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The impact of diesel vehicles on NO_x and PM10 emissions from road transport in urban morphological zones: A case study in North Rhine-Westphalia, Germany

Janos Lucian Breuer,*[a] Remzi Can Samsun,[a] Ralf Peters[a] and Detlef Stolten[a,b,c]

Harmful emissions like nitrogen oxide and particulate matter are one of the big challenges facing modern society. These emissions are especially apparent in agglomerations. Possible solutions to overcome this challenge within the framework of the transformation of the transport sector are the change of the transport vehicles of freight and passenger transport or changing the fuel of the vehicles. Determining the viability of both approaches requires analyses to determine which vehicles are the main polluters in urban areas. This study outlines a bottom-up approach for the calculation of road transport emissions on street level in the representative model region of North Rhine-Westphalia in Germany, considering eight different vehicle classes as well as diesel and gasoline as fuel. Part of the approach is the development of a street-section traffic volume map considering all streets in the model region using a developed multivariate linear regression model for Germany and existing traffic counts. Using the approach developed here, the urban areas of Herne, Oberhausen and Bochum were identified as hotspots with the highest specific nitrogen oxide emissions, while the urban areas of Herne, Oberhausen and Gelsenkirchen were identified as hotspots with the highest specific particulate matter emissions. A detailed investigation of Oberhausen as a representative emission hotspot showed that 91% of road transport nitrogen oxide emissions are produced by vehicles that use diesel fuel and 9% from vehicles with gasoline fuel, while gasoline vehicles account for 43% of the total distance driven and diesel vehicles for 57%. With respect to particulate matter emissions in the urban area of Oberhausen, 29% are produced by gasoline vehicles and 71% by diesel vehicles. However, only 22% of particulate matter emissions are exhaust emissions, while 78% are produced due to the abrasion of tires, brakes and the road.

1. Introduction

Greenhouse gas (GHG) emissions are the main driver of climate change (IPCC, 2013). For Germany, in 2016, the three main polluters were the energy sector, with 38%, the industry sector, with 21%, and the transport sector, with 18% (BMU, 2017). Moreover, in 2015, 96% of the GHG emissions from the transport sector were caused by road transport (BMU, 2017). Another challenge of modern society is harmful pollutants in urban areas, such as nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM10 & PM2.5). PM and ozone are responsible for an increased risk of mortality and respiratory morbidity, while NO_x, ozone and PM are responsible for allergic reactions (WHO, 2005). Furthermore, PM has been rated as the 13th leading global cause of mortality by the World Health Organization and contributes to approximately 800,000 premature deaths each year (Anderson et al., 2012). The 2017 report on air quality in Europe from the

[a.] Electrochemical Process Engineering (IEK-3), Forschungszentrum Jülich GmbH, 52425, Jülich, Germany.
[b.] JARA-ENERGY, 52056 Aachen, Germany.
[c.] Chair for Fuel Cells, RWTH Aachen University, 52072, Aachen, Germany.
*Corresponding author.
Tel: +49 2461 61-96984; E-mail address: ja.breuer@fz-juelich.de

European Environment Agency also came to the conclusion that Europe's most harmful pollutants are PM, nitrogen dioxide (NO_2) and ground level ozone (EEA, 2017). Ozone is not formed initially, but through a photochemical reaction, mainly from NO_x and non-methane volatile organic compounds (NRC, 1991). These harmful emissions are especially perceptible in agglomerations. For this reason, in 1999, with Council Directive 1999/30/EC (EC, 1999), the European Commission for the first time set limit values for emissions such as PM and NO_x. The latest limit values for an averaging period of one year stipulated in the Directive 2008/50/EC are 40 µg/m^3 for NO_2 and 40 µg/m^3 for PM10 (EC, 2008). In the wake of the so-called *Dieselgate* affair and the lawsuits of the Environmental Action Germany (in German: Deutsche Umwelthilfe) against 34 German cities due to exceeded NO_x emission limits, harmful air pollution has gained public attention in Germany.

Road transport accounted for 29% of NO_x emissions in Europe in 2018 and is therefore one of the main sources of harmful emissions (EEA, 2018). Solving the challenge of increasing harmful emissions in urban areas requires analyses to determine which vehicles are the main polluters in them. These analyses will form the basis for the assessment of pollution mitigation strategies. Pollution mitigation strategies include, amongst other measures, the utilization of alternative fuels. Alternative fuels offer not only a viable opportunity for reducing GHG emissions, but also harmful emissions like NO_x and PM (Geng et al., 2017).

The contribution made by this study is an approach to identifying emission hotspots and analyzing the polluters with respect to different vehicles classes, as well as gasoline and diesel as fuels. Using this approach, this work provides an in-depth analysis of the optimal observation level for analyzing harmful emissions through the use of urban morphological zones as balancing areas for harmful emissions for the first time. Furthermore, an extensive analysis of representative emission hotspot was carried out and offers detailed information about the emission reduction potential of different vehicles and fuels.

As an application example, a suitable model region in Germany was selected. 14 of 34 cities affected by the lawsuits from the Environmental Action Germany are located in the state North Rhine-Westphalia (NRW). Furthermore, NRW is responsible for approximately 20% of Germany's total CO_2 emissions (statistische Ämter der Länder, 2017a). These facts make NRW a suitable model region for a case study as part of this work to take a deeper look at the most problematic vehicles in the transport sector.

The work presented here is structured as follows. First, a short overview of prior work is given. Second, the methodology is outlined for creating a street mileage map of NRW incorporating the five German street classes of federal highway (in German: Bundesautobahn), federal road (in German: Bundesstraße), state road (in German: Landesstraße), district road (in German: Kreisstraße), as well as all other streets and the eight vehicle classes of passenger cars, motorcycles, light duty vehicles, buses, rigid trucks, trailer trucks, articulated trucks and other vehicles. Third, the methodology for the calculation of harmful emissions, greenhouse gas emissions and fuel consumption, as well as necessary assumptions and boundaries, is defined. Finally, the hotspots for NO_x and PM emissions in NRW for the year 2018, considering diesel and gasoline as fuels, are analyzed in detail in the results and discussion sections.

