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Methodology for Estimating the NO_x Saving Potential by Building Charging Infrastructure for Electromobility

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Abstract

Currently, the topic of air pollution control is of great interest in Germany. The reasons for this are the longer-lasting exceedances of the mandatory NO_2 limit since 2010. These have led to lawsuits by the Environmental Action Germany. To comply with the demands quickly, one plotline is the promotion of electromobility. In this context, a methodology for estimating the potential savings of NO_x emissions by modelling the substitutable vehicle kilometers of conventionally powered vehicles is being developed. One of the aims is to derive the connection between the expansion of the charging infrastructure or rather the promotion of electromobility and the reduction of NO_x pollution. To this end, analyzes and forecasts relating to developments in the vehicle market and mobility in Düren are linked with the emission factors resulting from a traffic situation model. The basis for this includes region-specific, spatially highly resolved infrastructural, spatial structural and traffic data.

Keywords: electromobility; charging infrastructure (CIS); emission calculation; nitrogen oxide (NO_x); site selection; HBEFA

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1. The Significance of Nitrogen Oxides in the Context of Air Quality

The term nitrogen oxides (NO_x) describes nitrogen monoxides (NO) as well as nitrogen dioxides (NO_2). The anthropogenic main sources are predominantly combustion processes of combustion plants and motors. Therefore, the transport sector is with 486,200t NO_x/year (as of 2016) the largest producer of NO_x, which measures up to a percentage of about 40% [UBA 2018a]. From a medical perspective, NO_2 is especially dangerous for humans due to its damaging impact on the lung function [UBA 2019]. For this reason, NO_2 limits were introduced worldwide. When comparing the limiting values of NO_2-immission of different countries or regions globally, it becomes apparent that the limit of NO_2 classified as harmful differs significantly (table 1). This is, among other factors, a reason why the specification of limiting values is repeatedly subject to discussion between various expert groups.

Table 1. NO_2 immission limiting values in comparison
[own visualization based on 2008/50/EG, LRV (2018), BMU (2019), Herold (2015), WHO (2000)]

Region	1-hour limit (*µg/m³*)	Annual limit (*µg/m³*)	24-hour average (*µg/m³*)
EU	200	40	-
Switzerland	100[1]	30	80
USA	191	100	-
USA / California[2]	339	57	-
China	200	40	80
India	-	30 or 40	80
Brazil	320 or 190	100	-
Brazil / Sao Paulo	260	60	-
WHO Guideline	200	40	-

[1] limit applies to 95% of the ½-h average of a year
[2] limits apply to California as well as 16 other US states

1.1. Development of Limit Exceedance in Germany and Its Implications

In Germany, the atmospheric and environmental pollution with different harmful substances, for example, NO_x, has been observed for years. Thus, it is possible to map out the development of the pollution load. According to the data of the Federal Environment Agency (UBA), NO_x pollution in Germany has decreased by 58%, which corresponds to around 1.7 million tons a year, between 1990 and 2016, while the share of NO_2 pollution has increased [UBA 2018b]. This means that even though the overall pollution has decreased, the limiting values (see table 1) are regularly exceeded. These exceedances occur unequally at the measuring stations at differently classified sites with rural, urban/suburban or traffic-oriented backgrounds [UBA 2017a, UBA 2018b]. In 2018, special attention was paid to the subject of air pollution control because, due to ongoing exceedances of limiting values, the Environmental Action Germany filed numerous lawsuits against German cities and municipalities. One result is the sentence of the Federal Administrative Court from February 27th, 2018. It states that limited driving bans for (specific) diesel vehicles on specific roads or road sections are valid if they are the only appropriate measure for adhering to the NO_2 limits quickly [BVerwG 2018]. Consequently, there have already been driving bans in some cities.

1.2. Emissions, Transmissions, Immissions: Electromobility as a solution to comply with the limits

With regard to the discussion of the exceedance of pollution limits in cities, the differentiation between emissions and immissions is important. According to the Federal Immission Control Act [BMJV 2017], emissions are air pollutions, noises, vibrations, light, heat, radiation and similar environmental impacts emanating from facilities. In the context of traffic, this also applies to pollutants generated by motor vehicles, as for example the in this paper discussed pollutant NO_x. These emitted pollutants can be identified with the help of different models. The different model approaches are discussed in more detail in Chapter 2. Immissions, on the other hand, are not emerging impacts but rather air pollution, noises, vibrations, light, heat, radiation and other similar environmental impacts that affect humans, plants, and animals. Therefore, they result from emissions and can be tackled indirectly by controlling emission sources. Due to different diffusion processes (transmission), emerging emissions are not equal to existing immissions in one place. Rather, diffusion models must be considered for the analyses of the spatial distribution of different pollutants. The connection between emissions, transmissions, and immissions is shown in figure 1.

