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Projecting traffic flows for road-based passenger transport in Europe for the analysis of climate impact

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Abstract

Road-based transport is a significant contributor to global transport emissions of greenhouse gases and local pollutants, thus contributing to the environmental impact of the mobility of people and goods. In order to develop strategies to mitigate this impact, it is necessary to build reliable emission inventories that include sector-specific emissions. Furthermore, the methods for creating these inventories should be applicable for forecasts and scenario calculations to facilitate the evaluation of pathways towards a more sustainable transport system. The study at hand proposes a model-based framework to predict travel demand and its spatial distribution for a bottom-up calculation of road transport emissions in Europe. With this framework, it is possible to calculate emissions based on the road network structure, traffic flows and vehicle types. In order to demonstrate the applicability of the framework for scenario calculations, it is applied to three exemplary scenarios where population data is modified. With the developed methodology, a tool for the large-scale assessment of emissions from road transport is provided, which is able to simulate the impact of socio-economic and economic changes on these emissions.

Keywords Transport emissions, Transport models, Climate impact, Emission inventory, Scenario modelling, Emission models

1 Introduction

Emissions from transport and related sectors contribute significantly to climate change. Associated emissions continue to increase, putting the achievement of the Paris climate targets at risk. In addition, these sectors contribute in a particular way to noise and air quality degradation. In particular, land-based transport by motor vehicles is responsible for a large proportion of emissions [22]. As transport volumes are expected to continue to increase, not only continuous monitoring is required. Rather, differentiated transport and emission models can be used to describe possible development paths and to assess mitigation measures.

Comprehensive and high-quality emission inventories at global, European and national level are an important prerequisite for both monitoring current emissions and forecasting future trends. The interdisciplinary project ELK (EmissionsLandKarte), which has been running at the German Aerospace Centre (DLR) since 2022, is making an important contribution to the development of such directories in several respects and has – among others – two main objectives: (1) to establish three- or four-dimensional global emission inventories (gases and particulates) for the transport sector as well as for the energy and related sectors for the target year 2019, and (2) to achieve scenario capability for the emission inventories. An essential component of reliable inventories is external data on population development, economic and political conditions, from which global transport demand

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can be derived. Based on this transport demand, sector-specific emissions are calculated, with further differentiations for sub-sectors. However, especially the spatial distribution of land transport and its emissions proves to be a challenging task, due to the multitude of impact factors like population distribution, the structure of road networks, land use and the general economic status of individuals. Furthermore, inconsistencies in the data are possible in national emissions reporting, and especially the issue of cross-border travel is insufficiently addressed.

To address these issues, this paper presents a tool to calculate spatially disaggregated road transport emissions for Europe, including international travel, with a common bottom-up approach. The approach aims at harmonising the activity data for all European countries, deriving vehicle movements from them, multiplying them by emission factors and finally calculating the resulting emissions. It also allows for scenario calculations and forecasts. The paper describes the methodology and demonstrates the functionality by means of an example. This methodology will be applied to generate emission inventories of road transport emissions for Europe in future applications.

2 State of the art

The spatial distribution of anthropogenic emissions and their impact on climate have been a focus of climate research, especially in atmospheric physics and modelling. Road-based transport emissions as part of land transport emissions are also part of current emission inventories used for climate impact assessment and the development of mitigation strategies. Smith et al. [19] highlight the necessity of complete, accurate and source-specific emission inventories, both for greenhouse gas emissions and local pollutants. These inventories are a key tool for policy makers to evaluate mitigation strategies. Often, national inventories are created, with more standardised methods for greenhouse gases than for short-lived emissions and pollutants. However, the development of inventories often relies on excessive national data collection and reporting, which requires considerable resources. Smith et al. [19] suggest coordinated efforts to develop bottom-up methods for both greenhouse gas and pollutant inventories. This would allow the impact of anthropogenic emissions to be assessed with consistent baseline data, and would also help countries with limited data resources.

For example, the European Commission's Emissions Database for Global Atmospheric Research (EDGAR) provides emission maps for globally produced greenhouse gases and air pollutants using a common methodology [7]. The background for this is the need for national emission inventories as a tool to measure compliance with the Paris Agreement on greenhouse gas emissions, with EDGAR helping to fill data gaps. It mainly considers the greenhouse gases CO_2, CH_4, N_2O and F, but there are also inventories for air pollutants (e.g. BC, PM10, NO_x or CO). The inventories are created with bottom-up methods for all relevant sectors, including land transport, for all European countries. EDGAR provides an excellent base for impact assessments of transport emissions; however, its applicability is limited when it comes to evaluating the mitigation potential of road transport in particular, as there is not only a lack of further disaggregation of road transport segments, but also a lack of information on background data for its spatial distribution.

Other efforts to build bottom-up road transport emission inventories often include the use of a geo-referenced road network and traffic count data, like Chan et al. [3] in their emission inventory software YETI 1.0 or Schneider et al. [17] in their gridding tool for German national emissions. These approaches can produce very accurate representations of road-level emissions, but they require a lot of data, which can limit both transferability and scalability. Furthermore, using current counting data does not allow for the forecast of emissions under any given scenario. This problem can be solved by combining emission models with transport models, thus replacing observed traffic data with modelled data. Such a method was applied by Matthias et al. [13] to analyse the climate impact of three future transport development pathways up to the year 2040. The developed modelling chain covers the process from a travel demand model to an atmospheric chemical transport model and includes an accurate spatial representation of road traffic density. Furthermore, it is possible to include different propulsion technologies and their respective emission factors, as described in Ehrenberger et al. [4]. As a result, the climate impacts of global and regional mitigation measures can be analysed at both the behavioural and the technological levels. Hendricks et al. [10] describe the advantages of using this approach for Germany in combination with chemical transport models for long-lived greenhouse gases and short-lived trace gases. They also highlight the importance of spatial allocation, particularly when modelling trace gases and aerosols. The frameworks developed in these studies were applied to Germany, but are theoretically transferable to other countries. Once again, the main issue preventing wider application is the availability of appropriate input data required to build sophisticated travel demand models, especially on a larger scale.