2. Prior Work

The existing literature on the spatial modeling of harmful emissions is limited. Emissions can be calculated via a top-down or bottom-up methodology. For the top-down approach, emissions are calculated on a national level or taken from national inventories and afterwards distributed on a desired grid using activity data such as road density (Alam et al., 2018; Fameli and Assimakopoulos, 2015a; Romero et al., 2020; Sun et al., 2016), traffic volume (Alam et al., 2018; Fameli and Assimakopoulos, 2015b; Gioli et al., 2015; Guevara et al., 2017; Schneider et al., 2016b; Thiruchittampalam et al., 2013), population density (Fameli and Assimakopoulos, 2015b) or fuel consumption (Gioli et al., 2015; Pallavidino et al., 2011). In contrast, the bottom-up approach uses site-specific data such as the street-specific traffic mileages of different vehicle categories and taking into account vehicle speed, fuel, weight, etc. (Pallavidino et al., 2011). Pallavidino et al. (2014) performed a comparison between a bottom-up and top-down approach for road transport emissions in the province of Turin, Italy. They came to the conclusion that a bottom-up approach is more reliable and should be preferred. López-Aparicio et al. (2017) compared seven bottom-up approaches for urban areas in Norway and three top-down approaches considering nitrogen oxide and particulate matter emissions from road transport, residential combustion, non-road transport and industrial sectors. They came to the conclusion that bottom-up approaches for on-road transport emissions in urban areas are likely to be more accurate than top-down ones.
Peace et al. (2004) used spatially resolved emissions and the ADMS Urban Gaussian dispersion model to identify the contribution of different road transport vehicles to air pollution. Their simulations indicated that goods vehicles are the main contributor in the case of air pollution and as a conclusion need to be addressed by local authorities. Romero et al. (2020) developed a top-down approach that disaggregates air pollutants to 1km × 1km and 0.5km × 0.5km cells in the Lima Metropolitan Area, using the primary and secondary road network. They compared their approach with real traffic conditions and found that the 1km × 1km disaggregation is more accurate. Requia et al. (2017) researched the correlation between municipality emission inventories in Brazil and six different statistical values. As a result, they identified five representative groups of municipalities out of 5570 in total. Moldanova et al. (2015) analyzed a 1 km² grid in Sweden to explore different future scenarios. Schneider et al. (2016b), as well as Thiruchittampalam et al. (2013), investigated the emissions of the sectors energy economy, services, households, agriculture, industry and transport in Germany. Alam et al. (2018), meanwhile, developed a top-down approach for emissions in Dublin using a neural network to predict the traffic volume with consideration of different vehicle classes. Sun et al. (2016), in turn, investigated in detail emissions in the Shandong Province in China, considering vehicle classes, driving speeds, fuel quality and meteorological standards for the years 2000-2014 at the prefecture level. Fameli and Assimakopoulos (2015b) examined road transport emissions in the greater Athens area via a top-down approach that uses population data to distribute emissions on urban areas. Guevara et al. (2017) explained the High-Elective Resolution Modelling Emission System for Mexico that transforms the emissions of the Mexico City Metropolitan Area into hourly and gridded emissions for comparison with the measured data. Furthermore, there is a detailed model from the State Agency for Nature, Environment and Consumer Protection (in German: Landesamt für Natur, Umwelt und Verbraucherschutz) NRW, in which all emissions for different sectors are calculated for counties, municipalities and a 1 km² grid (LANUV, 2018). At the time of this work, only three studies in the literature investigated the spatial distribution of emissions in Germany (LANUV, 2018; Schneider et al., 2016a; Thiruchittampalam et al., 2013). Two of these used top-down approaches and one used a bottom-up approach.
The novelty of this work lies in its holistic and detailed bottom-up approach to harmful road transport emissions in urban areas in Germany, with North Rhine-Westphalia as the representative model region. The model presented here uses calculated street-specific mileage data for the eight different vehicle categories of motorcycles, passenger cars, light duty vehicles, buses, rigid trucks, trailer trucks, articulated trucks and other vehicles (see electronic supplementary information, Table A 2 for a detailed description) considering different landscapes, fuels and velocities. Relating to the European Monitoring and Evaluation Programme (EMEP) and the European Environment Agency (EEA) air pollutant emission inventory guidebook 2016 (EEA, 2016), the methodology used is rated as Tier 3, which is the most accurate form. This level of detail is mandatory for the analysis of emission sources in terms of vehicles in urban areas. To the best of our knowledge, an analysis that considers area-specific emissions in urban areas has not been performed previously.

3. Methodological framework

This section is subdivided into the discretization of road transport mileages (i.e., the total distance driven by road transport vehicles) for the model region NRW, the calculation of emissions for the year 2018 for the model region and a brief description of the applied visualization tools.

3.1 Discretization of road transport mileage for North Rhine-Westphalia

Mileages must be spatially- and temporally-discretised. A frequently made assumption in the literature is that the spatial distribution of mileages is time-independent (Knörr et al., 2016; Schneider et al., 2016b; Thiruchittampalam et al., 2013). Therefore, spatial discretization and temporal development are subdivided into two approaches in this work.

Street mileages for the model region North Rhine-Westphalia are available from automatic traffic stations and through manual traffic counts of the Federal Highway Research Institute (in German: Bundesanstalt für Straßenwesen)(Bast, 2018). However, the Federal Highway Research Institute only subdivides into light and heavy traffic (Bast, 2018). The specific fleet composition from the automatic traffic stations was obtained from the Ministry of Building, Accommodation, Urban Development and Transport of North Rhine-Westphalia (in German: Ministerium für Bauen, Wohnen, Stadtentwicklung und Verkehr NRW)(MWEBWV NRW, 2014). However, this data only covers 26% of the federal highways, 6% of the federal roads and 1% of the state roads. For the resulting streets with manual and temporarily counts, the composition of light and heavy traffic was assumed to be equal to the vehicle stock of light and heavy traffic in NRW, which was obtained from the Federal Motor Transport Authority (in German: Kraftfahrtbundesamt) (Kba, 2014a). This data covers 99% of the federal highways, 87% of the federal roads, 85% of the state roads, 41% of the district roads and 0% of the other streets. To cover the remaining roads, a top-down approach was developed to distribute national mileages published by the Federal Highway Research Institute (Bast, 2017), onto these streets. A possible approach is to use population data (Brinkhoff, 2018). However, this approach limits accuracy. A detailed analysis of activity data in the course of this work revealed that the vehicle stock is suitable for distributing mileages from national level to the state level, but is not at all suitable to distributing mileages at more detailed communal levels, such as counties or municipalities. A combination of different spatial data (BKG, 2018; EEA, 2014; GADM, 2018), statistical data (Brinkhoff, 2018; Kba, 2014a; Statistische Ämter der Länder, 2017b; Statistische Ämter der Länder, 2017c; Statistische Ämter der Länder, 2017d) and literature mileages at the county and municipality level (LUBW, 2018), using multivariate linear regression (MLR) (§), has resulted in an acceptable coefficient of determination. These values will be shown and discussed later in this chapter.

The discretization of mileages is subdivided into different steps: First, national mileages for Germany, given by the Federal Highway Research Institute (Bast, 2017), were distributed to each federal state. Second, the mileages in the states were distributed to each county using the afore-mentioned approach, henceforth termed the multivariate linear regression (MLR) model. Third, the mileages in each county were distributed to each municipality using the MLR model for municipalities. Fourth, a balance around each municipality was calculated with consideration of the mileages from traffic counting stations and the calculated mileages of each vehicle class. Last, the resulting mileages from the balance were distributed symmetrically onto the streets without traffic counts. In the following section, this method will be described in detail.

The national mileages given by Federal Highway Research Institute (Bast, 2017) were distributed to each state using the average mileages per vehicle class from the Federal Motor Transport Authority (Kba, 2014b), as well as the vehicle stock (Kba, 2014a). The calculated percentages for NRW of the national mileages from Germany for the different vehicles classes are 19.58% for motorcycles (MC), 21.33% for passenger cars (PC), 20% for light duty vehicles (LDV), 21.15% for buses, 20.7% for rigid trucks (RT), 12.7% for trailer trucks (TT), 22.57% for articulated trucks (AT) and 11.95% for other vehicles. Table 1 shows a comparison of the calculated values in this work, with literature values from the statistical offices of the federal states (statistische Ämter der Länder, 2017a) from an assessment in 2008. The vehicle classes from the cited literature source were motorcycles, passenger cars, buses, trucks and tractors and articulated trucks. The corresponding vehicles classes from the calculation are shown in Table 1.

For the calculation, the following assumptions were made:

- The relationship between trailer truck and rigid truck mileages is 0.87 (this value was validated by means of a target value analysis in this work).
- Average mileages per vehicle are equal for all states
- Mileages are proportional to vehicle stock at the state level

Table 1. Comparison of the calculated state mileages for NRW with literature values from the statistische Ämter der Länder (2017a) for 2008.

Vehicle class (calcu-lation)	Vehicle class (statistische Ämter der Länder, 2017a)	Literature (statistische Ämter der Länder, 2017a)	Calcu-lation	Difference
Motor-cycles	Motor-cycles	20.64%	19.58%	1.06%
Passenger cars	Passenger cars	21.53%	21.33%	0.19%
Buses	Buses	21.28%	21.15%	0.13%
Light duty vehicles, rigid trucks, trailer trucks and other vehicles	Trucks + tractors	17.97%	18.70%	-0.73%
Articulated trucks	Articulated trucks	22.32%	22.57%	-0.25%

As seen in Table 1, the deviation of the calculated values from the literature values is very small. As a conclusion, the chosen approach is sufficient.

