CAMS-REG-v4: a state-of-the-art high-resolution European emission inventory for air quality modelling

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**Supplementary information**

This document contains 3 chapters where more detail is provided on specific aspects. For the tables S1-S7, please refer to the Excel file of the SI. Given the overlap in table numbering with the tables in the Excel file, table numbering in this document starts from Table S8.

Contents

[1. Emissions from combustion in other energy industries 2](#_Toc77250341)

[2. Agricultural waste burning emissions 5](#_Toc77250342)

[3. Road transportation 10](#_Toc77250343)

# Emissions from combustion in other energy industries

Within the energy sector, emissions from combustion are to a large part the result of emissions from power and heat plant and from refineries. However, there are other energy industries where fuel is combusted. The most important of these activities in Europe are coal mines, oil extraction, gas extraction and coke ovens. Reporting of these in national inventories however is in most cases for the aggregated sector “Other energy industries” as a whole (CRF and NFR category 1A1c). Only for greenhouse gases this split is available for specific countries (not all), and the different subsectors are also not reported in a consistent manner.

For a proper spatial distribution of the emissions from other energy industries, a split between the different sectors is necessary. Therefore, the reported emissions collected at the aggregated level of “other energy industries” (CRF/NFR 1A1c) have been disaggregated to the most important 4 activities mentioned here. To split (reported) emissions, a bottom-up inventory has been constructed based on the IEA Energy Balances (2019 edition) combined with default emission factors.

The IEA Energy Balances provide annual energy consumption for each of the sectors per country and per fuel, for the period 1960-2017. The emission factors have been based on available literature and expert judgement, and are shown in Table S8.

Oil and gas production are shown together as one sector (Oil and gas extraction), and have been split into oil and gas production (separately) using the total annual production of oil and gas, which is also available from the IEA Energy Balances.

Table S8: Emission factors (in g/GJ) per fuel, applied for all sectors unless otherwise specified

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **CH4** | **CO** | **NMVOC** | **NOx** | **PM** | **SO2** |
| ANTCOAL | 10 | 150 | 20 | 300 | 35 | 1500 |
| BITCOAL | 10 | 150 | 20 | 300 | 35 | 1500 |
| BKB | 10 | 150 | 20 | 300 | 35 | 1500 |
| BLFURGS\* | 4 |  | 0 |  |  | 50 |
| COALTAR | 3 | 100 | 3 | 150 | 35 | 2500 |
| COKCOAL | 10 | 150 | 20 | 300 | 35 | 1500 |
| COKEOVGS\* | 4 |  | 0 |  |  | 50 |
| CRUDEOIL | 3 | 15 | 3 | 195 | 35 | 750 |
| ETHANE | 4 | 20 | 4 | 145 | 0.1 | 0 |
| GASWKSGS | 4 | 50 | 1 | 400 | 0.1 | 0 |
| INDWASTE | 3 | 100 | 3 | 150 | 35 | 2500 |
| LIGNITE | 10 | 150 | 20 | 300 | 35 | 1500 |
| LPG | 1 | 200 | 20 | 1400 | 1 | 50 |
| LUBRIC | 3 | 100 | 3 | 150 | 35 | 2500 |
| NAPHTHA | 1 | 200 | 20 | 1400 | 1 | 50 |
| NATGAS\* | 4 |  |  |  | 0.1 | 0 |
| NGL | 1 | 200 | 20 | 1400 | 1 | 50 |
| OBIOLIQ | 1 | 200 | 20 | 1400 | 1 | 400 |
| ONONSPEC | 3 | 15 | 3 | 195 | 35 | 2500 |
| OTHKERO | 1 | 200 | 20 | 1400 | 1 | 400 |
| OVENCOKE | 10 | 150 | 20 | 300 | 35 | 1500 |
| PEAT | 10 | 150 | 20 | 300 | 35 | 1500 |
| PETCOKE | 10 | 150 | 20 | 300 | 35 | 1500 |
| REFINGAS | 4 | 50 | 1 | 1700 | 1 | 400 |
| RESFUEL | 3 | 15 | 3 | 195 | 35 | 2500 |
| SUBCOAL | 10 | 150 | 20 | 300 | 35 | 1500 |
| WHITESP | 1 | 200 | 20 | 1400 | 1 | 400 |
| NONBIODIES | 3 | 15 | 3 | 195 | 35 | 2500 |
| PRIMSBIO | 10 | 150 | 20 | 300 | 35 | 1500 |
| NONBIOGASO | 3 | 15 | 3 | 195 | 35 | 2500 |
| OGASES\* | 4 |  | 0 |  |  | 50 |
| OILSHALE | 3 | 15 | 3 | 195 | 35 | 750 |
| PARWAX | 3 | 15 | 3 | 195 | 35 | 2500 |
| NONBIOJETK | 3 | 15 | 3 | 195 | 35 | 2500 |
| PEATPROD | 10 | 150 | 20 | 300 | 35 | 1500 |
| BIOGASES | 4 | 20 | 0 | 120 | 5 | 50 |
| MUNWASTEN | 3 | 100 | 3 | 150 | 35 | 2500 |
| MUNWASTER | 3 | 100 | 3 | 150 | 35 | 2500 |

