CO2MVS RESEARCH ON SUPPLEMENTARY OBSERVATIONS

CORSO
CO2MVS Research on Supplementary Observations

D1.1 Global maps of CO_2, CO and NOx emission factors and their uncertainties per sector for the year 2021

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1 Executive Summary

This work has been done as part of WP1, which aims to improve the estimation of emission factors (EF) and emission ratios for CO_2 and co-emitted species (NOx, CO) across key sectors, including road transportation, energy, industry and residential, for the year 2021. The emission uncertainty ranges derived in WP1 will be used as inputs to the global IFS-based CO2MVS system for constructing the prior emission error covariance matrix (B matrix) in WP2.

This report supports the objectives of Task 1.1.a of WP1, which proposes to compile EF and develop a first source-dependent global map of EF and associated uncertainties for key sources. In this report, we detail the methodology used to determine national EF, estimate uncertainties, and produce global ASCII and gridded files containing these results. The uncertainties in EFs are mainly due to the limited availability of local data. We have started the data collection on the road transportation sector. While the study primarily targets the year 2021, due to data constraints, the most recent EFs values from earlier years are used for certain countries.

The resulting dataset is provided in both CSV and gridded NetCDF formats, including average EF values, associated errors, and the lower and upper uncertainty bounds. The files are temporary available at the following link: https://drive.google.com/drive/folders/15EwhEfYYfb-4HtVfEx4nORpXHZACAzqY?usp=drive_link and will be shared on the Confluence.

The methodology described in this report, developed as part of CORSO WP1, will also be applied to the energy and residential sectors in priority and, if time allows, to industrial activities. The results of this work will be included in Milestone 3 due in month 30.

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2 Introduction

2.1 Background

To enable the European Union (EU) to move towards a low-carbon economy and implement its commitments under the Paris Agreement, a binding target was set to cut emissions in the EU by at least 40% below 1990 levels by 2030. European Commission (EC) President von der Leyen committed to deepen this target to at least 55% reduction by 2030. This was further consolidated with the release of the Commission's European Green Deal on the 11th of December 2019, setting the targets for the European environment, economy, and society to reach zero net emissions of greenhouse gases in 2050, outlining all needed technological and societal transformations that are aiming at combining prosperity and sustainability. To support EU countries in achieving the targets, the EU and European Commission (EC) recognised the need for an objective way to monitor anthropogenic CO_2 emissions and their evolution over time.

Such a monitoring capacity will deliver consistent and reliable information to support informed policy- and decision-making processes, both at national and European level. To maintain independence in this domain, it is seen as critical that the EU establishes an observation-based operational anthropogenic CO_2 emissions Monitoring and Verification Support (MVS) (CO2MVS) capacity as part of its Copernicus Earth Observation programme.

The CORSO research and innovation project will build on and complement the work of previous projects such as CHE (the CO_2 Human Emissions), and CoCO2 (Copernicus CO_2 service) projects, both led by ECMWF. These projects have already started the ramping-up of the CO2MVS prototype systems, so it can be implemented within the Copernicus Atmosphere Monitoring Service (CAMS) with the aim to be operational by 2026. The CORSO project will further support establishing the new CO2MVS addressing specific research & development questions.

The main objectives of CORSO are to deliver further research activities and outcomes with a focus on the use of supplementary observations, i.e., of co-emitted species as well as the use of auxiliary observations to better separate fossil fuel emissions from the other sources of atmospheric CO_2. CORSO will deliver improved estimates of emission factors/ratios and their uncertainties as well as the capabilities at global and local scale to optimally use observations of co-emitted species to better estimate anthropogenic CO_2 emissions. CORSO will also provide clear recommendations to CAMS, ICOS, and WMO about the potential added-value of high-temporal resolution $^{14}CO_2$ and APO observations as tracers for anthropogenic emissions in both global and regional scale inversions and develop coupled land-atmosphere data assimilation in the global CO2MVS system constraining carbon cycle variables with satellite observations of soil moisture, LAI, SIF, and Biomass. Finally, CORSO will provide specific recommendations for the topics above for the operational implementation of the CO2MVS within the Copernicus programme.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

The objective is to collect the emission factors (EFs) from the literature, determine their average values, and estimate their associated uncertainties at the national level for sectors such as road transportation, energy, industry and residential, with a particular focus on CO_2, CO and NOx for the year 2021.

The title of this deliverable is “Global maps of CO_2, CO and NOx EFs and their uncertainties per sector for the year 2021”. This deliverable includes seven files and this report which describes the methodology, but also shows the global maps for road transportation It contains the data for each species separately using CSV and gridded NetCDF as a file formats. WP2 will use these data in inverse modelling efforts and provide feedback on the current product.

2.2.2 Work performed in this deliverable

This deliverable was accomplished through a series of activities detailed in Section 3:

- Gathering the EF data containing emission factors (EFs)
- Formulating the methodology for determining national EFs and estimating their uncertainty
- Compiling the files containing the calculated average EF and their associated uncertainties.

2.2.3 Deviations and counter measures

The focus year is 2021, but due to the limited data availability, the earlier years have been considered for certain countries.

The initial plan was to develop EF maps for each sector, but collecting all the datasets for road transport took must longer than expected. EF data for the road transport sector is available from various sources, each with different units, formats, time periods, sub-sectors, metadata, etc. Harmonizing the data presented here required significant time and effort.

2.3 Project partners:

Partners	
EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS	ECMWF
AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	AGH
BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION	BSC
COMMISSARIAT A L’ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA
KAMINSKI THOMAS HERBERT	iLab
METEO-FRANCE	MF
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	TNO
RIJKSUNIVERSITEIT GRONINGEN	RUG
RUPRECHT-KARLS-UNIVERSITAET HEIDELBERG	UHEI
LUNDS UNIVERSITET	ULUND
UNIVERSITE PAUL SABATIER TOULOUSE III	UT3-CNRS
WAGENINGEN UNIVERSITY	WU
EIDGENOSSISCHE MATERIALPRUFUNGS- UND FORSCHUNGSANSTALT	EMPA

EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	ETHZ
UNIVERSITY OF BRISTOL	UNIVBRIS
THE UNIVERSITY OF EDINBURGH	UEDIN

3 Methodology

3.1 Gathering the emission factor (EF) data

The EF data comes from various sources such as the Intergovernmental Panel on Climate Change (IPCC, https://www.ipcc-nggip.iges.or.jp/EFDB/stat_tables.php), the Environmental Protection Agency (EPA, https://www.epa.gov/transportation-air-pollution-and-climate-change), the European Monitoring and Evaluation Programme / European Environment Agency (EMEP/EEA, https://efdb.apps.eea.europa.eu/), Dynamics Aerosol Chemistry Cloud Internationals in West Africa (DACCIWA), national statistics like the Chinese emission factor guidebook v3:

(https://www.mee.gov.cn/gkml/hbb/bgg/201501/W020150107594587831090.pdf)

and published papers. Most of them provides data at the regional level.

The data covers a wide range of sources, from global to specific, and points out time gaps between the study or reported year and when the data was published. The data is based on measurements, modeling, estimations, and expert judgment, with significant differences in sector or sub-sectors definitions across countries or data sources. The units may be different for the same sector. For example, for road transportation, EFs are provided in g/km or g/kg. A conversion between these two units was made using the following formula:

$$EF(g/km) = FC(kg/km) * EF(g/kg)$$

where FC represents fuel consumption with depends on multiple parameters including the vehicle category, fuel type, technology, vehicle size, etc. In this work, due to the lack of data specific to the different countries, the FC described by EMEP is considered for all countries (https://www.eea.europa.eu/publications/emep-eea-guidebook-2023).

Additionally, the unit of NOx is given in g of NO_2 or NO per km or kg. However, this information is generally not mentioned in the source materials. In this case, g of NO_2 is used as default.

The collection of EF data has focused on the road transportation sector (Figure 1). EFs were gathered for four vehicle categories and for different fuel types (diesel, petrol and others including natural gas, liquefied petroleum gas, bio-fuels, etc.) at the national level, specifically for NOx, CO and CO_2. The following vehicle types are considered:

- Passenger Cars (PC), include private vehicles used primarily for personal transportation.
- Light-Duty Vehicles (LCV), encompasses smaller commercial vehicles used for goods transportation.
- Heavy-Duty Vehicles (HDV), refer to larger commercial vehicles, such as trucks and buses, primarily used for heavy goods or passenger transport.
- Motorcycles (MOT), cover two-wheeled vehicles, primarily for individual transportation.

As previously mentioned, these definitions can be very different from one country to another.

While the focus is on the year 2021, due to data limitations, the most recent available EFs from previous years are used in some countries.