The MLR models for counties and municipalities were developed on the basis of mileages for these from the State Institute for the Environment in Baden Württemberg (in German: Landesanstalt für Umwelt Baden-Württemberg)(LUBW, 2018). The statistical data population, gross domestic product, gross value added, employed persons, compensation of employees, standard volume of employed persons, gross wages and salaries, available income of private households and vehicle stock (James et al., 2017; Kba, 2014a; Statistische Ämter der Länder, 2017b; Statistische Ämter der Länder, 2017c; Statistische Ämter der Länder, 2017d), as well as the street length of the four street categories (federal highways , federal roads, state roads and district roads), as well as the urban area percentage, were analyzed during the development of the MLR model for the counties. As result on this analysis, the population, gross domestic product, employed persons, compensation of employees, available income of private households, the street length and the urban area percentage were utilized in the model.

For the MLR model's development for municipalities, the available data was limited. As a consequence, only the population, length of the streets per category and percentage of urban area were used during the model's development.

For both model approaches, the mileages for passenger cars, light duty vehicles, heavy duty vehicles and motorcycles were calculated via equation (1):

$$\Gamma_{i,v} = c_v + \sum b_{v,s} \cdot I \quad (1)$$

, where $\Gamma_{i,v}$ is the mileage for county/municipality i and vehicle class v, c_v is the constant for vehicle class v, $b_{v,s}$ is the factor for vehicle class v and statistical/spatial value s and I is the statistical/spatial value.

Table A 1, in the electronic supplementary information, shows the determined constants c_v and factors $b_{v,s}$ for the different vehicle classes v for the calculation of the mileages of the counties (see equation (1)).

A comparison of the calculated model results for the counties of Baden-Württemberg, with the values from the State Institute for the Environment in Baden Württemberg (LUBW, 2018), indicated that the coefficient of determination between the MLR model values and literature values was 94% for passenger cars (PC), 86% for light duty vehicles (LDV), 74% for heavy duty vehicles (HDV) and 86% for motorcycles (MC). Figure 1a shows that these values are always higher than the calculated linear regression model values for gross domestic product, population and vehicle stock. Moreover, Figure 1a shows that the vehicle stock is not suitable to distribute mileages on the county level or more detailed communal levels, because the coefficient of determination for all vehicle classes is below 2%. The linear regression model for the gross domestic product has higher coefficients of determination (from 47% for passenger cars to 34% for heavy duty vehicles), while the coefficients of determination of the linear regression model for the population are the closest to the ones of the MLR model (from 71% for light duty vehicles to 49% for heavy duty vehicles). However, there is still a large gap between the coefficients of determination of the linear regression model of the population and the ones of the MLR model, making the MLR model the most accurate amongst the approaches considered. The elucidated values of the MLR model also point out, that the model calculates the mileages for passenger cars with the highest accuracy (94%), while the mileages of heavy duty vehicles are calculated with a lower accuracy (74%). The calculation accuracy of light duty vehicles and motorcycles is with a determination coefficient of 86% between those of passenger cars and heavy duty vehicles.

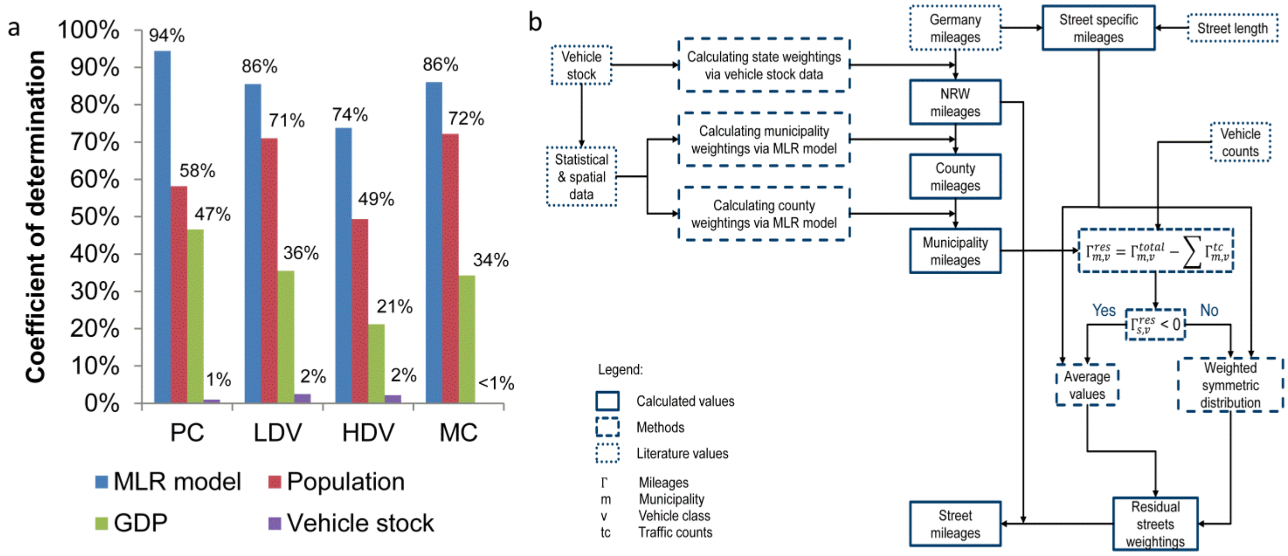

Figure 1. (a) Comparison of the calculated MLR model values with the calculated linear regression models from population, gross domestic product and vehicle stock for Baden-Württemberg. (b) Methodology for the calculation of vehicles mileages for each street section in North Rhine-Westphalia without traffic counts.

Table A 2, in the electronic supplementary information, displays the determined factors of the MLR model for municipalities (see equation (1)). A comparison of the MLR model for municipalities for Baden-Württemberg and the literature values from the State Institute for the Environment in Baden Württemberg (LUBW, 2018) came to coefficients of determination of 63% for passenger cars, 57% for light duty vehicles, 39% for heavy duty vehicles and 60% for motorcycles. These values indicate that the MLR model for municipalities has the best calculation accuracy for passenger cars, following with the calculation accuracies of motorcycles and light duty vehicles. Of all four vehicles classes, the MLR model has the lowest calculation accuracy for heavy duty vehicles.

Weightings for the four different vehicle classes, PC, LDV, HDV and MC, for each municipality for the state of NRW were calculated using the developed MLR model. The following steps were carried out to calculate the mileages on each street (see Figure 1b): First, the national mileages from Bast (2017) were distributed to each of the municipalities, along with the respective weightings. The vehicle classes of the MLR model differ from those of the national mileages. The weightings for passenger cars were also used for other vehicles, while those for heavy duty vehicles were used for the vehicle classes of buses, rigid trucks, trailer trucks and articulated trucks. Second, the resulting mileages for the eight vehicle classes were calculated for each municipality with a balance around each considering the calculated mileages as well as the mileages from the traffic counts from Bast (2018)). Third, the calculated mileages were distributed across the five street categories in each municipality with consideration of the length of the streets without traffic counts inside each municipality and street-specific mileages. The street-specific mileages of eight vehicle classes and five street classes for the year 2014 were calculated with the national mileages for each vehicle class on each street class using data from the Federal Highway Research Institute (Bast, 2017) and the length of each street class in Germany from the Federal Ministry of Transport and Digital Infrastructure (in German: Bundesministerium für Verkehr und digitale Infrastruktur) (BMVI, 2018a).

The calculated values are shown in Table 2. Fourth, these mileages are distributed symmetrically on the streets without traffic counts in each municipality. Branches (e.g., federal highway on-ramps and traffic circles) were neglected in the street grid used. The street grid was created using datasets from Bast (2018) and Land NRW (2019). As mentioned above, the mileages on each street with traffic counts were calculated on the basis of the literature (Bast, 2018; Kba, 2014a; MWEBWV NRW, 2014).