For selected fuels (marked with an asterisk in Table S8), sector specific emission factors were used as shown in Table S9.

Table S9: Sector specific emission factors for selected fuels and pollutants

|  |  |  |
| --- | --- | --- |
| **Fuel** | **Pollutant** | **Emission factors** |
| BLFURGS | CO | Coke ovens: 20 g/GJ  Coal mines: 50 g/GJ |
| NOx | Coke ovens: 75 g/GJ  Coal mines: 400 g/GJ |
| PM | Coke ovens: 5 g/GJ  Coal mines: 1 g/GJ |
| COKEOVGS | CO | Coke ovens: 20 g/GJ  Coal mines: 50 g/GJ |
| NOx | Coke ovens: 120 g/GJ  Coal mines: 400 g/GJ |
| PM | Coke ovens: 5 g/GJ  Coal mines: 1 g/GJ |
| NATGAS | CO | Coke ovens: 20 g/GJ  Coal mines: 50 g/GJ  Oil and gas extraction: 50 g/GJ |
| NMVOC | Coke ovens: 4 g/GJ  Coal mines: 1 g/GJ  Oil and gas extraction: 1 g/GJ |
| NOx | Coke ovens: 145 g/GJ  Coal mines: 400 g/GJ  Oil and gas extraction: 400 g/GJ |
| OGASES | CO | Coke ovens: 20 g/GJ  Coal mines: 50 g/GJ |
| NOx | Coke ovens: 120 g/GJ  Coal mines: 400 g/GJ |
| PM | Coke ovens: 5 g/GJ  Coal mines: 1 g/GJ |

The resulting bottom-up was used to split the emissions from category 1A1c as obtained from reported data or from GAINS.

Figure S1 shows the average share of the subsectors for the year 2017, as calculated from the bottom-up approach described above. It shows that oil and gas extraction (here merged together) are the main contributor for most pollutants. For PM and SO2 on the other hand, coal mines are the most important subsector in terms of emissions. It should be noted though that this split is a weighted average between countries, and given that the importance of the sectors varies considerably between countries (e.g. some countries do not produce any gas or oil), the shares of individual countries also show strong variations.

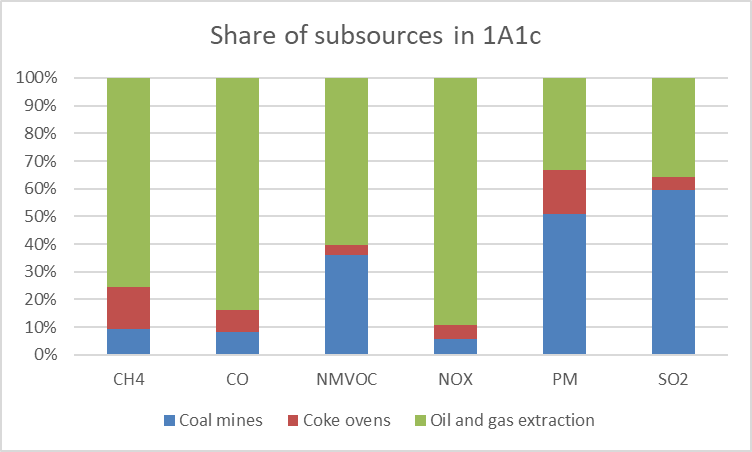


Figure S1: Contribution of coal mines, coke ovens and oil and gas extraction to the emissions in 1A1c (Other energy industries)