In summary, current state-of-the-art emission inventories represent different climate-relevant emission patterns at the global and national level. They use bottom-up methodologies to derive emissions by combining spatially distributed activity data with emission factors. When it comes to scenario readiness, the combination of

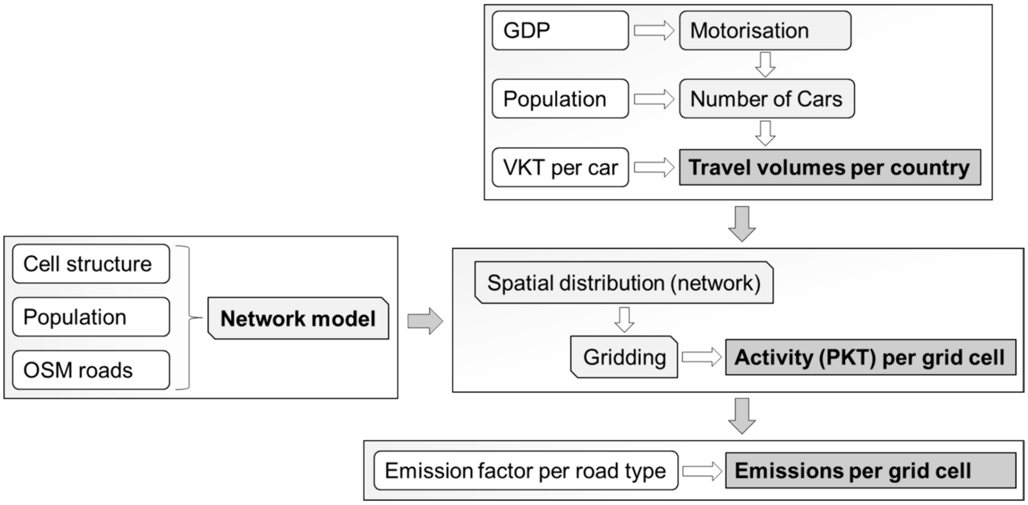

Fig. 1 Schematic overview of the modelling framework (GDP = gross domestic product; VKT = vehicle kilometres travelled; PKT = passenger kilometres travelled)

transport models with emission models provides a viable solution. However, existing applications often focus on smaller regions or single countries due to the data requirements for sophisticated travel demand models. This issue is addressed with the study at hand, where the proven methodology [13] of combining transport models with emission factors and emission models is applied to the whole of Europe. Thus, proven methods that are in line with current research findings are actually transferred to a large region, in this case an entire continent. The most important adjustment compared to previous studies is the underlying transport model, which is mostly based on open data and focuses on the distribution of trips, making the model an integral part of the inventory. Due to its modest data requirements, it can be applied on a larger scale while maintaining an accurate representation of road transport.

This paper presents the applied methodology and the results for three exemplary scenarios to demonstrate the scenario readiness of this modelling framework. The resulting inventories include national and cross-border traffic flows for road-based passenger transport in Europe. With the new framework, it is possible to enhance the transport data used for emission calculation, compared to current data.

3 Methodology

At the centre of the developed methodology is a travel demand model that produces spatially distinct traffic flows and emissions and was first described by Thomsen and Seum [21]. Using transport models as a basis for emission inventories entails the advantages of forecasting and scenario readiness, as these models can react to changes in structural or behavioural parameters. The proposed framework enables the development of international trip distribution models to generate network traffic flows that are transformed to spatially disaggregated emissions. The process is illustrated in Fig. 1. The main inputs are socio-economic attributes (GDP and population) and the spatial structure of the covered model region.

The process of calculating and distributing road transport emissions can be divided into three steps:

1) the calculation of national travel volumes (person kilometres travelled – PKT) based on socio-economic and economic developments,
2) the generation of road network models,
3) the distribution of national travel volumes using a travel demand model, and
4) the calculation of emissions based on traffic flows and emission factors.

The final result are emissions from individual road-based transport. While it is also possible to derive transport volumes for other means of transport, the distribution tool focuses on motorised individual traffic. This is due to the major contribution of this sub-sector of land transport.

3.1 Determining total travel volumes

In the first step, total annual travel volumes for passenger transport per country are derived based on population and gross domestic product (GDP). For this, motorisation rates are derived based on GDP per capita and world region using Gompertz Eq. (1).