The resulting traffic volume map, showing the traffic volume for the eight vehicle classes (motorcycles, passenger cars, light duty vehicles, buses, rigid trucks, trailer trucks, articulated trucks and other vehicles) for single street sections of a street grid map of NRW, consisting of 2,200 km of federal highways, 4,400 km of federal roads, 13,000 km of state roads, 9,700 km of district roads and 68,400 km of other streets, is open source available as a published dataset and can be downloaded in Breuer et al. (2019a).

Table 2. Street-specific mileages for Germany in 2014 in 1000 vehicle-km/street-km.

Vehicle class	Federal highways	Federal roads	State roads	District roads	Other streets
Motorcycles	142.36	73.04	52.93	27.71	9.49
Passenger cars	13044.87	3655.42	1349.90	664.48	189.50
Light duty vehicles	1467.35	318.61	92.39	46.00	13.84
Buses	46.39	22.38	11.71	5.96	2.55
Rigid trucks	546.02	152.71	35.62	19.73	7.61
Trailer trucks	869.98	70.83	9.73	6.36	1.97
Articulated trucks	1279.67	130.41	19.82	10.46	3.26
Other vehicles	151.15	18.64	6.78	3.04	0.42

3.2 Emission calculation

Exhaust emissions were calculated via equation (2):

$$TE_{p,i} = \sum_{s=0}^{s_{max,i}} \Gamma_{s,v,c,f} \cdot EF_{p,v,c,f} \qquad (2)$$

, where *TE* is the total emissions for the defined time period, grid cell *i* and pollutant *p*, Γ is the mileage of vehicle class *v* on street *s* in the landscape *c* with fuel *f*, *EF* is the emission factor for pollutant *p*, vehicle class *v*, landscape *c* and fuel *f* and $s_{max,i}$ is the number of streets in grid cell *i.*

The emission factors were aggregated using the Handbook Emission Factors for Road Transport Version 3.3 (Infras, 2017) for urban, rural and highways traffic conditions. Furthermore, an average weighted temperature of 10.24 °C (Infras, 2017) for Germany was assumed. Cold start emissions, evaporation soak, evaporation diurnal and running losses were also considered in addition to the exhaust emissions of the engine at operating temperature.

The developed dataset is based on the available data and is thus valid for the year 2014. The calculation of the emissions for the year 2018 requires the temporal development of the mileages. This temporal development is calculated based on the work of Schubert et al. (2014), who published passenger kilometers as well as the number of transported persons for the years 2010 and 2030 (projected) for motorized individual transport and public road transport. In addition to this, they also published the transported goods, tonne-kilometres (tkm) and average distances for, amongst others, road transport. Based on Schubert et al. (2014), the following yearly developments were calculated for the model:

- 0.26% for motorized individual transport
- 0.42% for public road transport
- 0.95% for road freight transport

A detailed description of the calculation is given in the appendix in the electronic supplementary information (see Table A 4 and Table A 5).

In this work, the average distance for motorized individual transport was applied to the vehicle classes of motorcycles, passenger cars and other vehicles, while for buses, the average driving distance for public road transport was applied (see Table A 4). For light duty vehicles, rigid trucks, trailer trucks and articulated trucks, the average transport distance was used (see Table A 5).

For the calculation of cold start emissions, average urban trip distances were required. The average urban trip distance for passenger cars of 8.19 km/trip was obtained from a report regarding mobility in Germany in 2017 for passenger cars published by the Federal Ministry of Transport and Digital Infrastructure (BMVI, 2018b). The following average urban trip distances for motorcycles and light duty vehicles were calculated using the mentioned report and a report regarding transportation in Germany in 2010 for all vehicle classes by the Federal Ministry of Transport, Building and Urban Affairs (in German: Bundesministerium für Verkehr, Bau und Stadtentwicklung) (BMVBS, 2012):

- 5.14 km/trip for motorcycles
- 6.68 km/trip for light duty vehicles

A detailed description of the calculation is given in the appendix in the electronic supplementary information (see Table A 6).

Abrasion emissions were calculated using the tier 2 methodology from the EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016 (EEA, 2016). Emissions were subdivided into tire wear, brake wear and road surface wear emissions. Tire and brake wear emissions were calculated with equation (6):

$$TE = \sum_{j} N_j \cdot M_j \cdot EF_{TSP,s,j} \cdot f_{s,i} \cdot S_s(V) \qquad (3)$$

, where TE represents the total emissions for the defined time period and spatial boundary in g, N_j is the Number of vehicles in category *j* within the defined spatial boundary, M_j is the mileage in km driven by each vehicle in category *j* during the defined time period, $EF_{TSP,s,j}$ is the TSP (total suspended particles) mass emission factor for vehicles in category *j* and emission source *s* (i.e., tire wear or brake wear) in g/km, $f_{s,i}$ is the mass fraction of TSP of emission source *s* that can be attributed to particle size class *I* and $S_s(V)$ is the correction factor of emissions source *s* for a mean vehicle travelling speed *V.*

The emission factor is, amongst other aspects, velocity-dependent. Average velocities per vehicle class and landscape category (i.e., rural, urban, highway) were taken from the Handbook Emission Factors for Road Transport (Infras, 2017). Moreover, the average number of truck axles and average load factors were needed for the calculation of the correction factor. These values were calculated on the basis of data from the Federal

Motor Transport Authority and the Federal Statistical Office (Destatis, 2019; Kba, 2018; Kba, 2019) and are listed in Table 3.

Table 3. Calculated number of truck axles and load factors for buses, rigid trucks, trailer trucks and articulated trucks using data from the Federal Motor Transport Authority and the Federal Statistical Office (Destatis, 2019; Kba, 2018; Kba, 2019).

	Number of truck axles	Load factors
Buses	2.27	0.20
Rigid trucks	2.51	0.32
Trailer trucks	4.83	0.33
Articulated trucks	4.94	0.36

For the calculation of the percentage of fuels on emissions per vehicle class, fleet percentages from the Handbook Emission Factors for Road Transport (Infras, 2017) were taken and are listed in Table 4. The values are subdivided into three different landscapes. Highways are equal to federal highways. Federal roads, state roads, district roads and other road types are subdivided, being either inside urban morphological zones or outside (rural). Urban morphological zones are defined by CORINE (Coordination of Information on the Environment) land cover classes (EEA, 2019). Further information on the methodology for urban areas is available through the European Environment Agency (EEA, 2014).

Table 4. Fuel mix in the researched fleet based on the Handbook Emission Factors for Road Transport (Infras, 2017).

Vehicle class	Landscape	Gasoline (two-stroke)	Gasoline (four-stroke)	Diesel
Motorcycles	Highways	3.9%	96.1%	0%
	Rural	19.1%	80.9%	0%
	Urban	46.2%	53.8%	0%
Passenger cars	Highways	0%	45.2%	54.8%
	Rural	0%	49.2%	50.8%
	Urban	0%	49.2%	50.8%
Light duty vehicles	Highways	0%	3.8%	96.2%
	Rural	0%	3.9%	96.1%
	Urban	0%	3.9%	96.1%
Urban buses	Highways	0%	0%	100%
	Rural	0%	0%	100%
	Urban	0%	0%	100%
Coaches	Highways	0%	0%	100%
	Rural	0%	0%	100%
	Urban	0%	0%	100%
Heavy duty vehicles	Highways	0%	0%	100%
	Rural	0%	0%	100%
	Urban	0%	0%	100%

3.3 Visualization

For the visualization of the following analysis, different balance areas (grids) were used for the calculation, whereby emissions were normalized to the area. The three grids used for the visualization are a grid with 1 km² cells, the municipality grid of NRW and urban morphological zones (EEA, 2014) in NRW with an area larger than 10 km². The classification of the different value intervals for the visualization was carried out using a Fisher Jenks optimization. The mean-based Fisher Jenks optimal classifier was used for the 1 km² grid due to performance reasons, while the mean-based using random sample Fisher Jenks optimal classifier was used for the municipality grid and urban areas grid. Further information on these classification schemes is available in the *Mapclassify* documentation (Pysal developers, 2019).