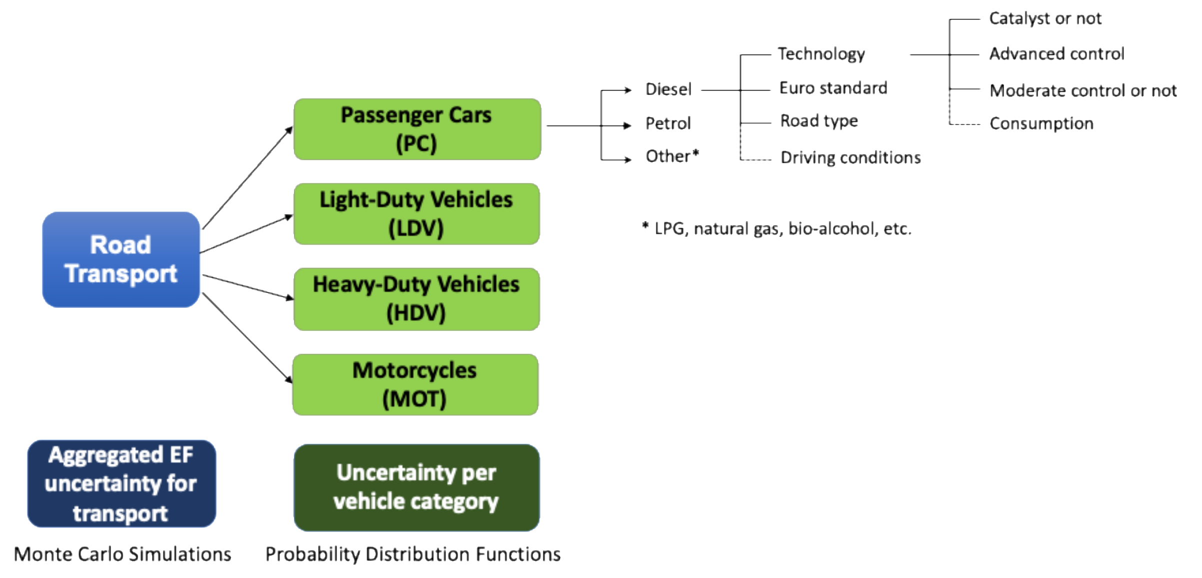


Figure 1: Schematic representation of the sub-sectors considered in the road transport sector.

Figure 2 displays a series of boxplots illustrating CO_2, NOx and CO EF for the defined vehicle categories and fuel types across different regions (2.a: Europe, 2.b: Germany, 2.c: the United States and 2.d: India) and datasets (EMEP, EPA, national statistics, published papers, etc.). Variations in EF are largely driven by differences in data sources, vehicle technology, road types (highways, national roads, etc.), driving conditions (hot, cold starts), Euro standards, time periods, and other factors taken into account in the dataset. The observed variations by country and region are also due to differences in regulatory and socio-economic factors including vehicle fleet composition in uses, which has been compiled and applied as a weighting factor for estimating the national average EF at countries where EF data does not exist.

Table 1 presents the average values derived from the boxplots. The average EF varies depending on the pollutant and region. For NOx, Diesel vehicles generally show higher EFs than Petrol, especially for LDV and HDV categories, while Petrol PC show relatively higher values. The “Other” category displays significant variability, reflecting the diversity of fuel types and technologies.

For CO_2 and CO, the highest average EFs are typically observed for Petrol PC and LDV, whereas for CO, this trend is true across all vehicle categories.

HDV display significantly higher EFs compared to other vehicle categories across all pollutants.

These results highlight that EFs are influenced by various factors, including combustion characteristics (temperature, air-fuel mixture), engine technology, vehicle age and other parameters. The EF data used includes these parameters to account for the substantial variability and provide an accurate uncertainty estimation.

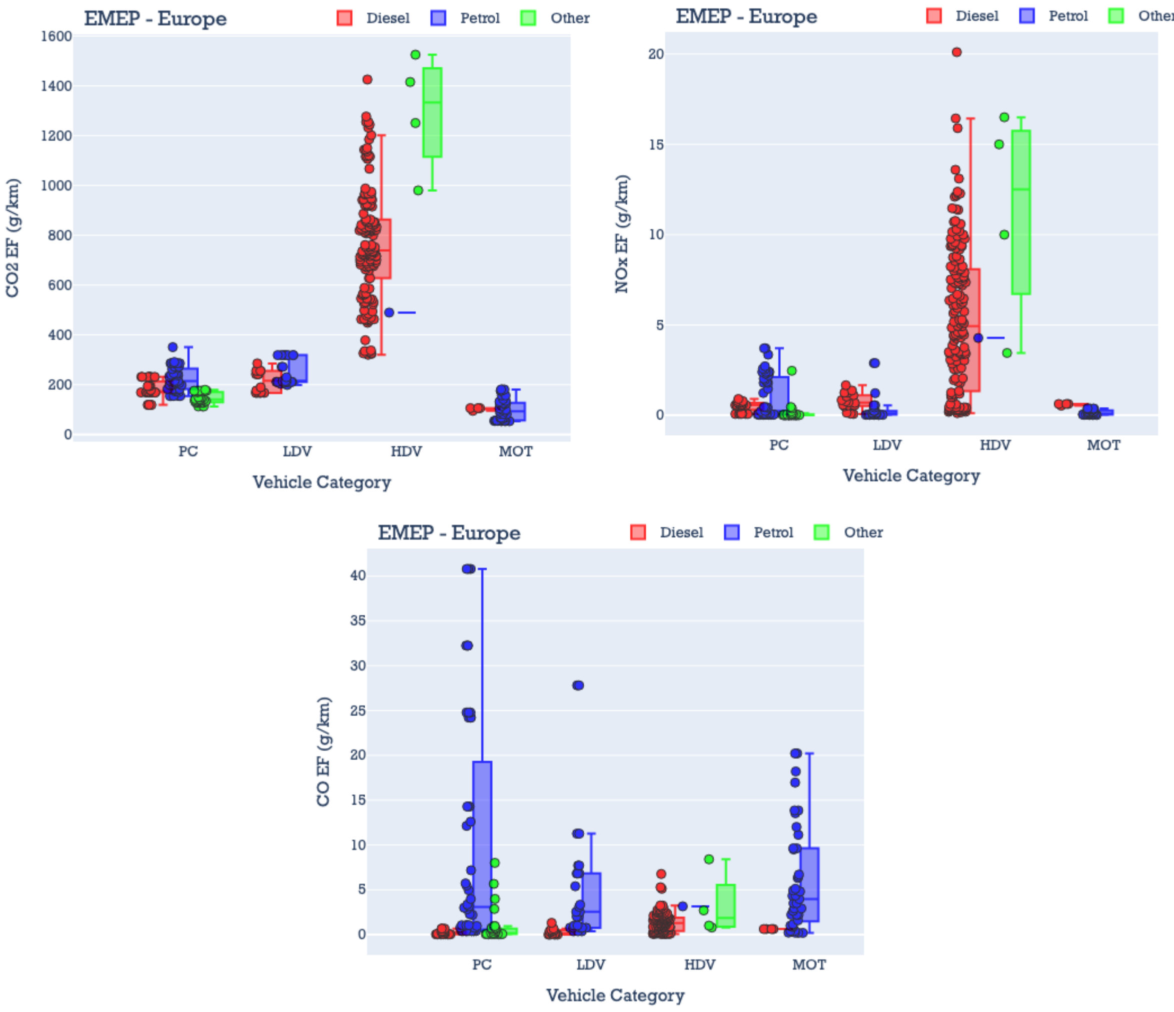
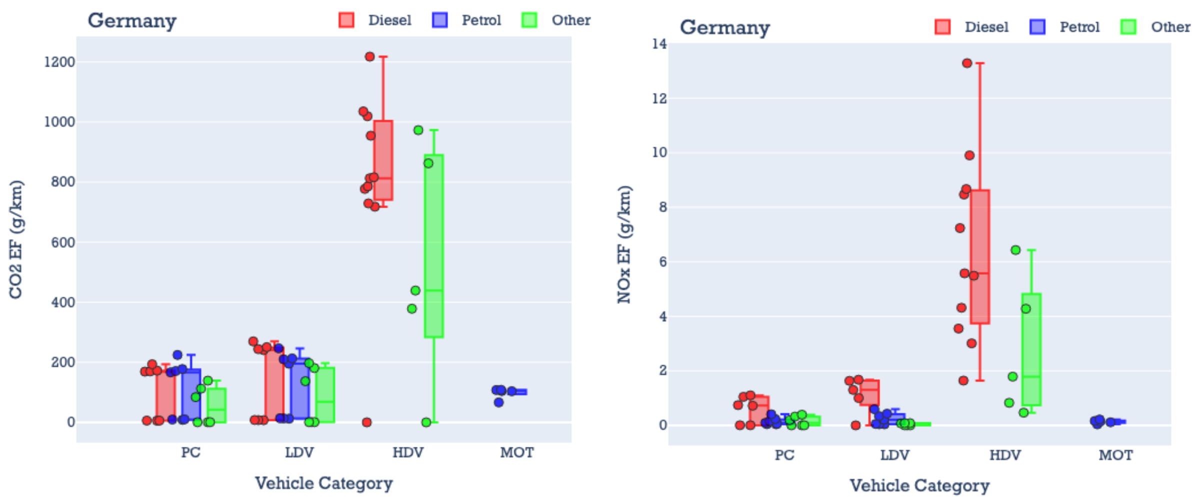


Figure 2.a: CO_2, NOx and CO EFs for Europe, compiled using local and regional data.



