential wood combustion activities (Denier van der Gon et al., 2015) and therefore most of the discrepancies observed are linked to specific components of this source, including mainly:

- Spatial allocation of domestic wood burning: the amount of wood that is burned in urban areas for space heating purposes can significantly vary from one country (or region) to another as a function of socioeconomic and legislation factors (e.g., ban on wood burning stoves).
- Emission factors: The CAMS-REG inventory estimates PM emissions from residential wood combustion emissions making use of emission factors that include the condensable fraction, which can be an order of magnitude higher than the emission factors that inly consider solid particles. Moreover, it should be noted that there are other factors besides the inclusion of organic condensable that can create important discrepancies between the emission factors used in the regional and bottom-up emission inventories, including: the appliance type splits considered (e.g., old versus new stoves, open fireplaces), assumption on burning practices, and wood characteristics (e.g., type of wood, dry/wet wood) (Simpson et al., 2020).

Note that other aspects than the ones listed above can also be causing the discrepancies observed between the downscaled and bottom-up $PM_{2.5}$ emissions. For example, in the case of London, the large discrepancy observed (-65%) is mainly related to the fact that the bottom-up inventory for this city includes emissions from commercial cooking activities, which are not included in the CAMS-REG inventory, neither in the official estimates that are reported to EMEP.

Part of the explanation in the discrepancies observed may also be the different cultural aspects with regard to wood burning, as well as local measures to reduce wood use impacts (awareness raising, fleet renewal or even local bans). These may substantially influence the local situation, whereas the CAMS-REG inventory uses a consistent approach across all of Europe.

In terms of spatial distributions, the patterns reported by the downscaled regional and bottom-up inventories are generally in line. It's worth noting how in Helsinki both the regional and bottom-up inventory tend to locate most of the $PM_{2.5}$ emissions outside of the city center, indicating than other sources of energies than wood (e.g., natural gas, electricity) are used for heating purposes in the inner city. In Rotterdam the bottom-up inventory reports hotspots in isolated grid cells that are not observed in the European downscaled inventories. Most of these hotspots are in the port area, where the presence of residential or commercial combustion activities is in principle low. We hypothesize that the bottom-up inventories constructed by RIVM in these two cities are including some emission sources related to (industrial) activities in the harbour area, that may be wrongfully attributed to the GNFR_C sector.

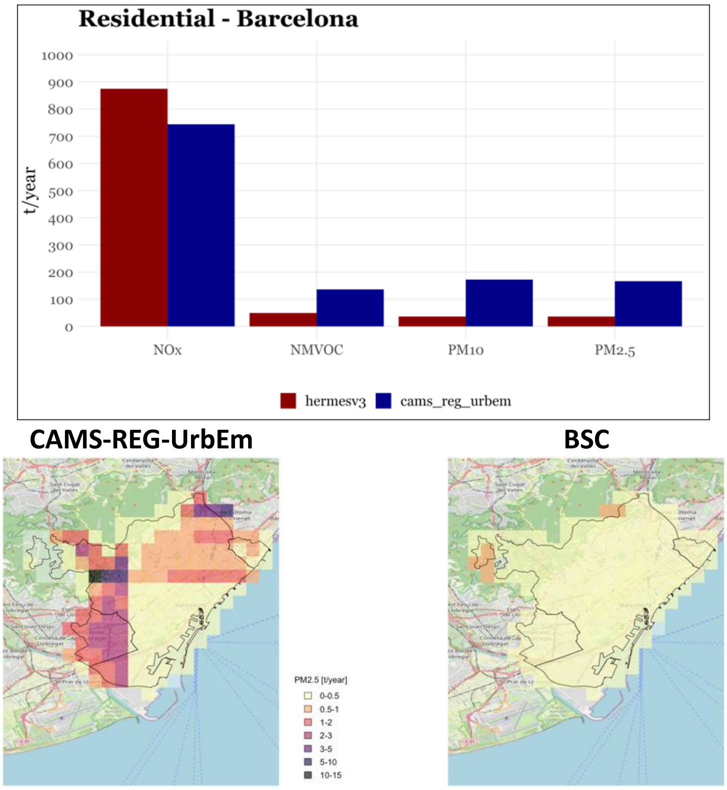


Figure 13. *Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded PM$_{2.5}$ (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and BSC for Barcelona.*