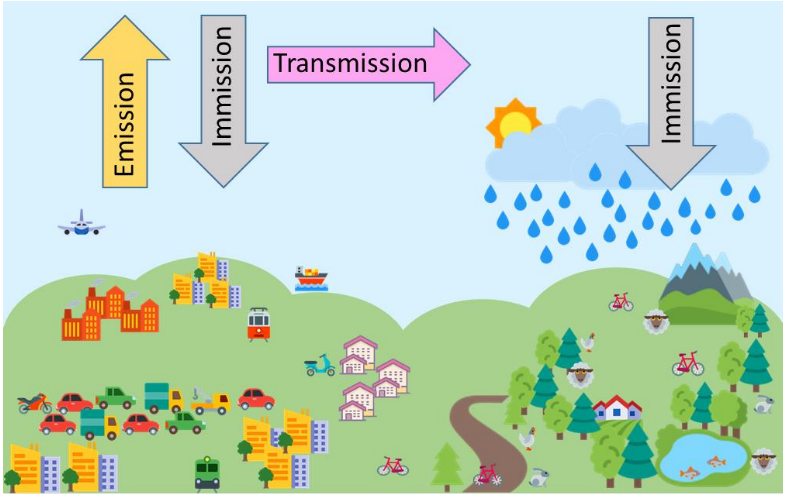

Fig. 1 Connections emissions, transmissions and immissions
[own visualization]

There are various approaches to decrease the emissions caused by traffic, and therefore the air pollution in general, and to adhere to limiting values: one strategy is the exclusion of vehicles as main emitters in the traffic sector from highly polluted areas. Another option, that is for instance pursued in Germany, is the substitution of conventional vehicles with electric vehicles. Electric vehicles do not pollute the air with direct combustion emissions so that the local pollution level can be reduced. However, it has to be considered that at the moment there are high emission levels of for example CO_2 caused by the vehicle provisioning and electricity supply. [UBA 2016]
In order to show the connection between the emissions of traffic and the immissions measured on roads, Forschungszentrum Jülich has published a nitric oxide calculator. For the different measuring stations in Germany, the required reduction of traffic emissions can be calculated, which is necessary to compensate for the respective local NO_2 exceedances of the limit value. [Forschungszentrum Jülich GmbH 2019]

2. Model approaches for calculating the emissions of the transport sector

The estimation of emissions emitted by a specific traffic volume is typically based on results of previously developed simulations, models or observations. Similar to the underlying input models and simulations, these estimation methods can be differentiated with regard to their level of detail into global, macroscopic or microscopic approaches (see figure 2).

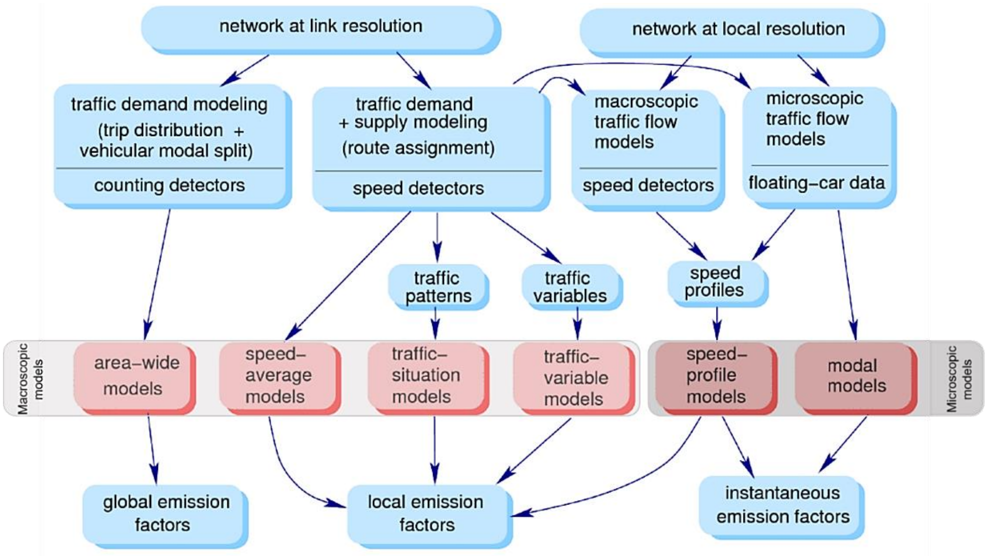

Fig. 2 Overview of emission models
[own modification based on Kanagaraj, Treiber 2017]