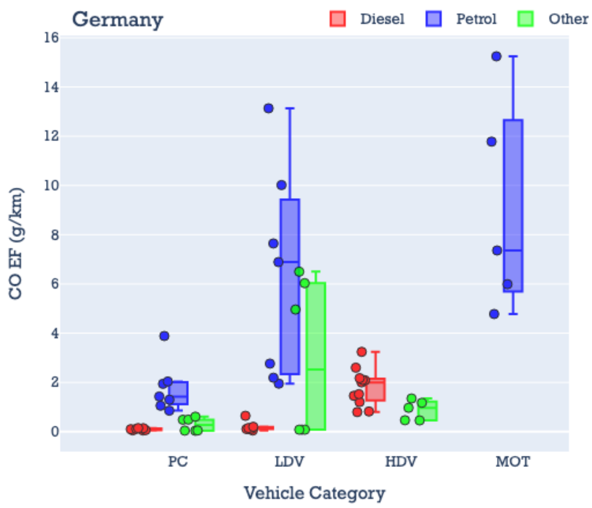


Figure 2.b: CO_2, NOx and CO EFs for Germany, compiled using local and regional data.

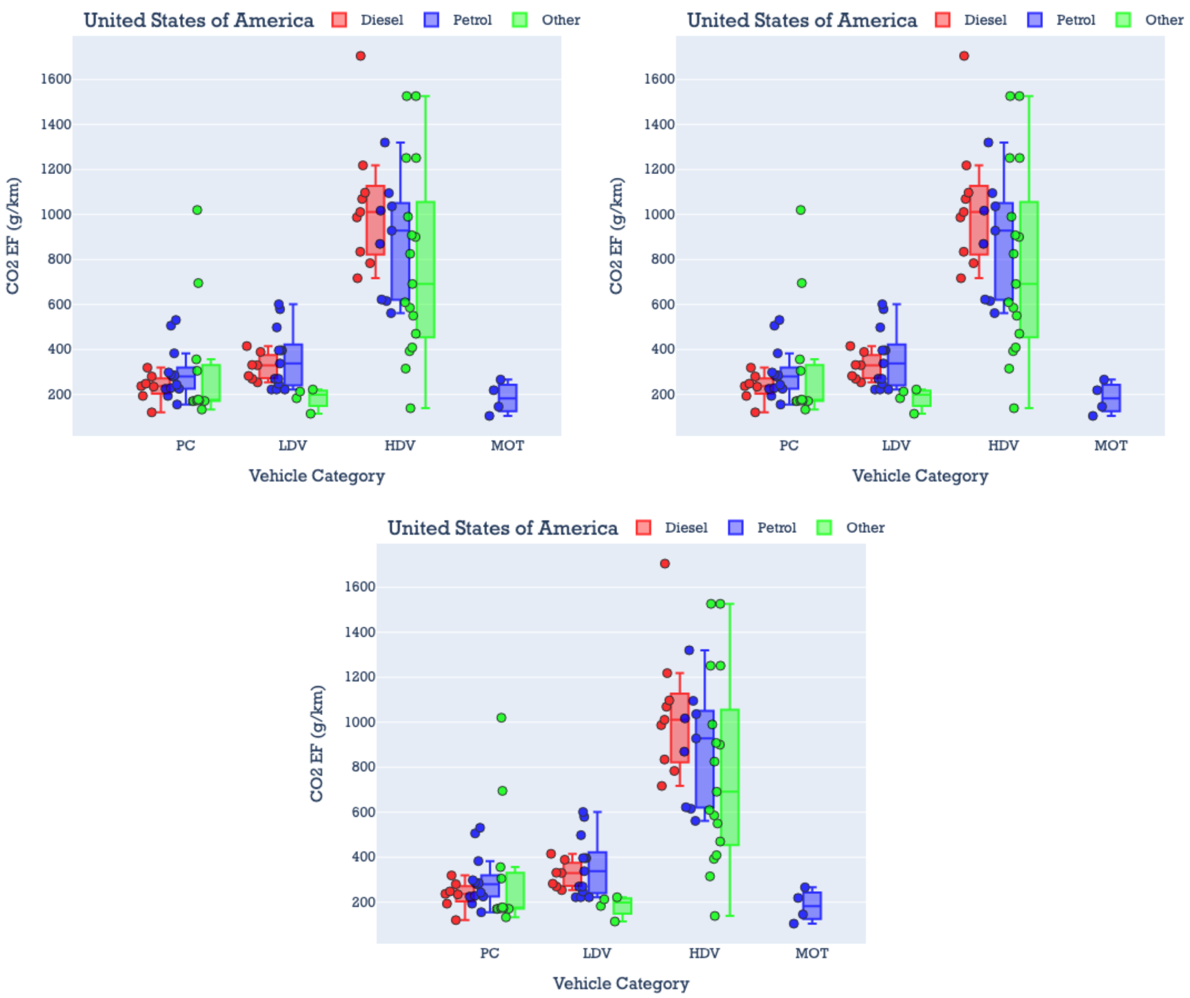


Figure 2.c: CO_2, NOx and CO EFs for the USA, compiled using local and regional data.

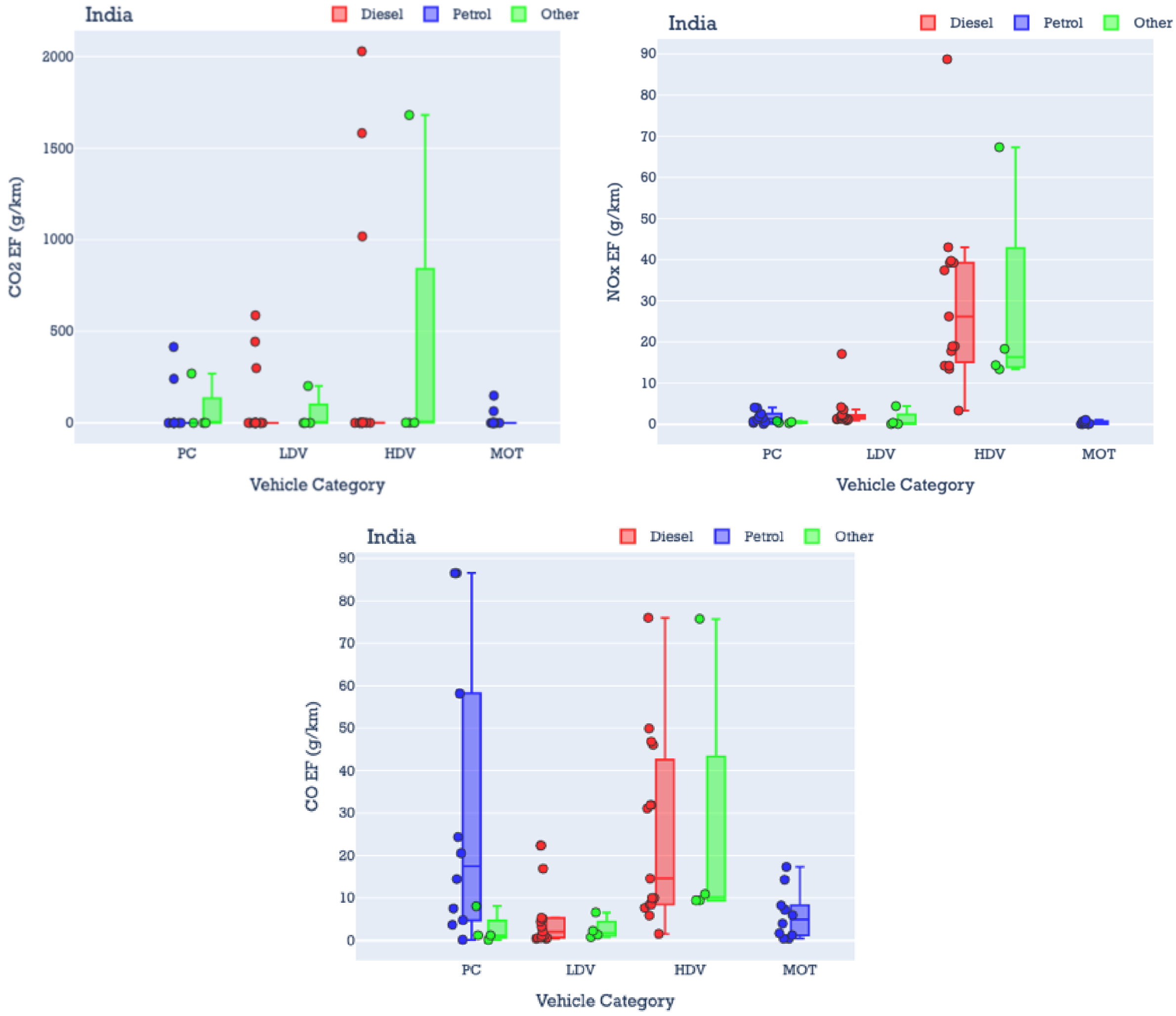


Figure 2.d: CO_2, NOx and CO EFs for the USA, compiled using local and regional data.

Table 1: Average EFs for NOx, CO_2 and CO across different vehicle categories (PC – Passenger Cars, LDV – Light Duty Vehicles, HDV – Heavy Duty Vehicles, and MOT – Motorcycles) and locations (EMEP – average over Europe, Germany, India and the USA).