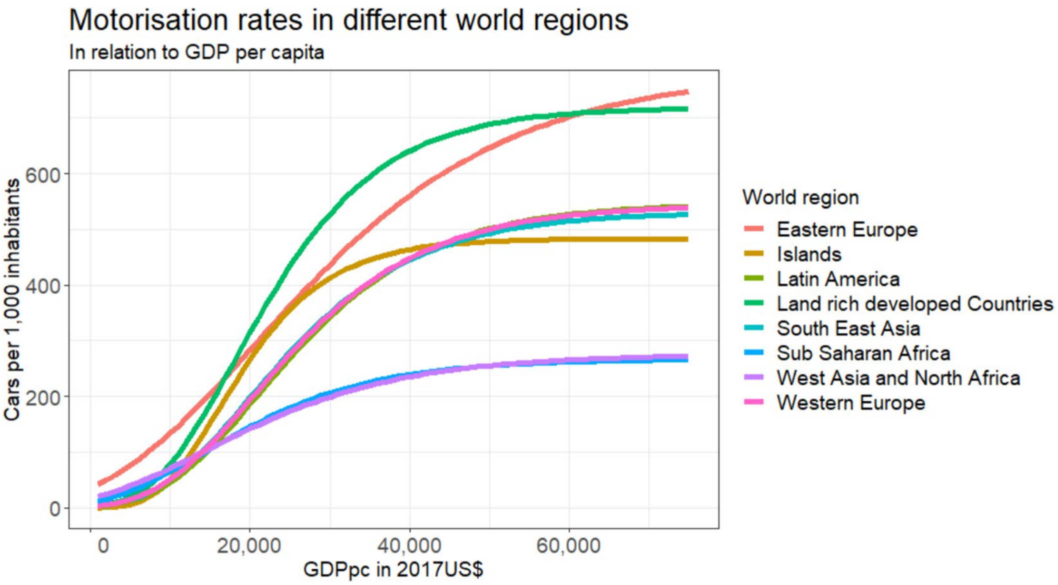

Fig. 2 Gompertz functions for motorisation rates in relation to GDP per capita for world regions

$$y(t) = ae^{(-be^{(-ct)})} \tag{1}$$

The Gompertz function was chosen after a comprehensive analysis of historical data on motorisation rates in developed countries, which indicate a correlation with the GDP per capita and can best be described with an S-shaped curve [18]. This means that, typically, the motorisation rate of a country with a medium GDP per capita rises substantially, while the increase in regions with very low or very high GDP is small. The parameters for the functions were derived for different regions of the world using data from representative sample states in order to consider the different levels of motorisation in different countries and thus also external factors such as the structure of the transport system. Figure 2 shows the resulting curves for the world regions.

By multiplying motorisation with total population, total vehicles per country are calculated. Then, PKT are determined using mean annual mileage and occupancy rates per car trip. The formulas and mean values for this step were developed as a result of extensive data research on travel volumes in different countries and world regions, ultimately using sources like Eurostat (e.g. the datasets for passenger road transport, [8]) and OECD statistics (e.g. the road traffic dataset provided by [14]). For forecasting purposes, it is possible to adjust input values like GDP and population based on predictions for socio-economic and economic development. Furthermore, mean annual vehicle mileage or occupancy rates can be adjusted to simulate regulatory changes.

Other means of transport, especially public transport, can be included by applying representative modal splits to derive their transport volume. However, the tool described in this paper focuses on individual motorised transport only.

3.2 Generation of road network models

Following the calculation of annual travel volumes, the basis for their spatial distribution is created in the form of road network models. For this, the network generation module of the open source software ULTImodel[1] [20] is applied, which was developed at the Institute of Transport Research at the German Aerospace Center (DLR).

ULTImodel creates the network model for a given region, which consists of cells (traffic analysis zones – TAZ) and the road network. It is therefore necessary to define the region's cell structure and to provide the TAZ as input. These TAZ correspond to the origins and destinations of traffic and are the locations where trips are generated. Based on the spatial expansion of these TAZ, the superordinate road network is extracted from Open Street Map (OSM) and then converted to a routable graph. The road types to be included in this network can be defined based on the OSM highway tag. It is possible to create the road network for separate sub-regions and to connect these at border crossings to optimise memory usage. Connecting the sub-regional road networks enables finding routes between TAZ in the covered region.

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[1] https://github.com/DLR-VF/ULTImodel

In addition, it is possible to include ferry routes for car ferries, so that islands are also part of the routable road network for the entire region. However, emissions from these ferry transfers are not yet part of the described tool, as the focus is on the tailpipe emissions of cars.

In a final step, the TAZ are connected to the generated road network. For this purpose, population centres for all cells are defined by applying a k-means algorithm to a population raster, for example using the Global Human Settlement Layer (GHSL) provided by the European Commission [7]. The identified centres are then moved to the nearest network node. These nodes mark both the entry and exit points of traffic in the network and thus the start and end points of trips between the TAZ in the spatial distribution. The final result of this step is a routable network model that is connected to TAZ representing the spatial structure of the model region.

Information on the trip attraction potential of each TAZ is required for the spatial distribution. This potential is quantified by the population per TAZ, as this data is readily available for larger regions (e.g. [6]). Since the road network only contains higher-ranking roads in order to reduce the file size, we also calculated the aggregated length of subordinate roads for each TAZ using OSM data. This allows road traffic to be determined even beyond the major axes. The network model in combination with total travel volumes per country sets the basis for the distribution of road traffic within the entire region.

3.3 Spatial distribution of road traffic

The results of the road traffic distribution are traffic flows along a road network that constitute the activity data for the emission inventory. Due to the large cell sizes of the global emission inventories, it is possible to simplify the transport distribution and to focus on accurately representing activity at a coarse granularity. The total annual travel volume is therefore distributed across the previously generated road network using the distribution module of ULTImodel [20]. ULTImodel distributes total PKT or VKT by applying a gravity model and is calibrated based on European statistics [8] and household travel survey data for Germany (Mobility in Germany – MiD, [1]). For a detailed description of the distribution model, including formulas, see Thomsen and Seum [21].

The distribution follows three steps of the traditional four step model [15]: trip generation, trip distribution and network assignment. The step of mode choice is not included in the spatial distribution, as the target values for travel volumes per mode are already determined in the first step of the algorithm. This is why ULTImodel so far only covers the distribution of individual road-based transport.