# Agricultural waste burning emissions

Open biomass burning, also referred to as vegetation fires, is combustion of organic matter in various ecosystems on Earth. It can stem from naturally occurring fires, e.g. in savannahs and boreal forests, as well as anthropogenic influenced fires, e.g. during deforestation and agricultural waste burning (AWB) such as burning of crop stubble. In the EU28 agriculture waste burning is not allowed, however, it still occurs. So, while this activity has been reduced in Europe, it is now complicated to get consistent estimates from official reporting by countries. Therefore, agriculture waste burning emissions in the CAMS European regional emission inventory (CAMS\_REG) and its predecessors (TNO\_MACC inventories; Kuenen et al., 2014) have been taken directly from the GAINS model (Amann et al., 2011), and more specifically, the scenario TSAP\_Mar13\_CLE was used. These emission estimates are highly uncertain due to the aforementioned lack of data, do not have a geographical location other than the country to which they are assigned and do not vary between years. In the new CAMS-REG v4 it was decided to use a new source of information; the CAMS Global Fire assimilation system (<https://atmosphere.copernicus.eu/global-fire-emissions>). The CAMS Global Fire Assimilation System (GFAS) assimilates fire radiative power (FRP) observations from satellite-based sensors to produce daily estimates of wildfire and biomass burning emissions ( Kaiser et al., 2012. ) FRP observations currently assimilated in GFAS are the NASA Terra MODIS and Aqua MODIS active fire products (<http://modis-fire.umd.edu/>). Data are available globally on a regular lat-lon grid with horizontal resolution of 0.1 degrees from 2003 to present. Virtually all land masses except deserts, ice and permafrost are affected by fires (Figure S2). This includes many agricultural areas, in which agricultural waste burning (AWB) remains an active practice, often against despite being officially banned.