	EMEP			Germany			India			USA		
	EF NOx											
	Diesel	Petrol	Other	Diesel	Petrol	Other	Diesel	Petrol	Other	Diesel	Petrol	Other
PC	0.40	1.00	0.11	0.60	0.15	0.15	-	1.67	0.49	0.42	0.56	1.54
LDV	0.76	0.38	-	1.12	0.24	0.04	2.92	-	1.22	0.75	0.56	0.41
HDV	5.35	4.28	11.24	6.47	-	2.76	30.25	-	28.34	5.14	1.87	9.70
MOT	0.60	0.15	-	-	0.13	-	-	0.31		-	0.30	-
	EF CO_2											
PC	180	222	146	103	110	56	-	66	68	233	296	310
LDV	212	248	-	147	129	86	89	-	50	324	358	183
HDV	762	489	1293	806	-	530	309	-	421	1047	896	785
MOT	103	99	-	-	98	-	-	21	-	-	184	-

	EF CO											
PC	0.17	10.21	0.74	0.09	1.78	0.28	-	30.67	2.65	1.15	9.54	4.77
LDV	0.28	5.28	-	0.19	6.37	2.95	5.78	-	2.73	0.95	9.34	2.55
HDV	1.33	3.15	3.22	1.82	-	0.88	25.35	-	26.36	2.60	31.64	6.56
MOT	0.62	6.03	-	-	9.03	-	-	6.08	-	-	11.10	-

3.2 Methodology to estimate uncertainties

The methodology used for estimating yearly uncertainties in EFs for each sector and country is represented in Figure 3.

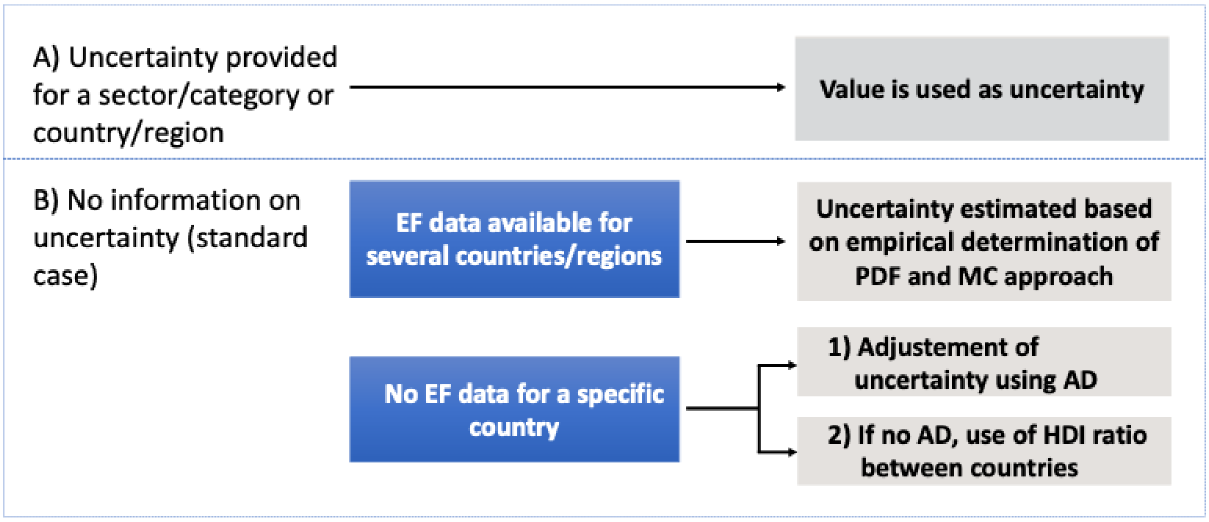


Figure 3: Methodology for estimating the EF uncertainty at country level for each sector.

If uncertainty values are already provided for a specific sector (road transport, energy, industry, residential) and country, they are used directly. In the absence of such information, one of the following approaches is applied:

- If multiple EF data is available for a country or region, statistical techniques such as probability distribution functions (PDFs) and Monte Carlo (MC) simulations, are used to estimate the uncertainties.
- If no EF data exists for a particular country, uncertainties are scaled using activity data (AD) of that country. When activity data are not available, the Human Development Index (HDI) ratio between countries is used as a proxy. Population size is also taken into account to ensure the comparison is made between countries with similar characteristics. An example of the correlations between the HDI and the Gross Domestic Product (GDP) is shown in Figure 4.

The structured approach we have used in this work helps address data gaps and provides consistency uncertainty estimates.

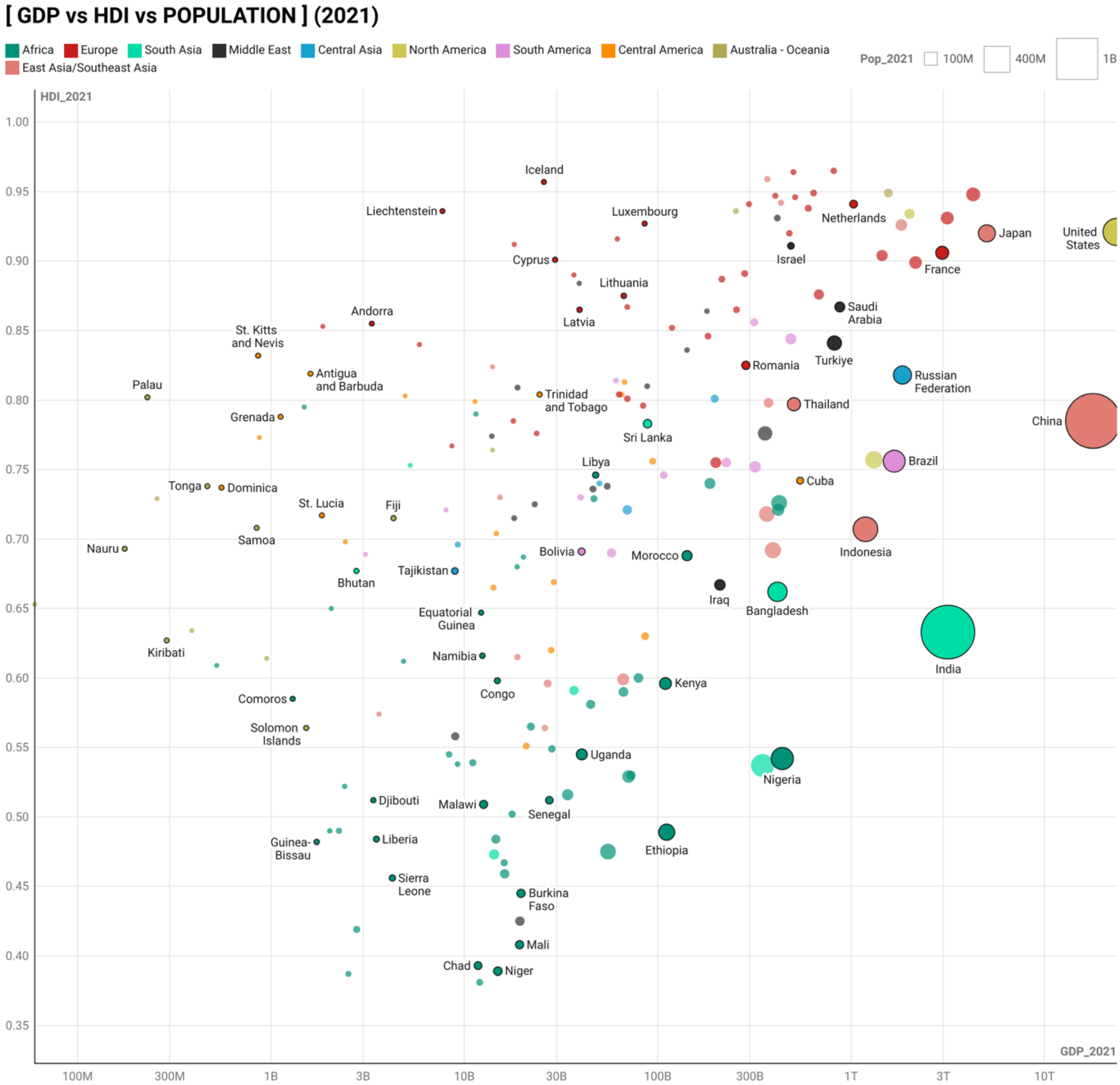


Figure 4: Human Development Index (HDI) versus Gross Domestic Product (GDP) as a function of the population size. These indicators are downloaded from the World Development Indicators (https://databank.worldbank.org/source/world-development-indicators).

The structured approach we have used helps addressing data gaps and provides reliable uncertainty estimates.

Figure 5 illustrates the probability density functions derived from computed normal or truncated (to prevent negative EF values) parameters. The Monte Carlo approach simulates variability using the input mean and standard deviation, enabling the generation of probabilistic uncertainty bounds (2.5th and 97.5th percentiles) accounting for approximately 95% of the values. The average uncertainty can be approximated as: (max - mean)/2, which is equivalent to 2*sigma. The figure displays calculations for the road transportation sector, covering various EF sub-sectors, such as PC, LDV, HDV and MOT.