Before starting the spatial distribution, travel volumes are split into short- and long-distance travel as well as cross-border (international) travel. This distribution is calibrated based on household travel survey data for Germany [1]. Based on population data per TAZ and average trip distances per country, a gravity model is applied to generate origin-destination trip matrices for national long-distance and international trips. The distribution functions and their parameters as well as the functions to calculate average distances were estimated using household travel survey data for Germany [1]. To determine traffic loads, a shortest-path network assignment is performed for the trip matrices and a load factor to derive vehicle trips from person trips is applied. This involves connecting the TAZ to the road network at the nodes closest to population centres.

Due to the large size of the model region, the network and cell structure is coarse. This leads to a high number of inner-cell trips for short-distance travel, which are usually not included in network assignments. However, short-distance travel accounts for a large proportion of the road transport volume, and thus plays a major role in the generation of emissions. Therefore, inner-cell trips are assigned to the roads within a TAZ either by equally distributing them on the roads, weighted by road type, or by repeating the gravity model and network assignment between population centres within the TAZ, using the population for each centre as weighting attribute. In order to also include traffic in the subordinate road network, a share of the short-distance transport volume is not distributed across the road network, but added as an attribute of the TAZ. This share is determined based on the subordinate network length compared to the aggregated length of roads in the road network. The subordinate transport volume can later be spatially distributed using a proxy like population density. The result of the modelling and distribution procedure consists of a road network and TAZ with information on traffic flows.

The emissions are generated based on the vehicle kilometres travelled in the network. Therefore, it is important to validate the model results in this regard. ULTImodel was validated for Germany by comparing the results to national statistics. For example, the distribution of the network's car mileage on different road types can be validated using data from the German vehicle mileage survey 2014 [12]. The total car mileage is slightly overestimated by 7%, while there is a slight underestimation for urban and outside-of-settlements roads. In this comparison, the mileage on motorways is overestimated. However, comparing the assignment result to the data from automatic traffic counts on motorways and federal roads [2], there is an underestimation of traffic flows on motorways. Over all counting stations, the mean difference is lower

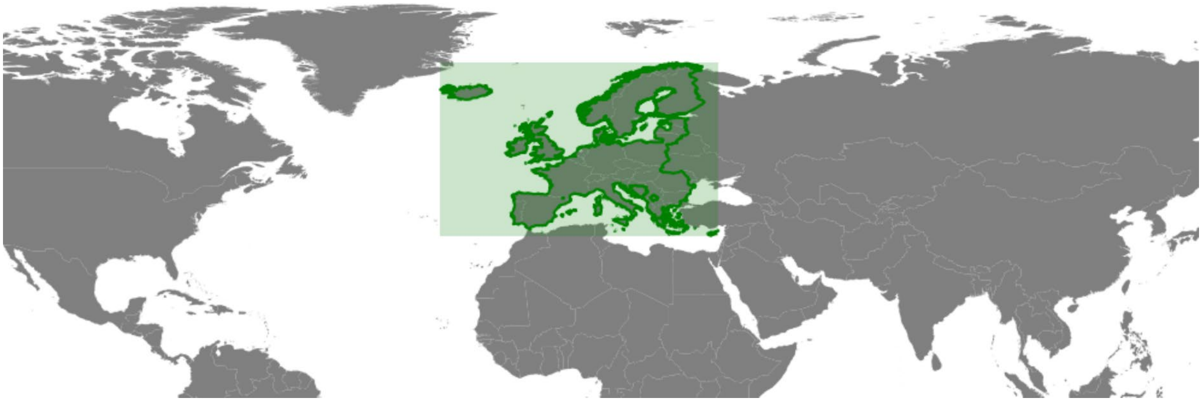

Fig. 3 Covered region for application example

than 1%, with ULTImodel tending to underestimate traffic counts. Ultimately, it is important to find a balance between fitting the model to multiple validation sources while avoiding overfitting.

3.4 Creating an emission grid

The final step is the calculation of emissions from road passenger transport based on the results from trip distribution. In spatial terms, the emissions are represented on a grid, which is created by aggregating the categorised vehicle kilometres from the network for each grid cell. In order to integrate traffic in the subordinate network, the previously calculated vehicle kilometres per TAZ are distributed across the grid based on population density. To generate the associated emissions, the categorised vehicle kilometres are multiplied with emission factors, which can be differentiated by road type, speed and vehicle type to represent the influence of driving style on emissions. In addition, different emission factors can be applied per region to account for the different composition of car fleets in different countries. Within this framework, weighted emission factors from HBEFA [11] are applied, which aggregate information on traffic situations and vehicle stock for urban and non-urban roads as well as for motorways [9].

The resulting grid can be used to identify hotspots for road emissions as well as to calculate total road transport emissions for parts of the region. To support decision-making by policy makers, areas in need of emission reduction measures can be identified on a large scale. It can also be used as input to chemical transport models to simulate interactions in the atmosphere and to calculate emissions to the environment. With a similar methodology, it is also possible to include road-based freight transport in the emission inventory, as described by Thomsen & Seum [21].

4 Applicability for scenarios

The described methodology allows for forecasting and the calculation of scenarios by modifying the input values in the modelling framework at different levels. Possible scenarios can focus on socio-economic development, such as changes in GDP or population, or regulatory changes in terms of propulsion technologies that change the composition of vehicle fleets and their emission factors. Furthermore, adjustments to the network design can be implemented by changing attributes of the road network.

To demonstrate that, this paper shows two examples for potential scenarios and compares the results to a baseline scenario, regarding both the allocation of vehicle kilometres travelled and emissions for Europe. The region covered in this application example is shown in Fig. 3.