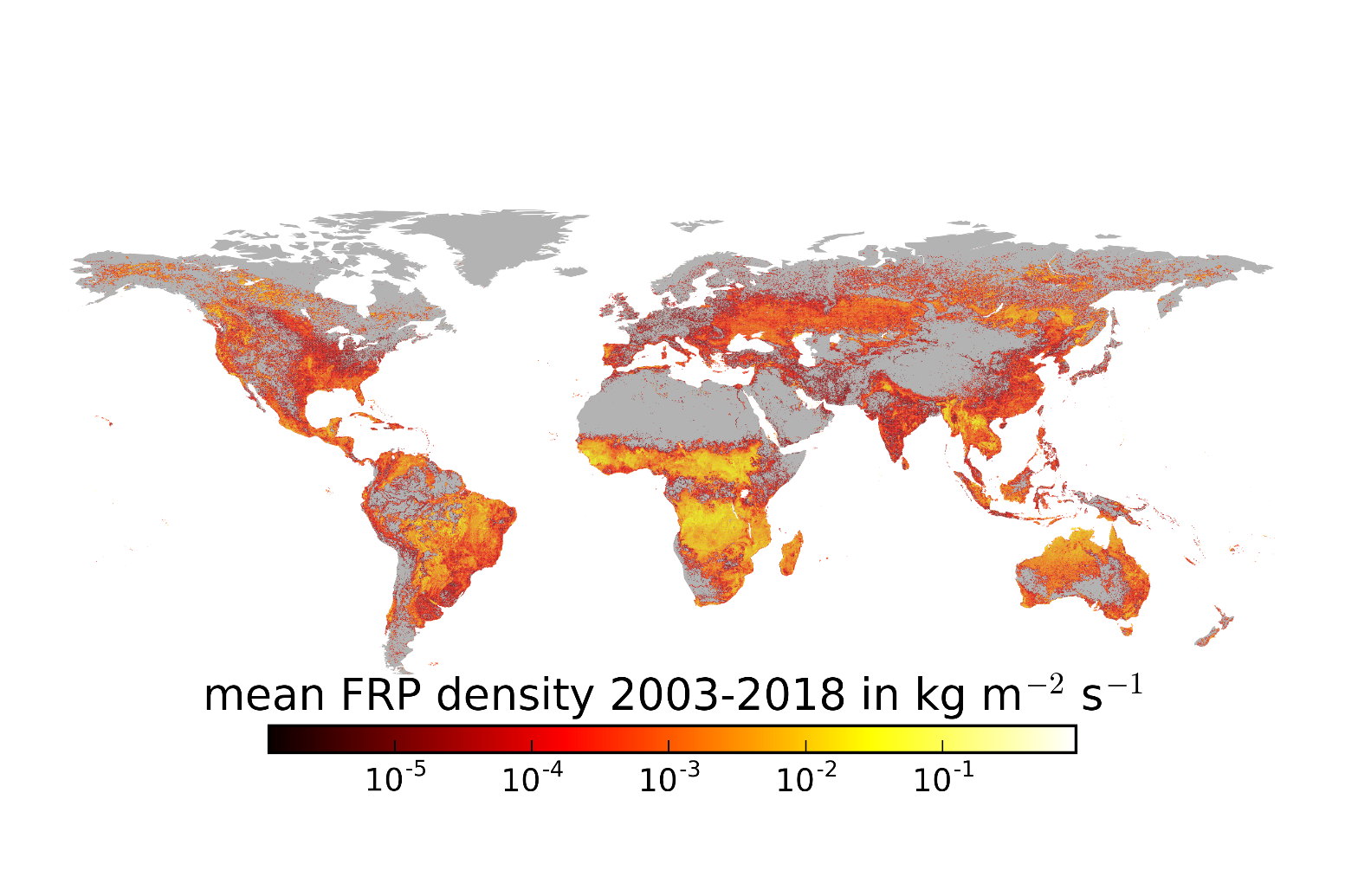


Figure S2: Global distribution of total mean Fire Radiative Power (FRP) density of mean daily values of the years 2003-2018 analysed using GFASv1.2. based on assimilated MODIS-Terra and Aqua and gridded to a 0.1° x 0.1°. Colours indicate mean FRP density as indicated in the colour bar. (Gehrke et al., 2019; Kaiser et al, 2012; (<https://atmosphere.copernicus.eu/global-fire-emissions>).

Compared to the inventories, the main strengths of GFAS are the abilities to localise AWB geographically and to represent strong interannual, and supposedly daily, variability. This originates from its use of actual fire observations. The attribution of detected fires to different types of vegetation fires is performed with a fixed land cover map that has been derived from the dominant fire types in the GFED3.1 dataset and several maps of organic soils (OS) and peat (Randerson et al. 2013). The main weakness of using GFAS for quantification of AWB emission in Europe is the attribution of observed fires to the correct (agricultural) land use. Otherwise wildfires or non-agricultural fires may be misinterpreted as AWB. In CAMS-REGv4 we use the land cover map based on the ESA CCI land cover database (https://www.esa-landcover-cci.org/). The 300 m-resolution ESA CCI map was re-gridded to the 0.1° resolution used in GFAS by calculating the percentage of agricultural land cover types in each 0.1° grid cell. The ESA CCI land cover mask includes areas with different levels of cropland density. By re-gridding to a 0.1° resolution the contribution to any given grid cell is calculated and it can be very small compared to the overall size of the grid cell. To assess the influence of different thresholds in agricultural contributions Gehrke et al. (2019) tested three different percentages, i.e. 55% agricultural coverage, 75% and 85%. Based on the results of this comparison a mask for agriculturally dominated land was generated by considering only grid cells with at least 85% of agricultural coverage. WE refer to Gehrke et al (2019 for more details). The estimated CO emissions from AWB per month for 5 years based on the GFAS system in combination with the ESA-CCI land use map with at least 85% of agricultural coverage in the re-gridded 0.1° resolution grid cells is shown in Figure S3. The data show a variation in the monthly budgets between the years. This variation is especially high in the beginning (March) or end (September, October) of the fire season.