4. Results

In this section, the results of the discretization of the road transport mileages and those of the emission calculation for the model region North Rhine-Westphalia for the year 2018 are presented. In the first section, a short overview of the traffic volume maps developed is given. In the second, the results of the NO_x emission calculation for the balance levels 1 km² grid, municipalities and urban areas are shown. Furthermore, a detailed analysis of the emission hotspots, as well as of the urban area of Oberhausen, is provided with consideration of different vehicles classes and fuels. In the last section, the results of the PM10 emission calculation for the balance levels 1 km² grid, municipalities and urban areas are displayed. Additionally, the hotspots and the urban area of Oberhausen are analyzed in detail in terms of the different vehicle classes, fuels and PM emission sources. The calculated values for the traffic volume, NO_x emissions and PM10 emissions are illustrated in Figure 2 to Figure 6, as well as in the electronic supplementary information in Figure A 1 to Figure A 8.

In addition to the NO_x and PM10 emissions, the emissions values for unburned hydrocarbons, carbon monoxide, carbon dioxide, nitrous oxide, ammonia, non-methane hydrocarbons, nitrogen dioxide, lead, particle number, sulfur dioxide, benzol and methane were calculated using the developed approach. The dataset with the discussed NO_x and PM10 emissions, as well as with carbon dioxide and carbon monoxide emissions values, is open source and can be found in Breuer et al. (2019b). (Please contact the corresponding author of this work if you are interested in the emission values that are mentioned above but not contained in the accessible dataset).

4.1 Traffic volume

Figure 2 shows the results of the discretization for passenger cars (PC) on federal highways (Bab), federal roads (B), state roads (L) and district roads (K) (a), as well as on other streets (b). The appropriate results for motorcycles, light duty vehicles, buses, rigid trucks, trailer trucks, articulated trucks and other vehicles are attached in the electronic supplementary information (see Figure A 1 to Figure A 7). The resulting dataset is available open source and accessible in Breuer et al. (2019a). Figure 2a displays that the highest traffic intensity of passenger cars is on federal highways, as well as in the Ruhr area and along the Rhine. The other vehicle classes have a similar distribution of mileages, whereas motorcycles and light duty vehicles have the highest traffic intensity in urban areas (see electronic supplementary information Figure A 1, Figure A 2) and heavy duty vehicles (i.e., rigid trucks, trailer trucks and articulated trucks) have the highest traffic intensity on federal highways (see electronic supplementary information Figure A 4 to Figure A 6).

4.2 NO_x emissions

Figure 3a shows the specific NO_x emissions in kg/km² visualized on the 1 km² grid. The major preponderance of emissions are produced on federal highways and in the urban areas in the Ruhr area, around Cologne and around Düsseldorf, reasoned by the high specific mileage on federal highways and the fleet composition. The share of heavy duty vehicles on federal highways is significantly higher than that on the other street types.

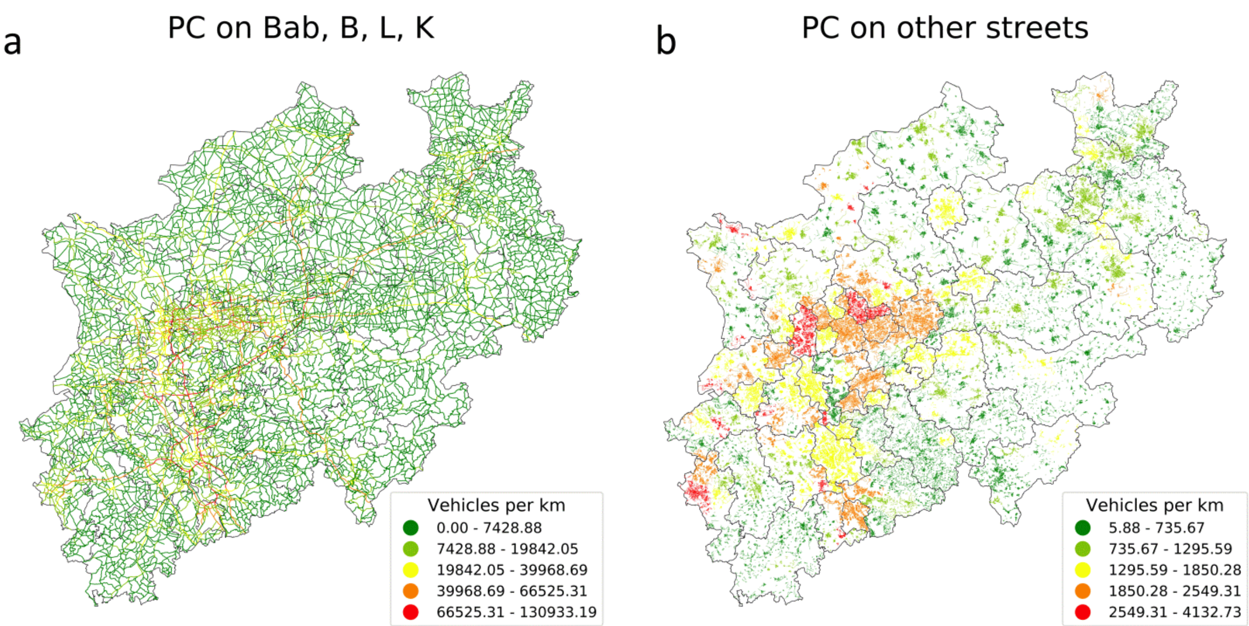

Figure 2. Passenger cars (PC) on federal highways (Bab), federal roads (B), state roads (L) and district roads (K) (a), as well as on other streets (b) in vehicles per km.

Figure 3 also displays the specific NO_x emissions in kg/km² for the municipalities (b), as well as the specific NO_x emissions for urban areas (c). The tendencies (see Figure 3 a, b, c) appear to be identical. Based on Figure 3, it can be concluded that the hotspots are in the Ruhr area, around Cologne and Düsseldorf, as well as Aachen. The ten urban areas with the highest specific NO_x emissions shown in Figure 3c are Herne, Oberhausen, Bochum, Duisburg, Wuppertal, Gelsenkirchen, Essen, Leverkusen, Bonn and Wesseling. The ten municipalities with the highest specific NO_x emissions (see Figure 3b) are Oberhausen, Herne, Sankt Augustin, Bochum, Gelsenkirchen, Duisburg, Gladbeck, Langenfeld, Essen and Hilden. Figure 3d shows the differences between the two balance levels, municipalities and urban areas, and the importance of observing urban areas instead of only municipalities. There are major differences in the specific emissions for urban areas and municipalities (e.g., Wuppertal, Leverkusen and Wesseling). One reason for this is the urban area share, which is different for each municipality (see Figure 3d). Another reason is the position and existence of federal highways. Whether these are inside or outside urban areas is decisive. For the cities of Hilden, Langenfeld and Sankt Augustin, the NO_x emissions of the municipalities are higher than the emissions in the urban area of the corresponding urban