The network model is created by combining submodels for each country in the region. For this application, European NUTS 3 regions are used as TAZ (NUTS: Nomenclature of territorial units for statistics). The NUTS classification scheme was developed by Eurostat and divides the territory of the European Union and the United Kingdom into regions for socio-economic analyses. Level 3, which is used here, represents the smallest available classification [5].

The road network in the model consists of all roads classified as ‘primary’ or ‘higher’ in OSM. Figure 4 shows the network model structure for the region. The distribution includes national as well as cross-border travel within Europe. In this application, CO_2 equivalents (CO_2e) and NO_x emissions from car travel are calculated using the emission factors from Table 1 for different road types, which are based on HBEFA [11]. These exemplary emission species represent climate-relevant greenhouse gas emissions (CO_2e) and local pollutants that affect air quality (NO_x).

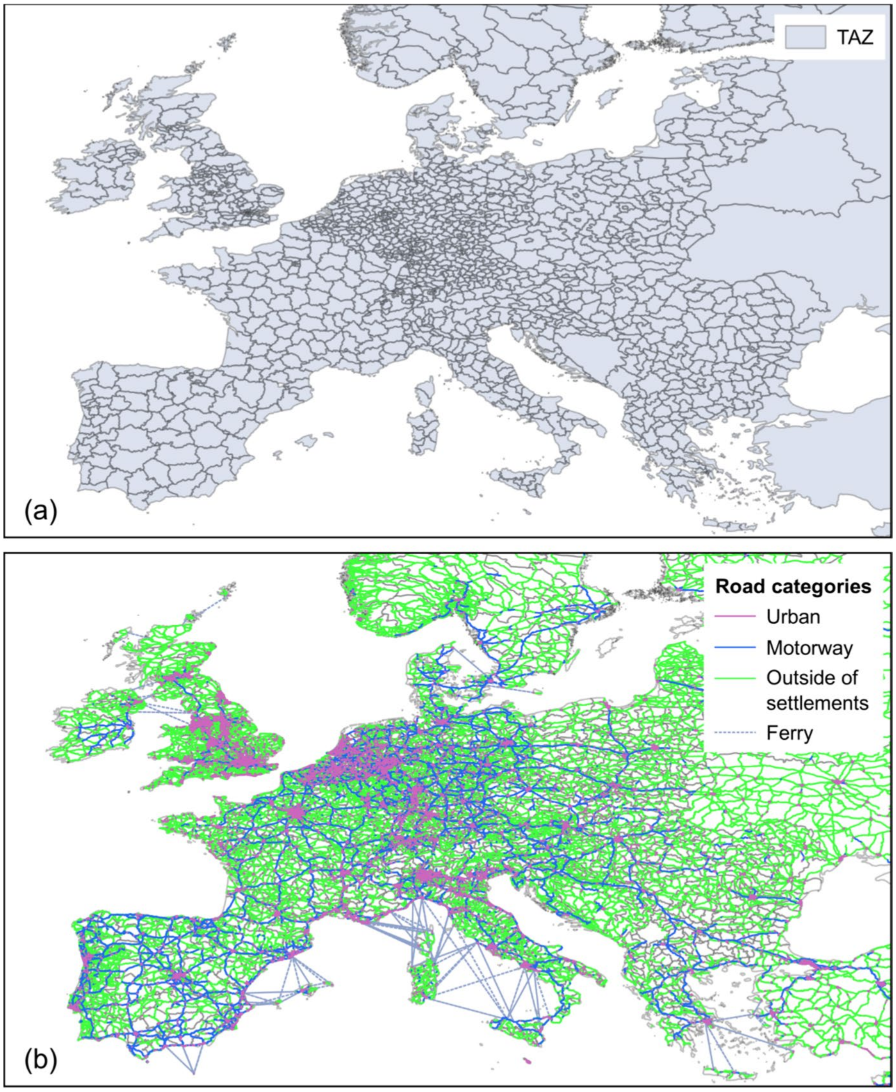

Fig. 4 Cell structure (**a**) and road network (**b**) in Europe

Table 1 Emission factors for all scenarios

Vehicle type	Year	Species	Road category	Emission factor (g/PKT)
car	2019	CO_2e	motorways	183.11
			outside of settlements	156.92
			urban	178.63
		NO_x	motorways	0.57
			outside of settlements	0.39
			urban	0.40

In the network model, the types ‘urban’ and ‘outside of settlements’ are classified by overlaying all primary and trunk roads with a settlement raster (built layer of the global human settlement raster, [7], for more information see [21]). This way, each road in the network model has a corresponding emission factor. The short-distance trips are spatially distributed using the weighted equal distribution approach.

4.1 Scenario definitions

The calculated scenarios are the following:

> Scenario 0 – Baseline: This scenario uses the current road network from OSM, population, population density and GDP of 2019 based on World Development Indicator (WDI) data [23]. We used the dataset for the GDP in PPP (constant 2017 international $, “NY.GDP.MKTP.PP.KD”) and the total population