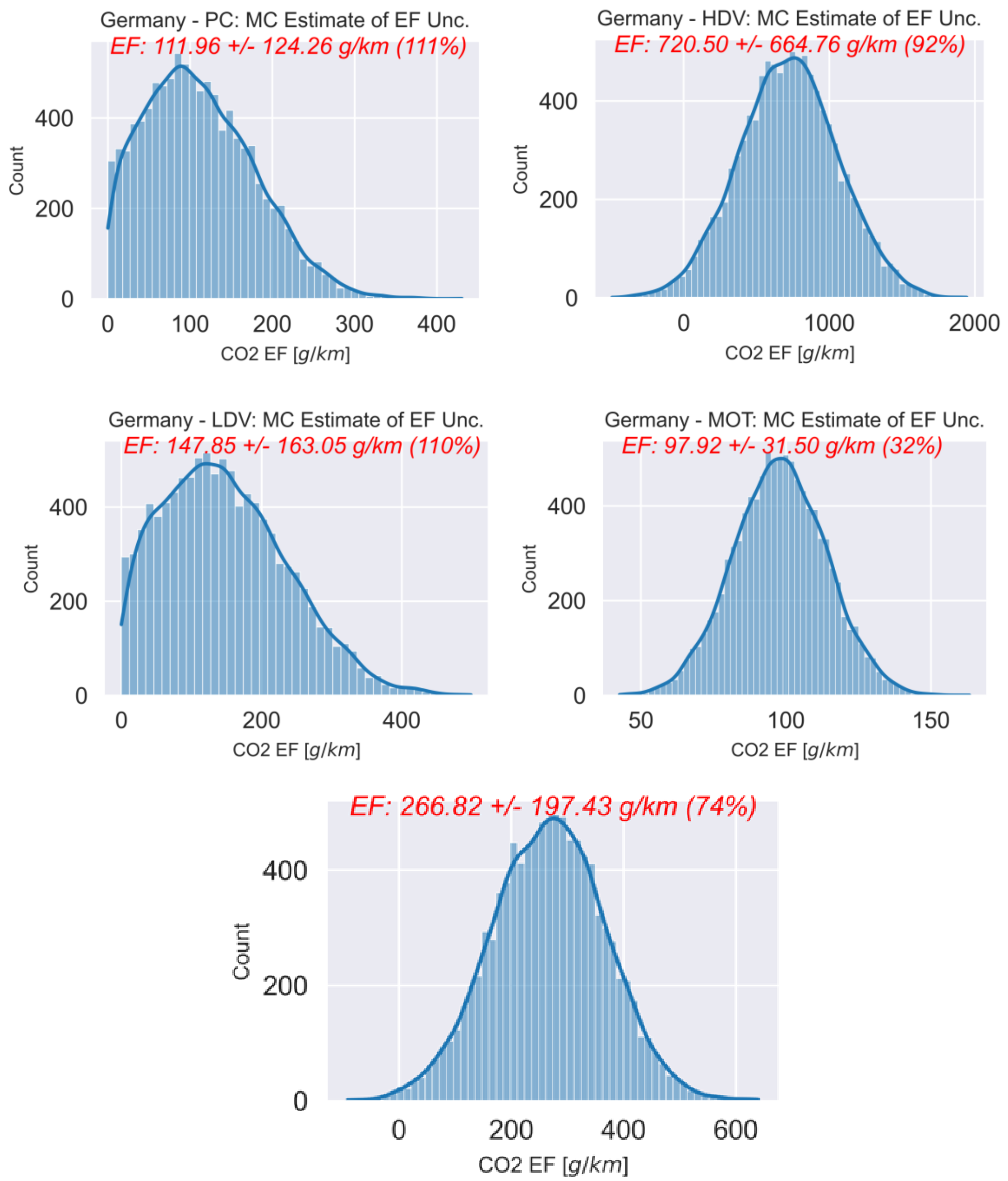


Figure 5: CO_2 EF uncertainty estimates in Germany based on probability distribution functions and Monte Carlo simulations. The figure at the bottom represents the aggregated distribution of all vehicle types.

As an example, the results for Germany, a developed country, are shown (Figure 5, bottom). The aggregated EF value is calculated to be 270 g/km, with an associated uncertainty of 74% (200 g/km). However, these values do not account for the composition of the vehicle fleet, which may significantly impact the average value. The number of vehicles in use by category in this work is obtained from various platforms, depending on the vehicle category and country. For example, we use the following references: World Road Statistics (https://datawarehouse.worldroadstatistics.org/dashboard/linegraph), Nation Master (https://www.nationmaster.com/nmx/ranking/vehicles-in-use), European Automobile Manufacturer's Association (ACEA, https://www.acea.auto/), International Organization of Motor Vehicle Manufacturers (OICA, https://www.oica.net/category/vehicles-in-use/), CEIC (https://www.ceicdata.com/), Statista (https://www.statista.com/), Eurostat (https://ec.europa.eu/eurostat/databrowser). When vehicle fleet composition (Table 2) is factored in, the average EF is reduced to 120 g/km, with the uncertainty decreasing to 46% (Figure 6). This reduction in uncertainty can be attributed to the lower standard deviation achieved through the use of a weighted average.

Table 2: Sample of vehicle fleet composition.

Country	PC	LDV	HDV	MOT
Faroe Islands	27 094	4 580	965	2 881
Fiji	113 588	19 972	1 880	13 544
Finland	2 755 349	343 927	105 247	249 992
France	37 880 000	5 977 000	686 000	3 620 700
Georgia	1 265 867	108 728	55 599	60 006
Germany	48 540 878	3 094 518	1 039 063	4 780 854
Ghana	723 598	378 356	66 769	893 263
Greece	5 604 192	944 308	253 605	1 675 804
Grenada	46 270	6 863	1 809	3 806
Guam	80 860	28 054	3 895	1 436
Guatemala	839 328	1 337 229	306 246	1 961 880
Guinea-Conakry	269 727	116 563	19 518	377 488
Honduras	405 075	678 111	221 319	1 084 706
Hong Kong	599 073	117 443	20 842	71 897
Hungary	4 020 159	499 641	155 731	202 521

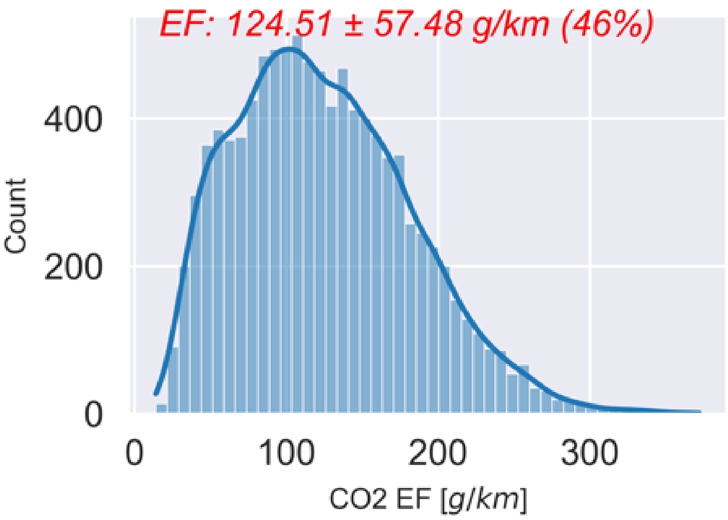


Figure 6: CO_2 EF uncertainty estimate in Germany taken into account the vehicle fleet composition.

3.3 Emission factors and associated uncertainties for road transportation

3.3.1 Adjusted emission factor using vehicle fleet composition and HDI

National EF data are unavailable for many countries, according to the species. For example, for the CO_2, most countries use same data from IPCC. In European countries, the CO_2 EF data is primarily from the COPERT v5.6 Guidebook (2022). To address the data gaps for countries with only activity data (vehicle fleet composition in the case of road transportation), a scaling approach has been used. Figure 7 shows the adjusted CO_2 EF across European countries by scaling EMEP data with vehicle fleet composition. Results indicated that the EF ranged from 170 to 250 g/km, with higher EF in the eastern Europe compared to the rest of the continent.