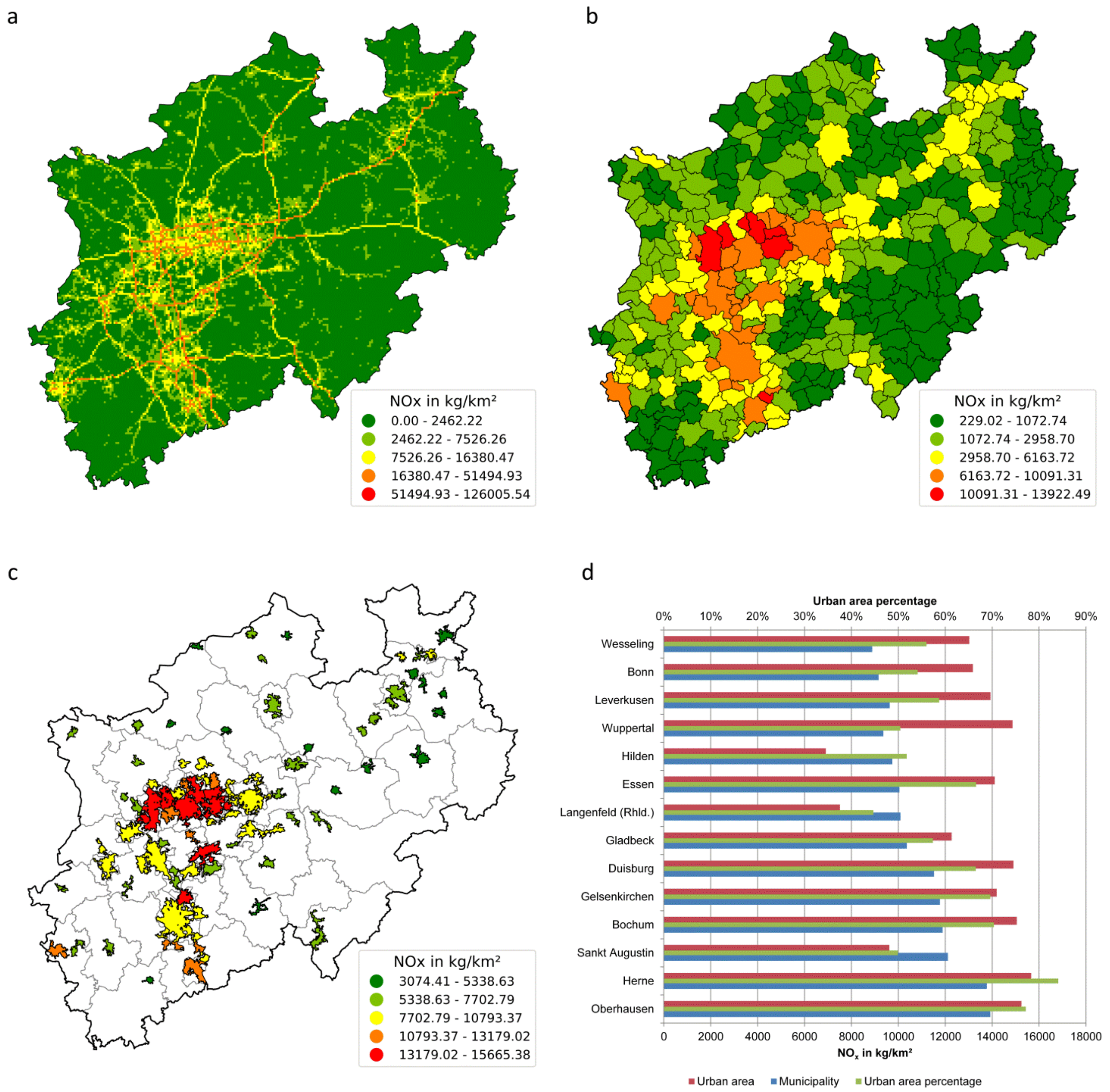

Figure 3. (a) Specific NO_x emissions 2018 from road transport for a 1 km² grid. Specific NO_x emissions in 2018 from road transport for urban areas > 10km² (b) and municipalities (c). (d) Specific NO_x emissions of urban areas and municipalities in 2018 as well as urban area percentage for each municipality.

areas. The reasons for this are that the federal highways are mainly positioned outside of the urban areas. The weight of federal highways for emissions calculation was discussed above, pertaining to Figure 3a.

Figure 4a shows the vehicle classes that emit the specific NO_x emissions in the ten urban areas in NRW with the highest NO_x emissions. Passenger cars are responsible, on average, for 62.66% of the specific NO_x emissions and are the largest source. With 0.57% and 0.21%, motorcycles and other vehicles are only responsible for a minority of total emissions in urban areas. In contrast, heavy duty vehicles (i.e., rigid trucks, trailer trucks and articulated trucks) produce 21.68% of NO_x emissions and are, as such, the second highest polluters. Light duty vehicles make up 10.05% and buses 4.83%. Figure 4a shows that the shares of polluters in the case of vehicles are not equal but similar for the different urban areas. Figure 4a also displays the percentage of fuels in the different vehicle classes. On average, for these ten cities, passenger cars running on gasoline and diesel are responsible for 7.56% and 55.1% of NO_x emissions, respectively. Additionally, diesel-fueled light duty vehicles emit on average 9.92% of the NO_x emissions, while light duty vehicles running on gasoline produce 0.11% of total NO_x emissions.

Figure 4b illustrates the shares of the different vehicle classes of the total NO_x emissions and the total mileages for 2018 in Oberhausen as the second highest polluter in terms of NO_x emissions in urban areas. With respect to mileages, the relationship between diesel and gasoline as fuel for passenger cars is nearly balanced (43% gasoline and 57% diesel), while for NO_x emissions, the majority is produced by passenger cars with diesel engines (91%). Motorcycle mileages constitute 3.3% of the mileages, but only produce 0.8% of the NO_x emissions. Of all the vehicle classes, buses exhibit the largest gap between the percentage of mileages (0.5%) and the percentage of produced NO_x emissions (8.8%). For heavy duty vehicles (i.e., rigid trucks, trailer trucks and articulated trucks), the relationship is mostly similar. The vehicle kilometers of rigid trucks, trailer trucks and articulated trucks are 2.4%, 0.9% and 2.7%, respectively, while their shares of NO_x emissions are 8.8%, 2.8% and 8.2%.

4.3 PM emissions

Figure 5a shows the calculated PM10 emissions for the year 2018 balanced around 1 km² grid cells. The visualization of the results looks similar to Figure 3a. Hotspots are, again, the Ruhr area as well as the areas around Cologne, Düsseldorf and Aachen and generally federal highways. The corresponding values of the PM10 emissions balanced around the urban areas and municipalities can be found in the electronic supplementary information (see Figure 8 A), with the visualization being similar to Figure 3 b, c.

Figure 5b shows the twelve (§§) municipalities and urban areas with the highest PM10 emissions, ranked from the lowest specific municipality PM10 emissions to the highest (top to bottom). The ranking differs from that for NO_x emissions because PM10 emissions consist not only of exhaust emissions, but also abrasion emissions. With increasing vehicle velocity, exhaust emissions increase, while abrasion emissions decrease. As can be seen in Figure 5b, the differences between specific emissions in urban areas and municipalities are even higher for some of the ranked cities (e.g., Aachen and Brühl). This is, again, amongst others, linked to the urban area percentage and spatial position of the federal highways.