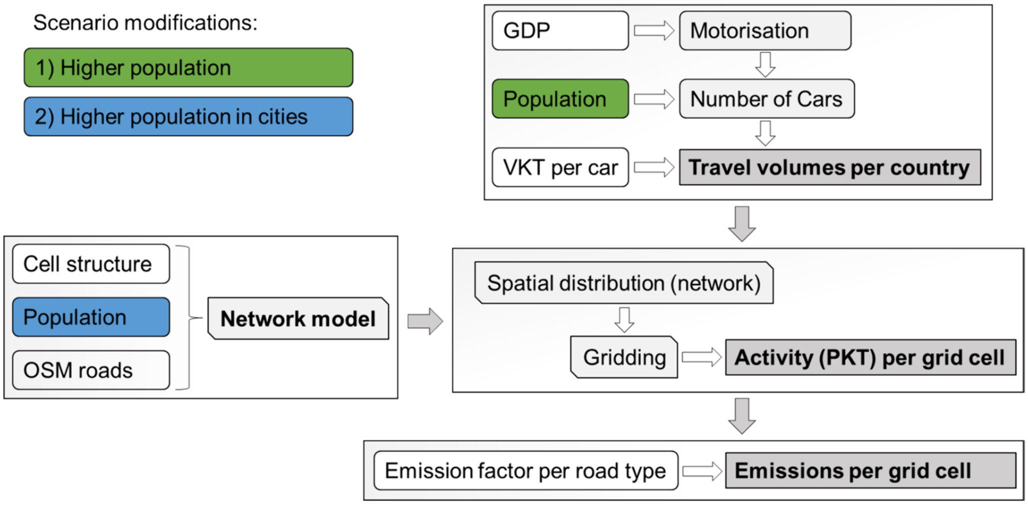

Fig. 5 Scenario modifications in the different modelling steps (GDP = gross domestic product; OSM = Open Street Map; VKT = vehicle kilometres travelled; PKT = passenger kilometres travelled)

dataset ("SP.POP.TOTL"), both providing input values per country.

Scenario 1 – Higher population: In this scenario, the total population of each country is multiplied with a factor of 1.25. The distribution of the population remains the same as in the baseline scenario (Scenario 0), i.e. the relative difference in population between different regions is similar. Scenario 1 changes the input value for the first step of calculating total vehicle kilometres per country.

Scenario 2 – Higher population in cities: For this scenario, the total population per country remains the same as in the baseline scenario (Scenario 0), but its distribution is adjusted. More people are expected to live in urban areas, thus multiplying the urban population per country by 1.25. The remaining population is distributed across rural areas based on the distribution in Scenario 0. Urban areas in Scenario 2 are defined as TAZ with more than 1 million inhabitants. This affects 92 of the 1,437 TAZ in the network model (approximately 6.4%). The scenario aims at changing the distribution of traffic, with urban areas having higher gravity.

Figure 5 shows the input values that are modified for the scenarios within the steps of the modelling framework. Other possible scenarios can include different emission factors in order to reflect changes in fleet composition or technology advancements. However, the application example in the study at hand focuses on scenarios affecting travel activity, where either the general socio-economic development or the transport infrastructure is adjusted.

4.2 Scenario results

It is to be expected that as the input values change at different steps of the modelling framework, the model results will also change. On the one hand, the spatial distribution of traffic flows is expected to differ between the scenarios due to different population densities or route choice between TAZ. On the other hand, the total emissions may change with different input values. Furthermore, there could be differences in the travel volume per road type due to the different distribution, which could also have an impact on total emissions. The presented scenarios are meant to demonstrate the scenario readiness of the framework and include only simple, generic changes. For more sophisticated forecasts, it is possible to modify the input parameters at a finer regional level.

The results of the presented modelling framework consist of total travel volumes per country, a loaded road network, and an emission grid. In this application example, Europe was covered as highlighted in Fig. 3. The total CO_2e emissions from passenger road transport for this region, as calculated in the scenarios, are presented in Fig. 6. It can be seen that the biggest impact seems to come from the input population and thus the total travel volumes per country (Scenario 1). It is only logical that with an increasing population, given the same motorisation rate and population distribution across the region, emissions will also increase. In Scenario 2, total CO_2e emissions decrease by approximately 1%.

Between the scenarios, the shares of emissions by road type are very similar. In all scenarios, most of the transport volume is consequently distributed across roads outside of settlements, as these roads make up the largest part of the total road network length. As shown in

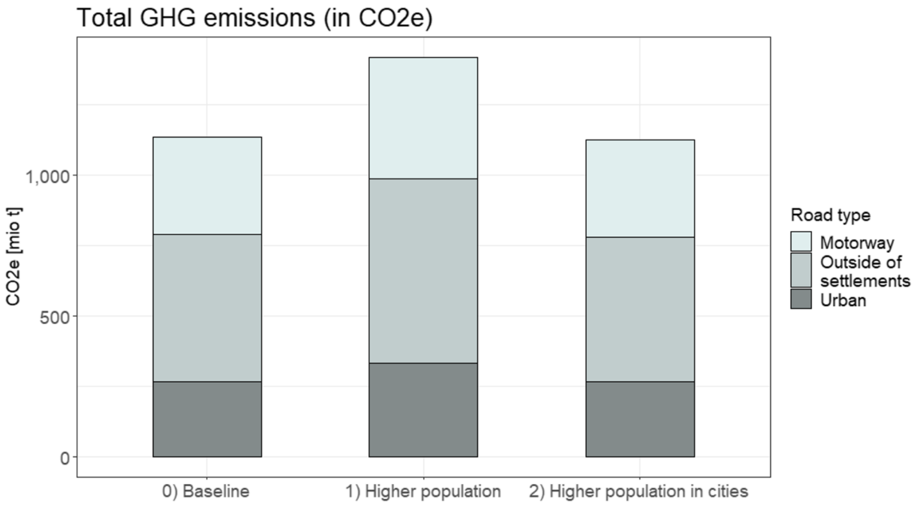

Fig. 6 Total CO_2e emissions in the scenarios

Table 2, most emissions are also generated on these roads. In Scenario 2, the share of CO_2e emissions from urban roads increases slightly by 1 percentage point, but there are no big changes in the composition of road emission sources.