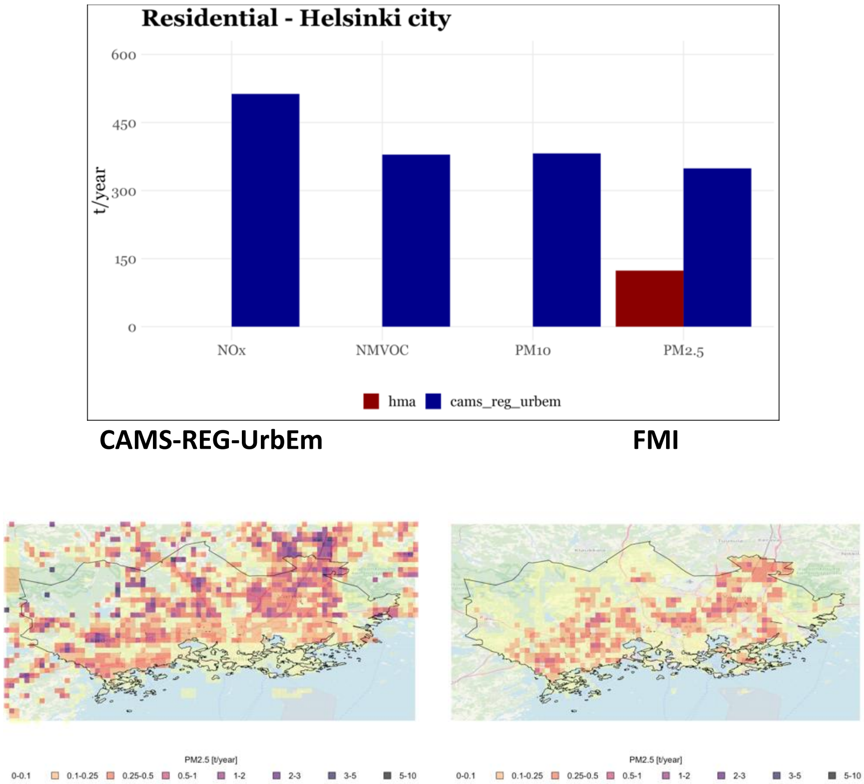
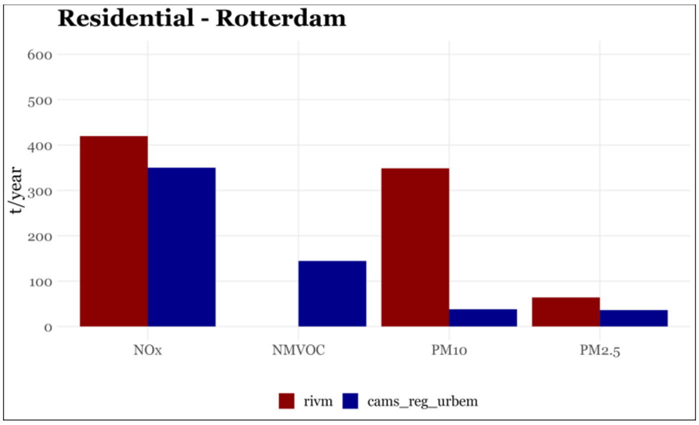


Figure 14*. Comparison between annual NO$_x$, NMVOC, PM$_{10}$ and PM$_{2.5}$ (top) and gridded PM$_{2.5}$ (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and FMI for Helsinki.*