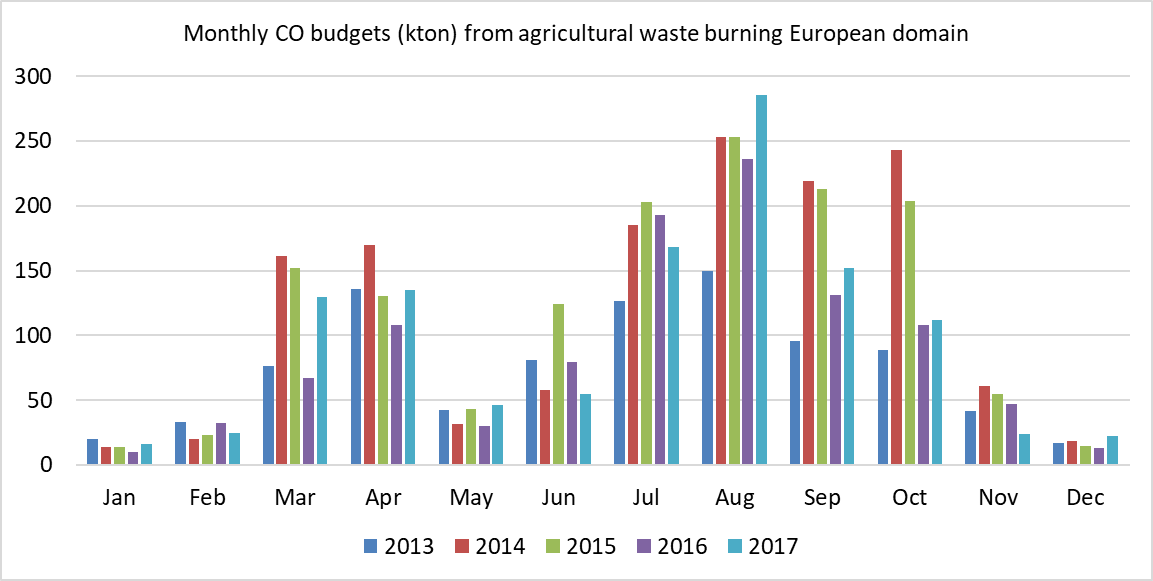


Figure S3: CO emission (kt/year) from agricultural waste burning in Europe for the years 2013-2017 derived from the GFAS system in combination with a ESA-CCI land use map

Based on the data in Figure S3 a monthly emission fraction as well as an average emission was derived. The AWB emissions in the new CAMS-REGv4 timeseries are kept constant throughout the 2000-2017 period because no consistent trends could be identified and the earth observation data to provide good estimates for individual years prior to 2013 seem limited or not available. A temporal monthly emission profile was derived from Figure S2 with low emissions in November to February and peaks in March-April and August-October (Table S10).

Table S10: Time profile for AWB in Europe based on data shown in Figure S3.

|  |  |
| --- | --- |
| Month | Fraction of annual emission derived from years 2013-2017 |
| Jan | **0.01** |
| Feb | **0.02** |
| Mar | **0.11** |
| Apr | **0.13** |
| May | **0.03** |
| Jun | **0.06** |
| Jul | **0.14** |
| Aug | **0.20** |
| Sep | **0.13** |
| Oct | **0.12** |
| Nov | **0.04** |
| Dec | **0.01** |
| **Total** | **1** |

The data by country that were made available by GFAS are with a 85% threshold in the pixels where fires are observed (Table S11). This implies that only when at least 85% of the pixel is agriculture the observed fire is attributed to AWB. This is rather conservative; in the future we may also consider a 70% cut-off. The fact that we are now able to attach time and place to the emissions will make it more likely that over time these estimates can be verified. Moreover, we believe that over time the quality of the GFAS product will further evolve whereas there are no reasons why the previous (GAINS-based) AWB estimates would improve and become more certain.

Unfortunately the current GFAS estimates by country do not cover all countries. Especially several small countries lack a GFAS AWB estimate (red countries in Table S11). These countries were gapfilled using the new GAINS estimates multiplied by the ratio of the average European GFAS/ GAINS estimate by pollutant (effectively reducing them to ~30-40% of their original GAINS value). In the future we hope that these countries can be filled by GFAS estimates as well. Part of the reason for the incomplete coverage can be related to the 85% threshold. In small countries a mixture of land use within one pixel may be more often occurring than in very large countries.