For pollutants like NO_x, the spatial distribution of the generated emissions is an important factor for the later processing in atmospheric chemical transport models. The spatial distribution of NO_x in the calculated scenarios is illustrated on a $0.1 \times 0.1°$ grid, as shown in Fig. 7. The first map shows the annual NO_x emissions per grid cell for Scenario 0 (baseline) in tonnes. It can be seen that the highest emissions are observed in densely populated areas and along the main axes connecting these areas. Furthermore, the pattern of emissions represents the locations of highest population density and economic activity.

The other maps in Fig. 7 show the difference in NO_x emissions per grid cell in Scenario 1 and 2 compared to the baseline scenario (Scenario 0). In Scenario 1, where the population generally increases, emissions also increase everywhere. The most pronounced increases are in the vicinity of larger cities and on the roads connecting them. In Scenario 2, there is a larger population in cities and a smaller population in rural areas, which does not have as strong effects as in Scenario 1. Nevertheless, a shift in emission sources can be observed, with slightly more NO_x emissions in metropolitan areas and along the roads connecting them. In the rest of the continent, the emissions are slightly lower, as indicated by the light green colouring of these grid cells. Overall, the changes in emissions per grid cell are small.

The exemplary scenario results show that the main influence on total emissions appears to come from the socio-economic and economic input data, as shown in Scenario 1. However, even with smaller changes in the spatial distribution of the population, a shift in the spatial distribution of these emissions can be observed. This demonstrates that the use of a transport model to distribute these emissions leads to a significant improvement in the calculation of road-based transport emissions and enables the scenario readiness of emission inventories. The exemplary scenario modifications were applied evenly to the entire model region, but it is also possible to consider regional changes with this approach.

5 Discussion and model limitations

The application shows that the model-based development of emission inventories for road-based passenger transport is possible with the presented framework. The model reacts to modifications in the input values according to the expectation, indicating its applicability for scenarios and forecasts. The methodology is in line with other model-based approaches (e.g. [3, 13]) using traffic flow data (either observed or modelled) as activity data and combining such data with emission factors. Even though the methods from other studies are theoretically

Table 2 Share of CO_2e emissions from road transport per road type and scenario

Road type	Scenario 0: Baseline	Scenario 1: Higher population	Scenario 2: Higher population in cities
Motorways	30%	30%	31%
Outside of settlements	46%	46%	46%
Urban	23%	23%	24%

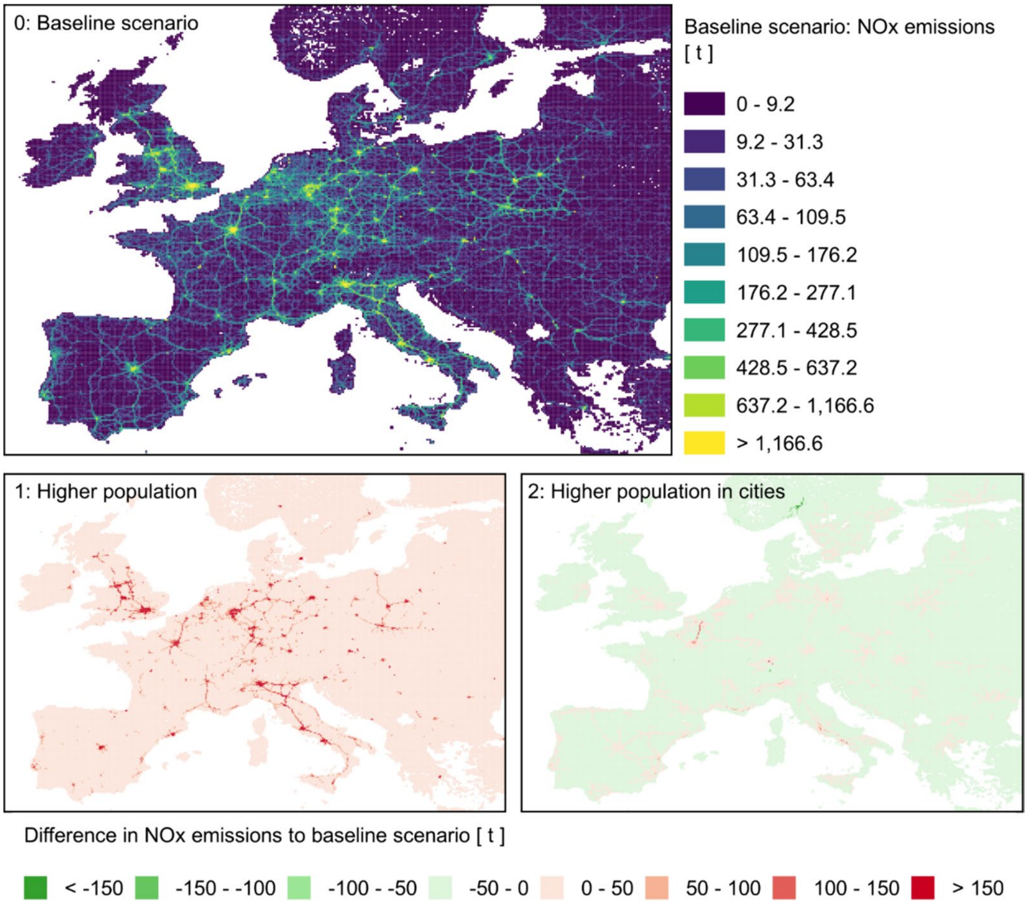

Fig. 7 Spatial distribution of NO_x emissions in the scenarios

applicable to all countries, all of them rely on extensive input data, which may be an obstacle for the implementation due to missing or inadequate data. Thus, the presented framework fills this gap by providing a simplified, yet accurate transport modelling software. It is open source and it uses on open data.