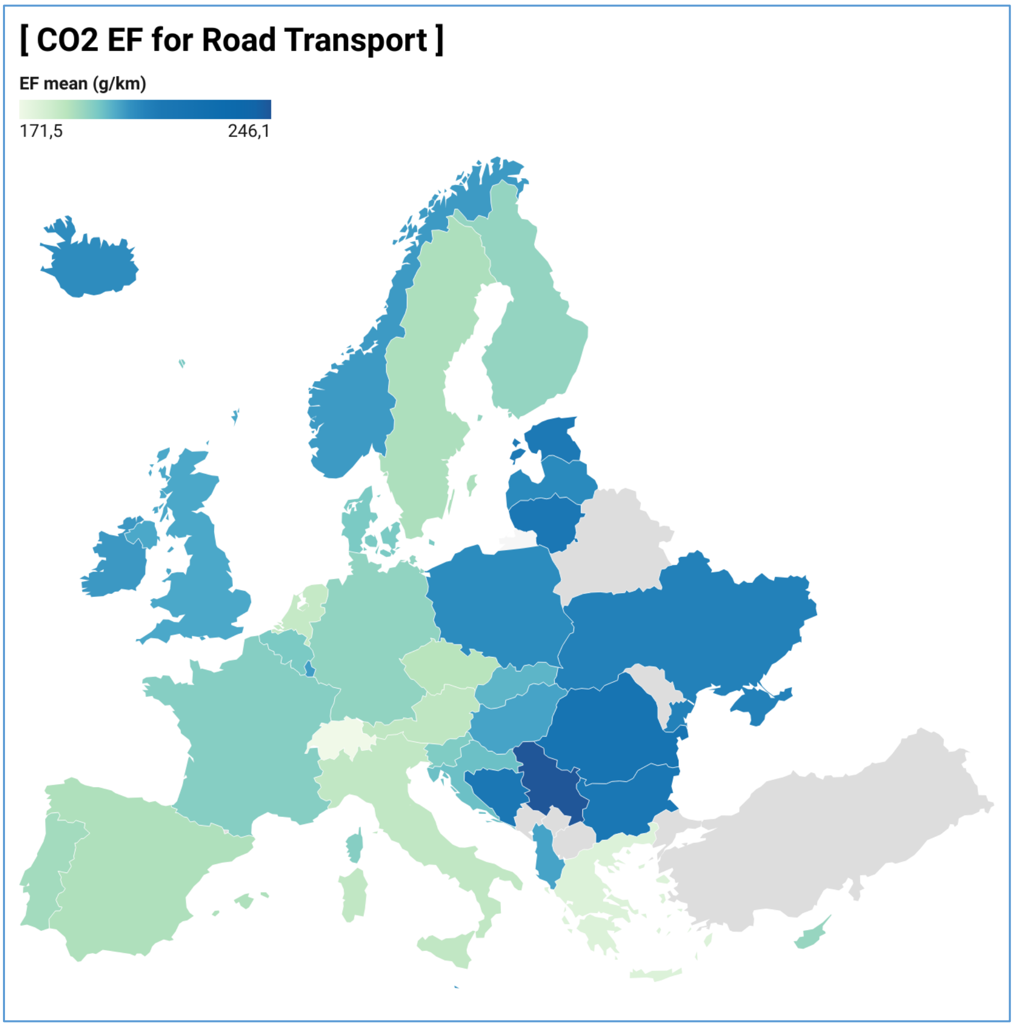


Figure 7: Adjusted CO_2 EF across European countries by scaling EMEP data with vehicle fleet composition.

The comparison of adjusted CO_2 EF derived from EMEP data with values from other sources (COPERT v5.6 Guidebook, 2022) shows a good agreement across datasets, with exceptions for countries such as Norway, Germany, Austria, Switzerland, Sweden and France, as shown in Figure 8. In these cases, the datasets include EF from specific sources such as lubricant oil usage and start modes, which have very low EF values, leading to greater variability compared to the EMEP data, as shown in Figure 9.

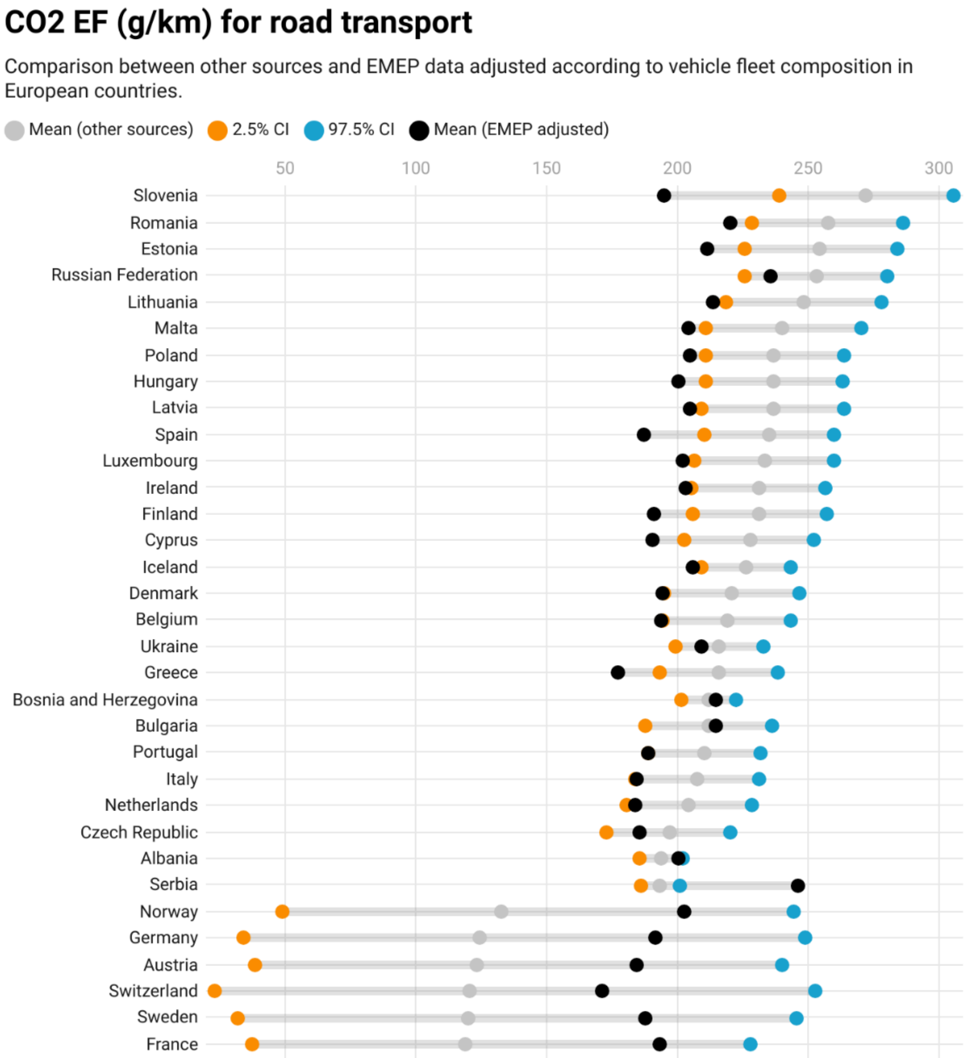


Figure 8: Comparison between CO_2 adjusted EF using EMEP and values obtained from other sources. The 95% confidence intervals are included to account for the variability.

In the global map, the adjusted EF values are used as they align with the typical national values reported in the literature. This will not apply to NOx and CO, as more EF data are available for these two species from various sources.

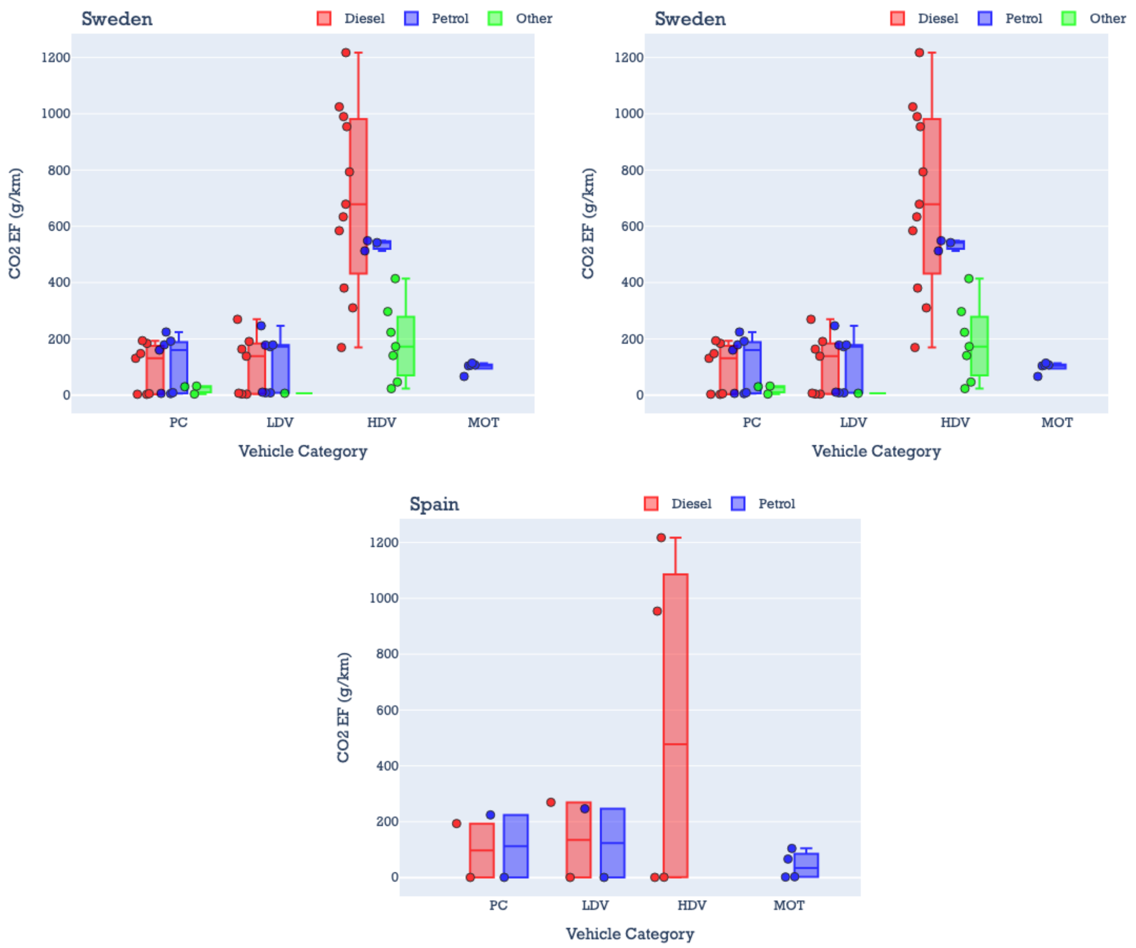


Figure 9: CO_2 EF for road transportation in selected European countries from sources other than EMEP.