Figure 5c shows the percentage of calculated brake wear,

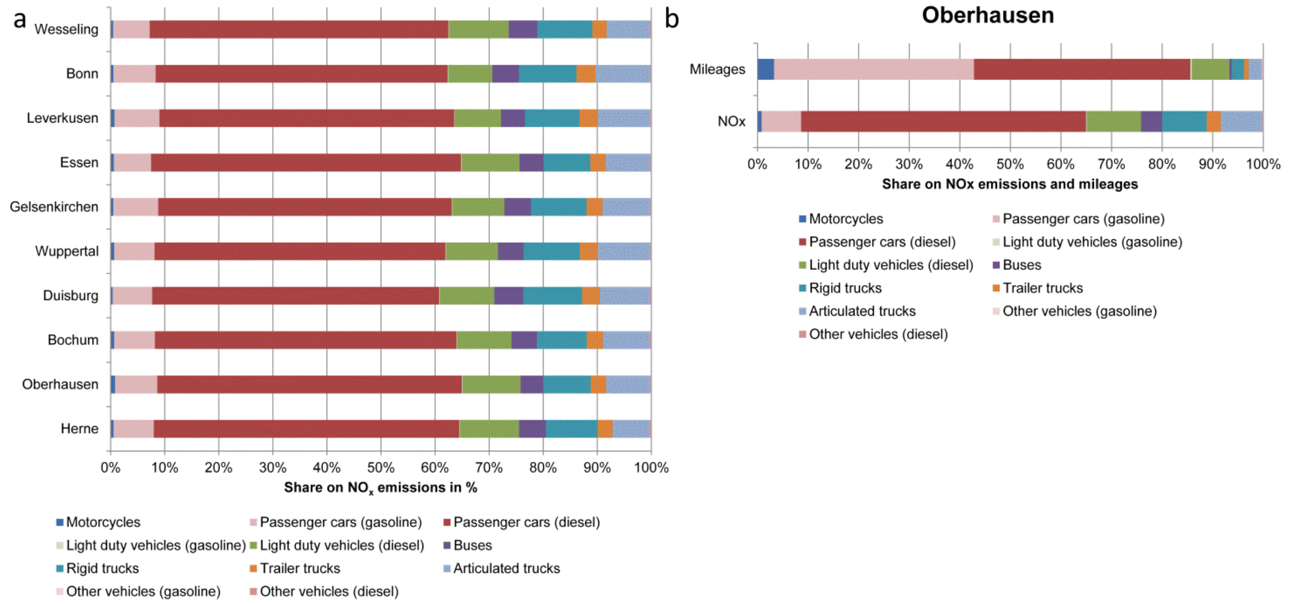

Figure 4. (a) NOx emissions of the 10 urban areas with the highest NOx emissions in 2018. (b) Percentage of the vehicle classes of total mileages and NOx emissions for Oberhausen in 2018.

tire wear, road surface wear and exhaust emissions of total PM10 emissions for the ten urban areas with the highest specific PM10 emissions in 2018. The shares of each PM10 emission source are mostly constant. On average, exhaust emissions make up about 22% of the total PM10 emissions. Furthermore, brake wear, tire wear and road surface wear are, respectively, responsible for 30%, 25% and 24% of the total PM10 emissions.

As discussed above, Figure 5c shows that the composition of PM emission sources is mostly similar in the investigated cities. Based on this similarity of the bars shown in Figure 5c, as before, Oberhausen is selected as a representative hotspot for the following, deeper analysis.

The shares of the different vehicle classes and fuels of the total mileages, as well as the shares of PM10 emissions from tire wear, brake wear, road surface wear and exhaust in the urban area of Oberhausen, are illustrated in Figure 5d. Light duty vehicles have lower shares of PM10 emissions in terms of abrasion (i.e., tire wear, break wear and road surface wear), while the corresponding share of PM10 emissions from exhaust is, in comparison, higher. In contrast, passenger cars emit a larger share of abrasion PM10 emissions and a lower percentage of exhaust emissions. Heavy duty vehicles (i.e., rigid trucks, trailer trucks, articulated trucks) and buses produce a higher share of PM10 emissions from road surface wear and a lower share of PM10 emissions from tire wear, brake wear and exhaust emissions.

Figure 6 displays the shares of total driven kilometers in Oberhausen with diesel fuel and gasoline fuel, the percentage of NO_x emissions of vehicles with diesel and gasoline fuel as well as the percentage of PM10 emissions

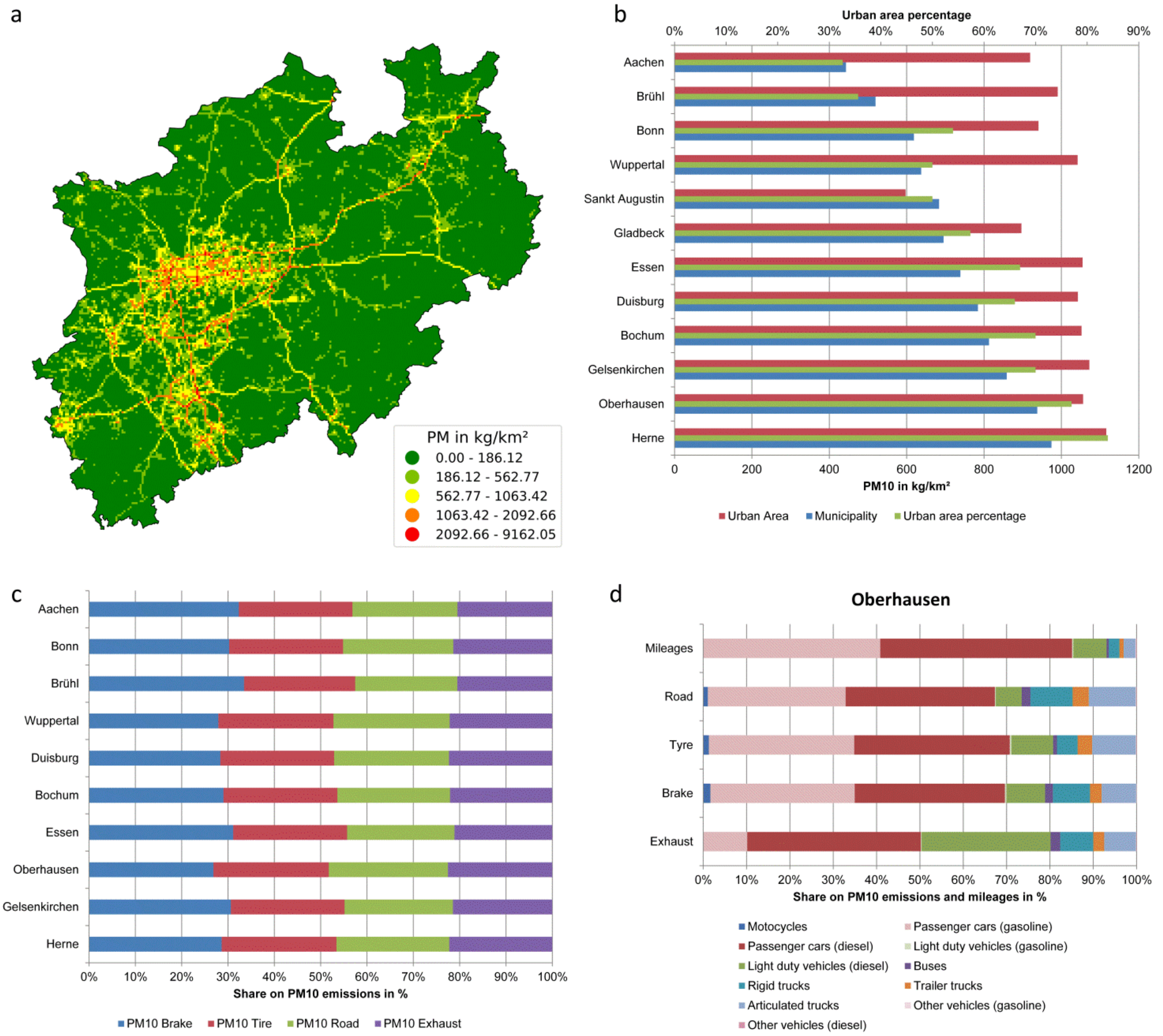

Figure 5. (a) Specific PM10 emissions 2018 from road transport for a 1 km² grid. (b) Specific PM10 emissions of urban areas and municipalities and urban area percentage of each municipality in 2018. (c) Percentage of brake wear, tire wear, road surface wear and exhaust emissions of total PM10 emissions for the 10 urban areas with the highest specific PM10 emissions in 2018. (d) Share of the different vehicle classes and fuels on PM10 emissions (road, tyre, brake and exhaust) and mileages in the urban area of Oberhausen.