CAMS-REG-UrbEm **RIVM**

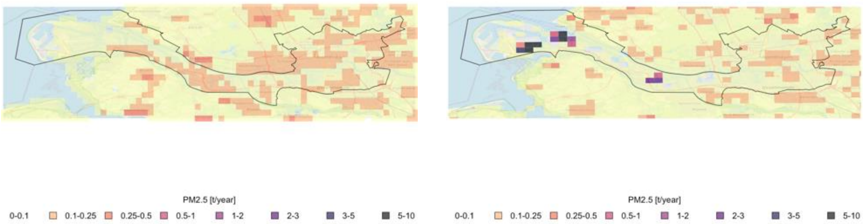
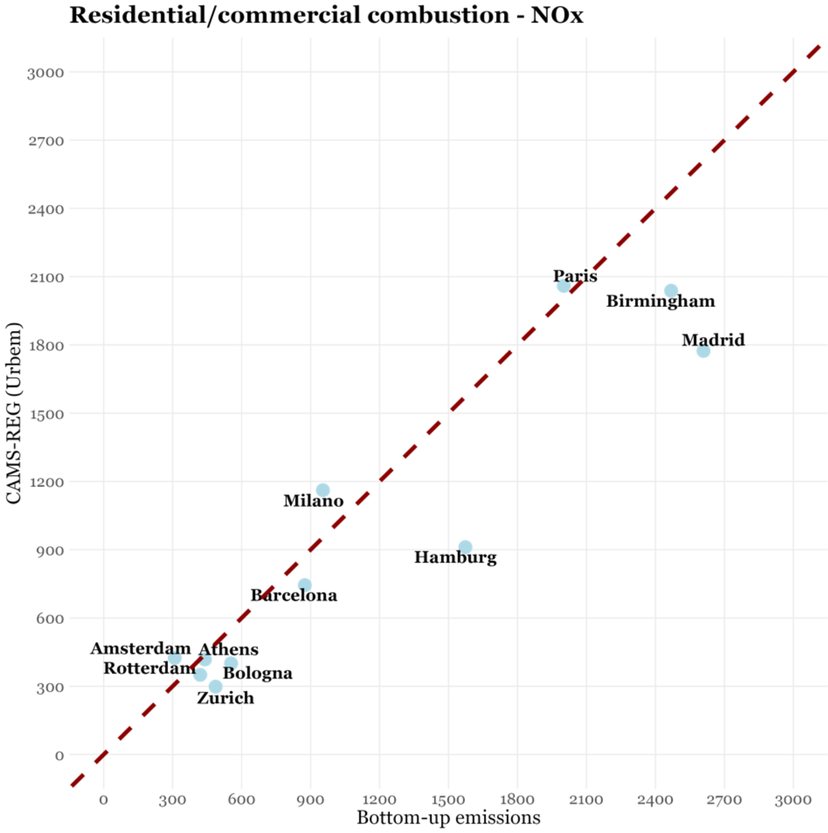


Figure 15. *Comparison between annual NO_x, NMVOC, PM_{10} and $PM_{2.5}$ (top) and gridded $PM_{2.5}$ (bottom) residential emissions [t/year] reported by CAMS-REG-UrbEm and RIVM for Rotterdam.*



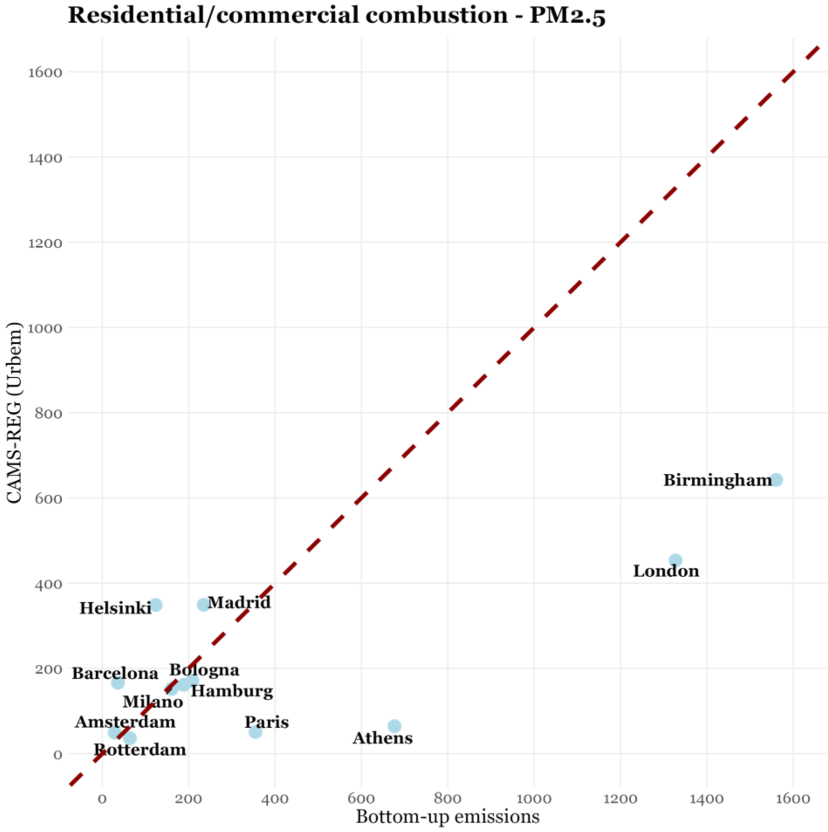


Figure 16. *Scatterplots showing the relationship between local bottom-up (X-axis) and CAMS-REG-UrbEm (Y-axis) NO$_x$ (top) and PM$_{2.5}$ (bottom) residential emission estimates per city (light-blue dots). Lines of equalities are represented with the dashed dark red lines.*

5. CONCLUSIONS AND RECOMMENDATIONS

The Service Tool (ST) for emission inventories provides guidance for the preparation of emission inventories in support of regional and urban scale modelling applications, including the development of European emission inventories at a horizontal resolution of ~ 6x6 km^2 and that includes estimates of air pollutants (incl. amongst others $PM_{2.5}$ and PM_{10} incl. non-exhaust, NH_3, NMVOC, NO_X) and ultra fine particles (UFP-PNSD), as well as of a downscaling tool to detail the aforementioned European emission dataset to a 1x1 km^2 resolution over urban areas in a consistent way. These datasets are also available for download through an FTP repository.