Similarly, a comparison for NOx indicates average EF values are generally of the same order of magnitude, except for Azerbaijan and Russia, where significant differences (higher than 50%) are observed, probably due to a larger uncertainty in available EF data (Figure 10).

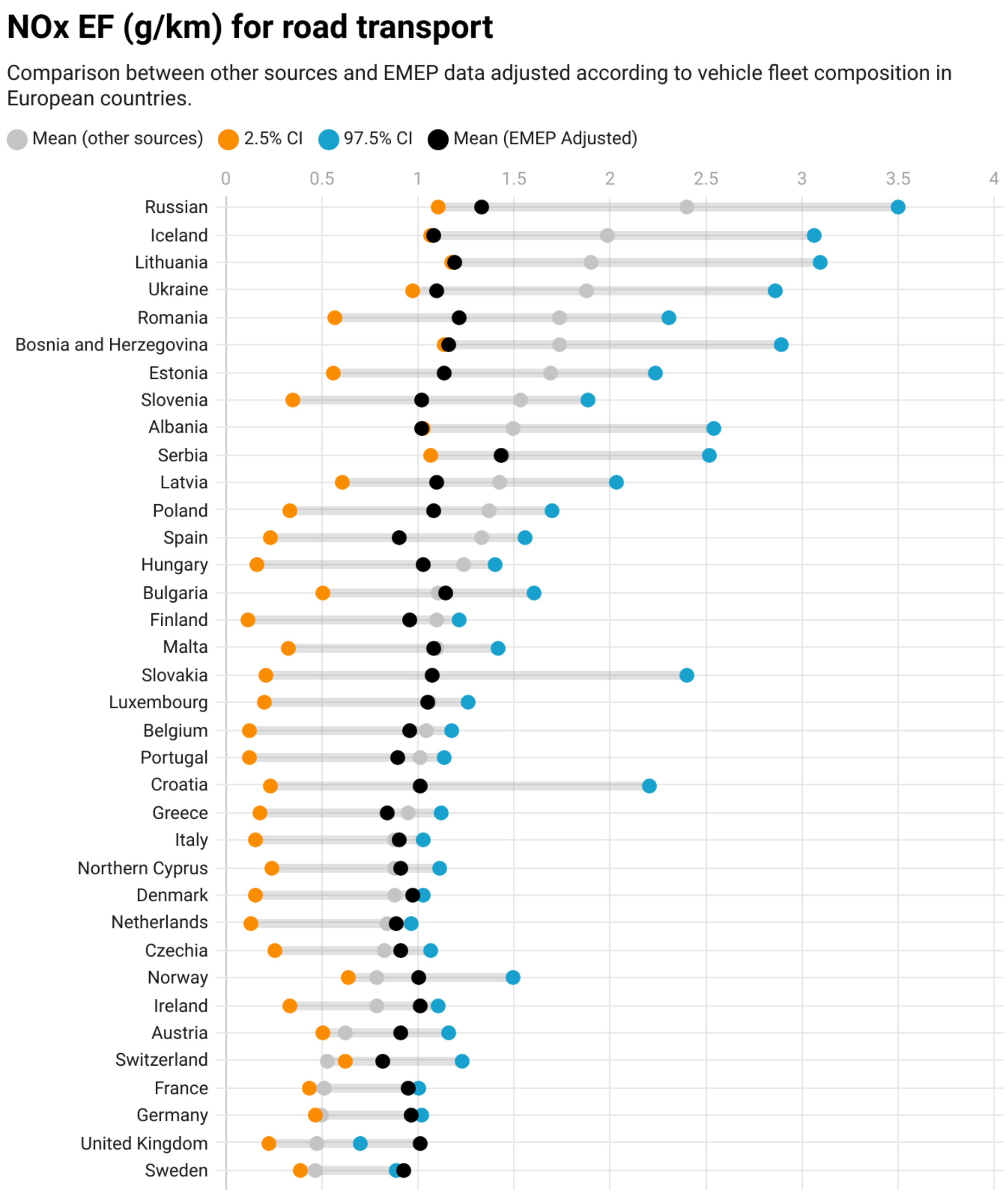


Figure 10: Comparison between NOx adjusted EF using EMEP and values obtained from other sources. The 95% confidence intervals are included to account for the variability.

The EF and uncertainties for countries lacking EF and activity data, such as vehicle fleet composition, are estimated using the HDI ratio between countries with similar characteristics.

3.3.2 Global maps of emission factors and uncertainties

The structured methodology applied in this work allows the determination of average EF and uncertainty ranges for CO_2, NOx and CO in road transportation and for each country. Figure 11 presents a global map of CO_2 EF, highlighting higher values in developing countries and regions with a significant number of heavy-duty vehicles, such as the United States of America, where EF values ranged from 114 to 560 g/km (i.e. 337 g/km +/- 223 g/km). The global maps for CO and NOx are included in Figures 12 and 13.

The developed database, which includes the estimated mean, error and uncertainty range (lower and upper limit values) of EF for each country, is available in both ASCII and NetCDF formats. Table 3 provides an example of the information contained in the CSV file. The data are available for download via the temporary link:

https://drive.google.com/drive/folders/15EwhEfYYfb-4HtVfEx4nORpXHZACAzqY?usp=drive_link.

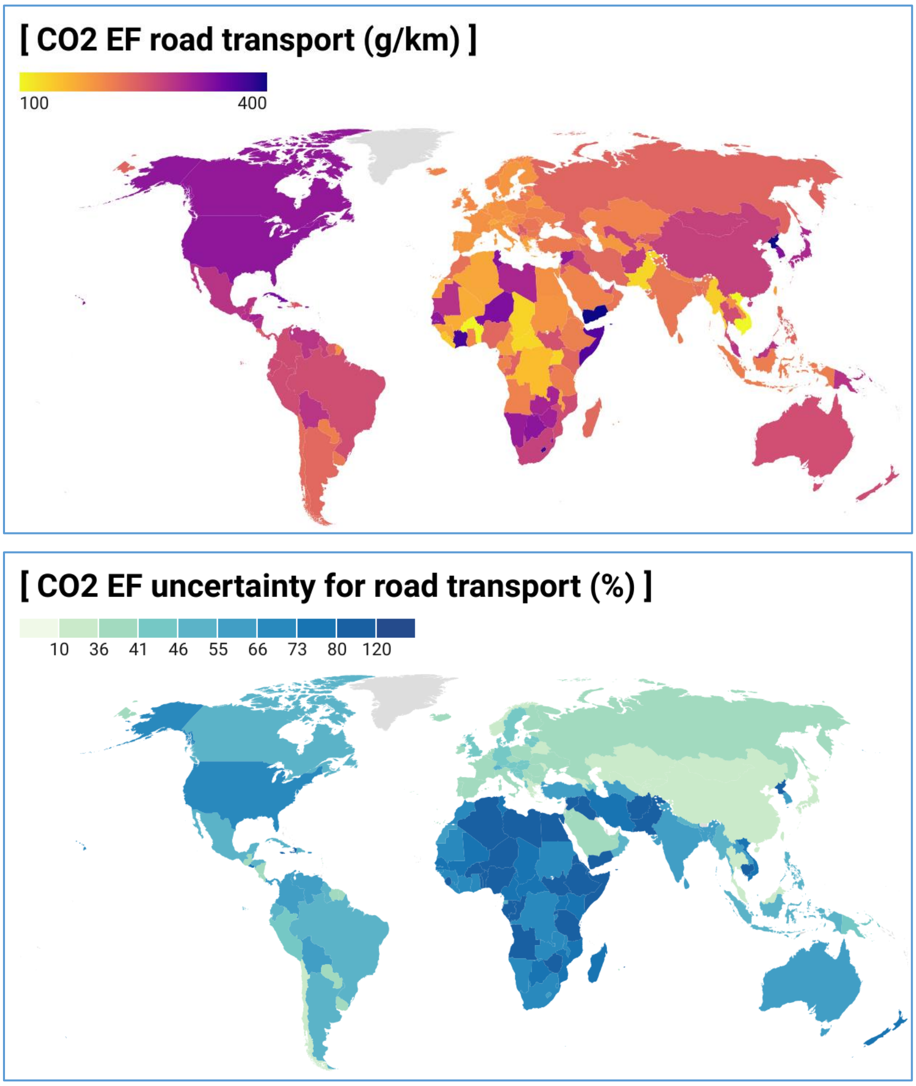


Figure 11: Global maps of CO_2 EFs (top) and their associated uncertainties (bottom).