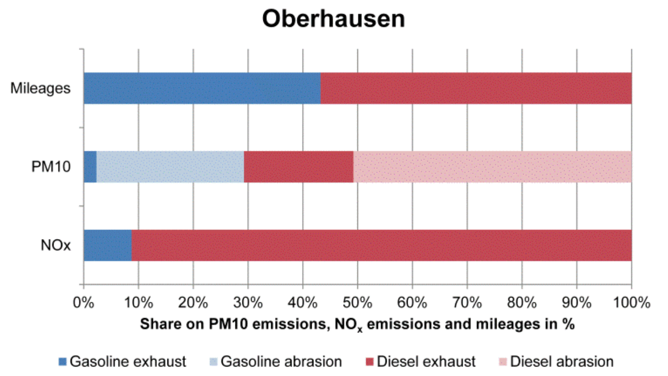

Figure 6. Percentage of mileages, PM10 emissions and NOx emissions from vehicles driven with gasoline (blue) and vehicles driven with diesel (red).

of vehicles with diesel and gasoline fuel. Figure 6 clearly shows the overall emission reduction potential in the urban area of Oberhausen. NO_x emissions can be reduced by up to 100% by replacing the fuel with an alternative fuel with no harmful emissions (e.g., hydrogen in fuel cell vehicles), up to 91% by replacing only diesel and up to 9% by replacing only gasoline. PM10 emissions can be reduced by up to 22% by replacing the fuel. 2% of PM10 emissions are from gasoline exhaust and 20% from diesel exhaust. The remaining 78% are abrasion emissions from bake wear, tire wear and road surface wear and would not change with the use of another fuel. 27% of abrasion PM10 emissions are from vehicles running with gasoline, while 51% are from vehicles running with diesel.

5. Discussion

An important finding of this work is the non-existent connection between specific emissions at structural community levels like municipalities and urban areas. As was stated above, in the case of harmful emissions, the local impact in highly populated urban areas is important. We showed in this study that there is no relationship between specific emissions in both balance areas. As a consequence, analyses of emissions at the municipality level as performed in the literature by LANUV (2018), Schneider et al. (2016a), Peace et al. (2004) or Fameli and Assimakopoulos (2015a) might be inaccurate. Using a grid with a specific size like 1 km² is state of the art in the literature (e.g., Romero et al. (2020), Fameli and Assimakopoulos (2015a)). Specific grids are especially suitable for identifying spatial emission hotspots. However, if the aim is to assess the share of emissions from different sources, a suitable balance area must be selected. As was stated above, to the best of the authors' knowledge, an analysis that considers area-specific emissions in urban areas using the urban morphological zones (EEA, 2014) has not been previously performed. Oberhausen, Holzwickede and Herne are the municipalities with the highest specific NO_x emissions refering to LANUV (2018), while for urban areas in this work, the urban areas with highest specific NO_x emissions are Herne, Oberhausen and Bochum. Holzwickede is a suitable example of the significance of considering urban areas instead of community structure levels. While, in the work of LANUV (2018), Holzwickede is the municipality with the third highest specific NO_x emissions, it is not even included in the ten urban areas with the highest specific NO_x emissions in this study. The reasons for this are that the urban area of Holzwickede is below 10 km², but also that the federal highway there is outside of the urban area. The combination of a federal highway with a high traffic intensity and a small municipality area probably leads to the high specific NO_x emissions reported in the LANUV (2018).

Fameli and Assimakopoulos (2015a) and Sun et al. (2016) state that heavy duty vehicles are responsible for the largest share of PM10 and NO_x emissions in the Attica region in Greece and the Shandong Province in China. These results differ from our in-depth analysis of the emission hotspot of Oberhausen, where passenger cars dominate the NO_x and PM10 emission production (see Figure 4b and Figure 5d). This has been caused through a different feet mix. While the share of diesel passenger cars in Greece and China is near to zero (Fameli and Assimakopoulos, 2015a; Transport & Environment, 2017), diesel cars in Germany account for up to 57% of passenger cars (see Figure 4b). Fameli and Assimakopoulos (2015a) also mention that the dieselization of passenger cars will increase NO_x emissions. Fameli and Assimakopoulos (2015a) and Sun et al. (2016) only consider exhaust emissions. This is the reason why heavy duty vehicles are the predominate PM10 source in their work. In this study, wear from tires, roads and brakes is also considered and accounts for up to 75% of PM10 emissions. Figure 5d clearly shows that the impact of heavy duty vehicles on exhaust PM10 emissions is higher than for wear emissions, especially considering that in China and Greece, passenger cars are mainly gasoline-fueled.

The most effective strategy to lower NO_x emissions in urban areas would be the prohibition of diesel passenger cars, which would lead to a NO_x reduction of approximately 55% for the exemplary emission hotspot of Oberhausen (see Figure 4b). For PM10 emissions, this strategy would reduce the emissions by only about 10% due to the share of unchanged wear emissions from passenger cars (see Figure 5). Other efficient approaches are the electrification of passenger cars by means of battery-electric vehicles or fuel cell-electric vehicles, which have zero exhaust emissions. Due to the large share of passenger cars in the total distances traveled, this would reduce road transport NO_x emissions by up to 65% and PM10 emissions by up to 11% (see Figure 4 and Figure 5). The only possibility for reducing road transport PM10 emissions in urban areas is to reduce the total driven distance from vehicles. Due to the high share of mileages passenger cars, strategies for them would be most effective.

6. Conclusions

In this work, we presented a bottom-up approach for the detailed calculation of emissions at the street level for the model region North Rhine-Westphalia in Germany incorporating the different vehicle classes, namely motorcycles, passenger cars, light duty vehicles, buses, rigid trucks, trailer trucks, articulated and other vehicles, as well as gasoline and diesel as fuels. Detailed spatial street level information on mileages and fleet composition is mandatory for calculating emissions with a high degree of accuracy and to analyze the emission sources in terms of vehicle classes and fuels. To determine this information, we introduce a methodology that draws on data from traffic counting, as well as a top-down approach we developed based on multivariate linear regression and different spatial and statistical data, considering eight different vehicle classes and five different street classes.

Furthermore, we present a detailed analysis of NO_x and PM10 emissions in the urban areas of North Rhine-Westphalia, and especially Oberhausen, as a representative emission hotspot. The main conclusions of this study are as follows:

- In the case of downscaling mileages and emissions via the top-down approach, the vehicle stock is not suitable as activity data for counties and municipalities.
- For analyzing harmful emissions, it is insufficient to only observe community structure balance area. It is essential to also investigate the urban areas of the counties/municipalities, because the values may strongly differ as a result of different urban area percentages and the position of highways.
- The urban areas with the highest specific NO_x emissions are Herne, Oberhausen and Bochum, while the urban areas with the highest specific PM10 emissions are Herne, Oberhausen and Gelsenkirchen.
- For PM10 as well as NO_x emissions, vehicles running with diesel produce the majority of exhaust emissions.
- For Oberhausen as a representative hotspot in the model region, the maximum emission reduction potential of NO_x exhaust emissions through the replacement of diesel and gasoline is 100%, while PM10 exhaust emissions can only be reduced to a maximum value of 22% by replacing diesel and gasoline.
- Aside from replacing the fuel, switching individual passenger transport or freight transport to other transport vehicles could be an option for reducing harmful emissions and should be investigated in the future.

The produced results identify the emission sources in the case of vehicles for harmful urban areas and are important for the discussion of using alternative fuels in different vehicles. The MLR model produced in the framework of the bottom-up approach and the resulting traffic flow dataset for the eight vehicle categories can be used for further investigations, such as the optimization of gas stations. The datasets *Road Traffic Volume Map 2014 for North Rhine-Westphalia, Germany* (Breuer et al., 2019a) and *Mileages and Harmful Emissions 2018 from Road Transport for North Rhine-Westphalia, Germany* (Breuer et al., 2019b) contain the resulting spatial maps of the mileage discretization and the emission calculation and can be accessed via the *Harvard Dataverse* without any charges.

Conflicts of interest

Declarations of interest: none.

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Notes and references

§ Multivariate linear regression is a special case of the common linear regression analysis. It is a statistical method to describe the relationship between one dependent variable and multiple independent variables with a linear function.

§§ 12 municipalities and urban areas with the highest PM10 emissions mean, at this point, that the 10 municipalities with the highest specific PM10 emissions, as well as the 10 urban areas with the highest specific PM10 emissions, were taken into account. Eight are included in both rankings, while Aachen and Brühl are only included in the urban area top 10 ranking and Sankt Augustin as well as Gladbeck are only included in the municipality top 10 ranking.

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