Currently, there are still some limitations, especially when it comes to transferring the approach to other world regions, and in particular regarding the trip distribution model. However, these limitations can be addressed through further research. At the moment, the distribution is calibrated and validated using German trip data. The applicability of the derived parameters has yet to be tested outside of Europe, especially in terms of assumptions for cost functions. In other world regions travel behaviour may change with respect to average trip distances and travel times. Furthermore, cross-border travel underlies very few restrictions within the European Schengen Area. In other regions, border controls may affect the volume of international travel and thus, the functions and parameters may have to be adjusted. Nevertheless, the methodology of the framework in itself is transferable, and – if adequate data sources are available – recalibrations for regions outside Europe are possible.

The framework can react to scenario modifications at different levels. It is possible to adjust total population and GDP per capita, thus influencing the national transport volumes. In addition, transport planning measures and changes in structural data that affect the spatial distribution of traffic flows can be included. In this study, changes in propulsion technologies, like a higher diffusion of electric vehicles, were not demonstrated with a separate scenario, but can easily be considered by adjusting the emission factors (see e.g. [4]). In the current set-up, however, there is a limitation regarding changes in travel behaviour: Mode choice is already performed before the actual transport modelling when generating the travel volumes, which limits the reactions within the distribution model. And since costs are currently represented as travel times and distances, other monetary measures cannot be implemented at present. Furthermore, changes in network design, such as speed regulations, can lead to modal shifts and changes in average travel distances, that cannot yet be accurately calculated.

Depending on the method of assignment in the distribution model, computation times vary. For the example presented in the study at hand, calculations for one scenario took less than 60 min on a notebook with an Intel Core i7 CPU (1.90 GHz) and 16 GB RAM. It has to be noted that for network creation, the computing times depend strongly on the quality of the internet connection, since data from OSM has to be downloaded for large areas. In addition to road-based passenger transport, road-based freight transport is also a significant generator of emissions, but this was not considered in the example scenarios, since methods to predict travel volumes of freight transport are not yet fully developed. It is, however, already possible to include freight transport in the distribution model and to calculate emissions based on the national total tonne-kilometres by using additional information on industrial areas from OSM [21]. Furthermore, model validation is still in process, especially for regions outside of the calibration country (Germany). Future research focuses on using remote sensing data to validate highway traffic flows and the validation of the resulting emissions.

With respect to future research activities regarding the calculation of consistent emission scenarios, the approach described above contributes to more precise results of the sub-sector 'individual motorised transport'. It is part of a much broader approach of emission calculation developed within the strategic project ELK – EmissionsLandKarte (en.: emission map) at the German Aerospace Center (DLR). ELK [16] aims at combining various species of emissions for all transport modes as well as related industrial sectors. Final results (data as well as comparative maps) will be published in 2024 at the publicly available ELK Information System ELKIS, that way facilitating future assessments, for example, of the effectiveness of climate policies and other measures to improve air quality and to reduce noise pollution.

6 Conclusion

The presented modelling framework provides a straightforward methodology for the creation of scenario-ready emission inventories for road-based passenger transport. It is a bottom-up approach with an easy-to-follow structure, where the points of modification for forecasting and the calculation of scenarios are clearly defined. The methods are transparent and the input parameters and functions can be easily adjusted if necessary. Furthermore, the amount of input data could be reduced to mostly open data, which improves the transferability of the methods. Lastly, the example application for Europe shows that emissions can be spatially distributed for a very large region, harmonising the methods and improving data consistency.

This framework enables the forecast of road transport emissions in various degrees. At the highest level, scenarios regarding the socio-economic and economic development can be applied that influence motorisation rates and the total travel volume. Using a transport model for the distribution of these travel volumes, it is possible to depict the impact of spatial structure and population density on the attraction potential of locations and thus on the calculated traffic flows. Furthermore, scenarios can include specific behavioural changes depending on regional types and changes within the road network. In the example scenarios, modifications were applied evenly across the whole region, but it is possible to only include changes in specific sub-regions or parts of the network. The resulting emission inventory is a valuable input for chemical transport models or the general fine-grained determination of emissions (e.g. per country, road type or vehicle type), enabling researchers and practitioners to assess impacts on health and climate and to develop mitigation strategies.

Abbreviations

BC	Black carbon
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur, engl. Federal Ministry of Transport and Digital Infrastructure
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EDGAR	Emissions Database for Global Atmospheric Research
ELK	EmissionsLandKarte; engl.: emission map
F	Fluorine
GDP	Gross domestic product
GHSL	Global Human Settlement Layer
HBEFA	Handbook Emission Factors for Road Transport
HGF	Helmholtz Association of German Research Centres
MiD	German national household travel survey 'Mobilität in Deutschland', engl. Mobility in Germany
N_2O	Dinitrogen oxide
NO_x	Nitrogen oxide
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Co-Operation and Development
OSM	Open Street Map
PKT	Person kilometres travelled
PM10	Particulate matter (coarse particles with a diameter of 10 μm (μm) or less)
PPP	Purchasing power parity
T	Tonne
TAZ	Traffic analysis zone
ULTImodel	Universal Transport Distribution Model
VKT	Vehicle kilometres travelled
WDI	World Development Indicators

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Authors' contributions

Nina Thomsen: Concept, methods, calculation, draft preparation; Angelika Schulz: Concept, draft preparation, review.

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Availability of data and materials

The results were calculated using the open source software ULTImodel (https://github.com/DLR-VF/ULTImodel). The emission inventories can be found on the information system platform ELKIS by the end of 2024.

Declarations

Competing interests

The authors have no competing interests to report.

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