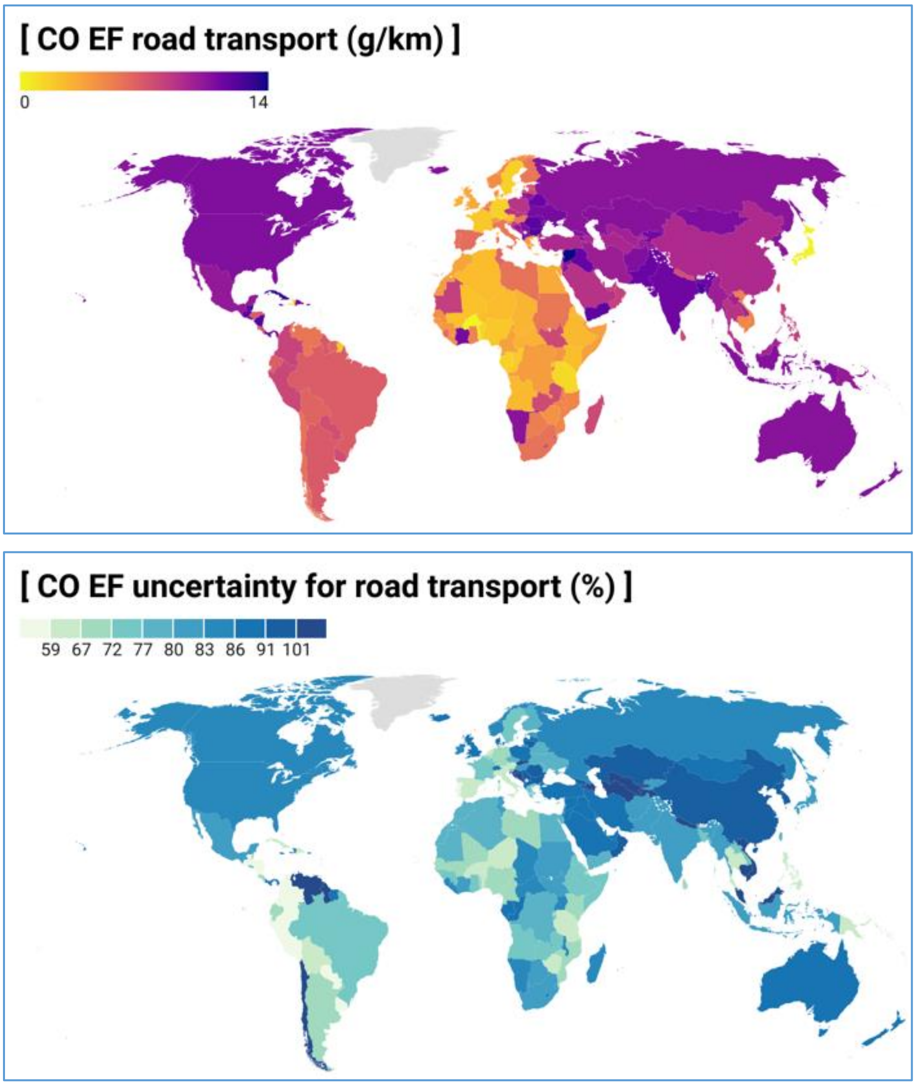
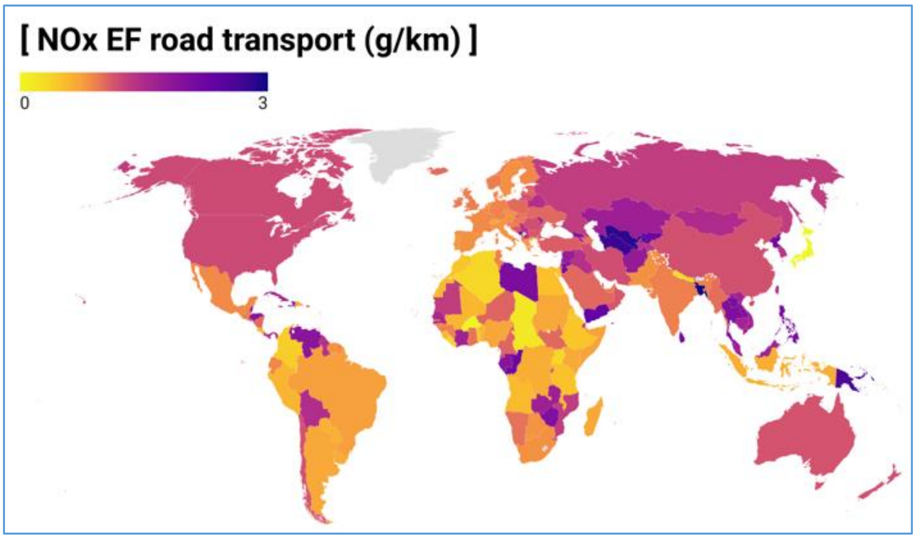


Figure 12: Global maps of CO EFs (top) and their associated uncertainties (bottom).



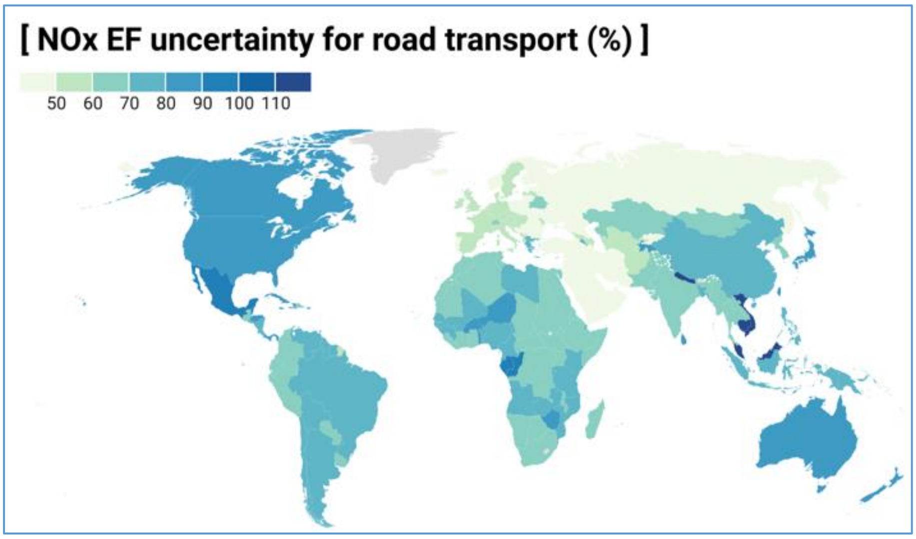


Figure 13: Global maps of NOx EFs (top) and their associated uncertainties (bottom).

Table 3: Example of the information included in the ASCII file.

	A	B	C	D	E	F	G	H	I	J
1	ID	Country	ISO_code	Region	Pollutant	Mean	Error sym	Rel. Unc. Sym.	Lower limit	Upper limit
2	1	Afghanistan	AFG	South Asia	CO	11	9	81	4	21
3	5	Albania	ALB	Europe	CO	11	10	86	3	22
4	64	Algeria	DZA	Africa	CO	3	2	77	1	5
5	6	Andorra	AND	Europe	CO	10	10	102	1	21
6	2	Angola	AGO	Africa	CO	3	2	73	1	5
7	8	Argentina	ARG	South America	CO	7	5	71	3	13
8	9	Armenia	ARM	Middle East	CO	11	10	94	2	22
9	14	Australia	AUS	Australia – Oceania	CO	11	9	88	3	22
10	15	Austria	AUT	Europe	CO	3	2	66	1	4
11	16	Azerbaijan	AZE	Middle East	CO	9	10	103	1	21
12	22	Bangladesh	BGD	South Asia	CO	12	9	72	4	22
13	33	Barbados	BRB	Central America	CO	2	1	68	1	3
14	28	Belarus	BLR	Europe	CO	12	9	77	4	21
15	18	Belgium	BEL	Europe	CO	6	4	68	2	10
16	29	Belize	BLZ	Central America	CO	14	10	69	6	25
17	19	Benin	BEN	Africa	CO	2	1	65	1	3
18	31	Bolivia	BOL	South America	CO	7	4	64	3	12
19	26	Bosnia and Herzegovina	BIH	Europe	CO	10	10	101	2	23
20	37	Botswana	BWA	Africa	CO	6	4	81	1	10
21	32	Brazil	BRA	South America	CO	7	5	74	3	13

4 Future work

This deliverable focuses on the collection of EF of CO_2, NOx and CO for road transportation and the determination of the national value and their associated uncertainty. This work will be complemented during the coming months by the following activities:

- Collection of EFs of the selected species, as well as the activity data for the other key sectors such as energy, industry and residential. Some of these data have already been gathered and have started to be analyzed for understanding their variability.
- The methodology applied for the road transportation will be extended to these sectors.
- The extension of the EF dataset to other sectors will be addressed as part of “Milestone 3: Public database to access all compiled emission factors”.

Document History

Version	Author(s)	Date	Changes
1.1	T. Doumbia, C. Granier, H. Merly	December 2024	Initial version
1.2	T. Doumbia, C. Granier, H. Merly	December 2024	Revised due to reviews

Internal Review History

Internal Reviewers	Date	Comments
Marc Guevara BSC, Jaroslaw Necki AGH	December 2024	