A spatial distribution map for AWB emission was obtained by summing all gridded CO emissions from AWB for the years 2013-2017 and calculating the fraction of CO emission per grid cell per country. In this approach the total for every country is always 1. Hence by multiplying the fraction maps with the emissions from Table S11 a gridded emsision map is derived which has emissions on all locations where AWB occurred over the 5 year period.

Table S11: Emissions based on GFASv1.2. Modified GFAS (based on ESA-CCI- 85% cut-off) for year 2015 (kt/year) – CH4, NMVOC, NH3, PM10, SO2 are scaled to CO emissions using the emission factors for agricultural waste burning. Red countries have been gapfilled.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | CO2bf | PM2.5 | CO | NOx | CH4 | NMVOC | NH3 | PM10 | SO2 |
| Country | ALB | 17.6 | 0.07 | 0.82 | 0.03 | 0.09 | 0.12 | 0.02 | 0.08 | 0.003506 |
|  | AUT | 0.1 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.83E-05 |
|  | BEL | 1.4 | 0.00 | 0.05 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.000225 |
|  | BGR | 265.0 | 1.67 | 18.64 | 0.64 | 2.09 | 2.69 | 0.35 | 1.88 | 0.079298 |
|  | BIH | 4.6 | 0.01 | 0.17 | 0.01 | 0.02 | 0.02 | 0.00 | 0.02 | 0.000723 |
|  | BLR | 165.2 | 0.70 | 8.09 | 0.28 | 0.91 | 1.17 | 0.15 | 0.79 | 0.034405 |
|  | CHE | 23.2 | 0.13 | 1.50 | 0.15 | 0.17 | 0.22 | 0.03 | 0.15 | 0.006386 |
|  | CYP | 4.5 | 0.01 | 0.17 | 0.01 | 0.02 | 0.02 | 0.00 | 0.01 | 0.000702 |
|  | CZE | 3.3 | 0.01 | 0.14 | 0.00 | 0.02 | 0.02 | 0.00 | 0.01 | 0.000608 |
|  | DEU | 17.8 | 0.07 | 0.73 | 0.03 | 0.08 | 0.11 | 0.01 | 0.07 | 0.003106 |
|  | DNK | 3.1 | 0.01 | 0.13 | 0.00 | 0.01 | 0.02 | 0.00 | 0.01 | 0.00054 |
|  | ESP | 211.3 | 0.92 | 10.63 | 0.37 | 1.19 | 1.54 | 0.20 | 1.03 | 0.045241 |
|  | EST | 41.5 | 0.24 | 2.69 | 0.27 | 0.30 | 0.39 | 0.05 | 0.27 | 0.011445 |
|  | FIN | 1.0 | 0.00 | 0.07 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.000318 |
|  | FRA | 28.7 | 0.15 | 1.71 | 0.06 | 0.19 | 0.25 | 0.03 | 0.17 | 0.007258 |
|  | GBR | 3.9 | 0.02 | 0.18 | 0.01 | 0.02 | 0.03 | 0.00 | 0.02 | 0.000745 |
|  | GRC | 88.0 | 0.55 | 6.04 | 0.21 | 0.68 | 0.87 | 0.11 | 0.61 | 0.025701 |
|  | HRV | 2.1 | 0.01 | 0.08 | 0.003 | 0.01 | 0.01 | 0.00 | 0.01 | 0.000332 |
|  | HUN | 18.5 | 0.11 | 1.24 | 0.04 | 0.14 | 0.18 | 0.02 | 0.13 | 0.005267 |
|  | IRL | 33.9 | 0.12 | 2.20 | 0.22 | 0.25 | 0.32 | 0.04 | 0.14 | 0.009347 |
|  | ITA | 315.9 | 1.42 | 16.24 | 0.56 | 1.82 | 2.35 | 0.30 | 1.60 | 0.069074 |
|  | KOS | 12.4 | 0.05 | 0.58 | 0.02 | 0.07 | 0.08 | 0.01 | 0.06 | 0.002485 |
|  | LTU | 19.6 | 0.06 | 0.73 | 0.03 | 0.08 | 0.11 | 0.01 | 0.07 | 0.003118 |
|  | LVA | 59.1 | 0.34 | 3.82 | 0.38 | 0.43 | 0.55 | 0.07 | 0.38 | 0.016239 |
|  | MDA | 81.8 | 0.52 | 5.68 | 0.20 | 0.64 | 0.82 | 0.11 | 0.58 | 0.024165 |
|  | MKD | 13.2 | 0.06 | 0.68 | 0.02 | 0.08 | 0.10 | 0.01 | 0.06 | 0.002872 |