The emission inventories at European scale are developed on a further development of the CAMS-REG emission inventories (Kuenen et al., 2022) which provide model-ready emission input for main air pollutants, and are widely used in the European air pollution modelling community. In RI-URBANS specific developments were made to the European emission inventories by improving the estimates for road transport and ultrafine particles. For ultrafine particles however, the information is currently quite scarce.

For road transport, improvements focused first on providing a consistent bottom-up inventory for Europe based on information on the registered fleet in each European country and its estimated mileages, which distinguishes around 500 different vehicle types (incl. fuels, engine capacity and Euro class). Consistent emission factors based on the Dutch emission inventory model (Geilenkirchen et al., 2023) are applied, which distinguish between hot engine emissions and cold start emissions, the latter being calculated separately based on average trip length assumptions. For particle number a novel set of emission factors was derived based on literature, focusing on the relatively new vehicle types, where for instance the split between different engine types for petrol-fuelled vehicles (port-fuel injection, direct injection) was incorporated. For many other sectors however, these had to be derived from a mass-based approach (first estimating PM0.3 in PM2.5, and then applying a size distribution and density assumption. To improve UFP emission estimates in the future, it is recommended to develop UFP emission estimation approaches and include those in the official guidance (e.g. EMEP/EEA Guidebook) so that emissions can be estimated consistently.

The downscaling of the European emission inventory is based on the UrbEm method and tool (Ramacher et al., 2021), which provides high-resolution (1x1km^2) emission inventories for city-scale air quality simulations over a number of cities including the RI-URBANS pilot cities. In particular, the spatial disaggregation of emission rates per 6x6 km^2 is performed using high-resolution, source-specific, open-access spatial proxies. In RI-URBANS specific developments were made to the downscaling approach for road vehicles, off-road activities, industry and shipping. In particular, the high-resolution spatial disaggregation proxies were enriched, incorporating the geolocation of industrial sites, ship lanes, the railway network and others. These efforts however require large efforts in order to produce accurate proxies at such high resolution over urban areas. It is therefore recommended to inmprove the collection of georeferenced information (e.g. road transportation data) at European level.

Subsequently, the downscaled 1x1 km^2 emission inventories were compared to local bottom-up emission inventories that were collected for a total of 13 urban areas, including 10 RI-URBANS pilot cities, for the sectors road transport and residential combustion. Results showed that for road transport NO_x Emissions were higher for all local inventories, suggesting an underestimation in the European-scale inventories. For PM emissions in the majority of cases the European-wide inventories resulted in higher emissions, related to the variety between cities in the use of wood burning within city boundaries.

Based on these findings, the spatial distribution for road transport in the European scale inventory was revised. Open Street Map was used to identify all individual roads, which was complemented by information on road intensities from Open Transport Map (Jedlička et al., 2016) where available, complemented by a machine learning approach to gapfill traffic intensities for other roads. The new spatial distribution method was used to update European-wide 6x6 km$_2$ emissions, which were subsequently downscaled using the UrbEm approach, further refined with an improved allocation of road emissions per road type. The new results were found to be significantly more consistent with local and independent bottom-up inventories.

The RI-URBANS European emission inventory can be obtained either directly via an FTP repository, using the details provided below. Once logged in, the final version should be selected (folder: “Final_inventory_Apr2024”) where separate emission grids can be accessed for size-speciated UFP emissions and for emissions of main pollutants, respectively. In addition, speciation profiles for PM and NMVOC can be obtained as well as simple time profiles and a default vertical distribution for emissions.

Host : web-ftp81.tno.nl

Protocol : FTP

Encryption : Require explicit FTP over TLS

Logon type : normal

Login : RI-URBANS@ftp0015.web-ftp81

Password : BDO1J9O5oYz8

In case of any questions or problems accessing the data, please contact Jeroen.Kuenen@tno.nl or Marya.ElMalki@tno.nl.

The urban (1x1km^2) emission datasets for Amsterdam, Athens, Birmingham and Helsinki can also be obtained via the above FTP repository (sub-folder: “Final_inventory_Apr2024/1x1km2”). In case of any questions or requests for data from other pilot cities of RI-URBANS, please contact Eleni Athanasopoulou (eathana@noa.gr).

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