|  | MLT | 1.7 | 0.01 | 0.10 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00044 |
|  | MNE | 58.1 | 0.33 | 3.74 | 0.06 | 0.42 | 0.54 | 0.07 | 0.37 | 0.015926 |
|  | NLD | 0.6 | 0.01 | 0.04 | 0.001 | 0.00 | 0.01 | 0.00 | 0.01 | 0.000166 |
|  | NOR | 2.7 | 0.01 | 0.10 | 0.003 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00043 |
|  | POL | 47.8 | 0.29 | 3.21 | 0.11 | 0.36 | 0.46 | 0.06 | 0.32 | 0.013635 |
|  | PRT | 46.0 | 0.19 | 2.06 | 0.07 | 0.23 | 0.30 | 0.04 | 0.21 | 0.008768 |
|  | ROU | 318.2 | 2.00 | 22.06 | 0.76 | 2.47 | 3.19 | 0.41 | 2.26 | 0.093835 |
|  | RUS | 6754.3 | 40.02 | 453.03 | 15.62 | 50.77 | 65.47 | 8.40 | 45.11 | 1.927349 |
|  | SRB | 79.7 | 0.48 | 5.25 | 0.18 | 0.59 | 0.76 | 0.10 | 0.54 | 0.022344 |
|  | SVK | 1.1 | 0.01 | 0.08 | 0.00 | 0.01 | 0.01 | 0.00 | 0.01 | 0.000323 |
|  | SVN | 6.0 | 0.03 | 0.39 | 0.04 | 0.04 | 0.06 | 0.01 | 0.04 | 0.001642 |
|  | SWE | 2.0 | 0.01 | 0.11 | 0.004 | 0.01 | 0.02 | 0.00 | 0.01 | 0.000459 |
|  | TUR | 3899.6 | 19.91 | 227.14 | 7.83 | 25.46 | 32.83 | 4.21 | 22.44 | 0.966348 |
|  | UKR | 5528.4 | 33.95 | 374.51 | 12.91 | 41.97 | 54.13 | 6.94 | 38.27 | 1.593319 |
|  | **Sum** | **18182.7** | **104.51** | **1174.81** | **41.15** | **131.66** | **169.79** | **21.78** | **117.78** | **5.00** |

**References**

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# Road transportation

Emissions from road transportation are obtained from reported data or from the GAINS model. These provide emissions at different level of sectoral detail.

Reported data distinguish 4 different vehicle categories:

* 1A3bi Passenger cars
* 1A3bii Light duty vehicles
* 1A3biii Heavy duty trucks + buses
* 1A3biv Two-wheelers

GAINS provides emission data for 6 vehicle categories, where heavy duty trucks and buses are individually included and two-wheelers are split into motorcycles and mopeds. Using the information from GAINS, reported data are disaggregated to these 6 different vehicle categories.

Subsequently, also the road types (urban, rural, highway) have been introduced since the distribution of emissions will take these into consideration. The shares of each road type per vehicle category were obtained from information received from EMISIA / University of Thessaloniki (personal communication) on the vehicle kilometers for each of the 6 vehicle categories and 3 road types. For each country and vehicle type the share of each road type in the total vehicle kilometers was used to distribute emissions for each pollutant. The vehicle kilometers used in this split are consistent with those used in the COPERT model (Ntziachristos et al. 2009) and made available by EMISIA (www.emisia.com). The COPERT model is an emission model which is widely used to calculate air emissions from road transport activities in European countries, and for Europe as a whole.

**References**

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