The present investigations in the context of the project eMIND (see section 3) intend to make statements regarding NO_x-saving potentials by substituting conventional vehicles with electric vehicles. The focus is on the overall result of a considered fleet composition instead of a single vehicle so that macroscopic model approaches regarding the applicability of this specific application case were analyzed in more detail.
With regard to the accuracy of the results of speed average models and traffic situation models, there are a number of studies with different findings. While previous studies have partly concluded that the speed average models would underestimate emissions [Haan, Keller 2000; Smit et al. 2008; Borge et al. 2012] the study by Smit et al. [2010] shows according to Borge et al. [2012] that NO_x emissions are underestimated in both speed average and traffic situation models. For this reason, the two model approaches COPERT V (Computer Program to Calculate Emissions from Road Transport) [EMISIA 2018], as an example of a speed average model, and the Handbook for Emission Factors of Road Traffic (HBEFA) 3.3 [2017], as an example of a traffic situation model, were compared for the planned research work within the project eMIND. In addition, other well-known model approaches for the determination of various pollutant effects such as TREMOD, VERSIT+, LIISA or GLOBEMI exist in Europe. Their use for the reporting of greenhouse gas and air pollutant emissions varies widely across European countries [Notter et al. 2016, p. 22]. However, the accessibility to the models is different. For example, the TREMOD model is not publicly available but is reserved for some German federal authorities and licensees [Knörr et al. 2016; Notter et al 2016]. For this reason, among other things, the analysis of this model for the application in the project eMIND is not pursued, even if the project area falls within the field of application (Germany) of the method. However, the spatial resolution levels differ, as TREMOD allows only a national overall emission representation. For the analysis of smaller-scale subareas, such as the project area Düren, a separate database would have to be created. [Notter et al. 2016]
All traffic emission models are based on emission datasets, which they then process with their methods to obtain as a result the pollutant emissions emitted by road traffic. Such an emission database is HBEFA. Within Europe, it is the most comprehensive road traffic emission model especially for the fleets of Germany, Austria, and Switzerland. HBEFA provides emissions per kilometer of a vehicle subsegment formed as a combination of the individual vehicle types (cars, LNF, SNF, buses, coaches, motorcycles) with the different characteristics (vehicle size, drive type, emission concept, emission reduction technologies) for different traffic situations. In turn, traffic situations depend on the type of area, the type of road, the prevailing speed limit and the traffic status. HBEFA provides this information on all regulated and individual non-regulated pollutants as well as fuel consumption. Thus, the output of a wide range of emission factors is possible. [UBA 2017b; Keller et at. 2017]
The model COPERT is currently used in most European countries. In addition to the distribution in Europe, there are versions for Asia, South America, Oceania and Australia [Notter et al. 2016, p. 33]. The method is suitable for calculating emissions from road transport at different spatial levels (countries, cities or roads). The temporal level can also be differentiated, whereby the smallest temporal level of observation is the period of one year. The model description of COPERT defines five submodules of the calculation method:

- Vehicle fleet (creates the stock data and differentiates the fleet segmentation by up to 266 categories)
- traffic activities (creates the driving performance input data, which includes, among other things, driving power shares and driving speeds differentiated by road, highway, rural and urban roads)
- emission factors (differentiated by type of emission, vehicle category, and road type)
- energy consumption (depending on vehicle type and average speed, based on HBEFA traffic situations)
- emission calculation (multiplication of fleet and traffic activity data with corresponding emission factors)

The results can be differentiated by vehicle type, road type, emission type and year. [Notter et al. 2016]

The strong point of COPERT to be applicable to many different European countries can, depending on the context, be construed as weakness at the same time. Since the case studied is a single region within Germany (see chapter 3), and the current research approaches have no intentions regarding an international application of the method to be developed (due to, among other things, lack of data in such detail for other areas), the model approach HBEFA specified for Germany is chosen. In addition, COPERT, as well as TREMOD, are partly based on HBEFA values, which makes the method of HBEFA the primary source, both because of its spatial relevance and because of its availability.

3. Project Study Düren

The project “eMIND – electric Mobility Integration Düren“ is part of the funding program “Charging Infrastructure for electric vehicles” as part of the ”Sofortprogramm Saubere Luft 2017 – 2020“ by the Federal Ministry for Economic Affairs and Energy (BMWi). It started in August 2018 and runs until September 2022. The consortium of the project is composed of three research partners as well as local actors of the city of Düren. Within the 90 municipalities designated by the BMWi, with exceedances of the annual average limit of 40 µg/m^3 NO_2 (as of 2016) [BAnz AT 04.01.2018 B2], Düren is among the eight most affected municipalities. Even though the trend has decreased between 2009 and 2017, the pollution level Düren is still at around 60 µg/m^3 (see figure 3). This results in the aim of the collaborative project to reduce the NO_x pollution in Düren significantly and sustainably. One approach to achieving this goal is the substitution of conventional vehicles with electric vehicles. To achieve this, the acceptance of electromobility by companies and private users should be increased. By building CIS at workplaces, the substitution of conventional with electric vehicles is promoted. For this purpose, semi-public CIS is built in the city of Düren within the project. The two use cases internal use in companies (fleets, employees) and public use (residents, tourists, customers) are to be distinguished. For the first user groups, statements of the employer can support assessments of the effects. For the latter user groups, different estimation methods need to be developed. To date, companies have already been selected after an application phase to build charging infrastructure (CIS). Other project partners will advise these companies and locations on the implementation quality and quantity of CIS in further steps.

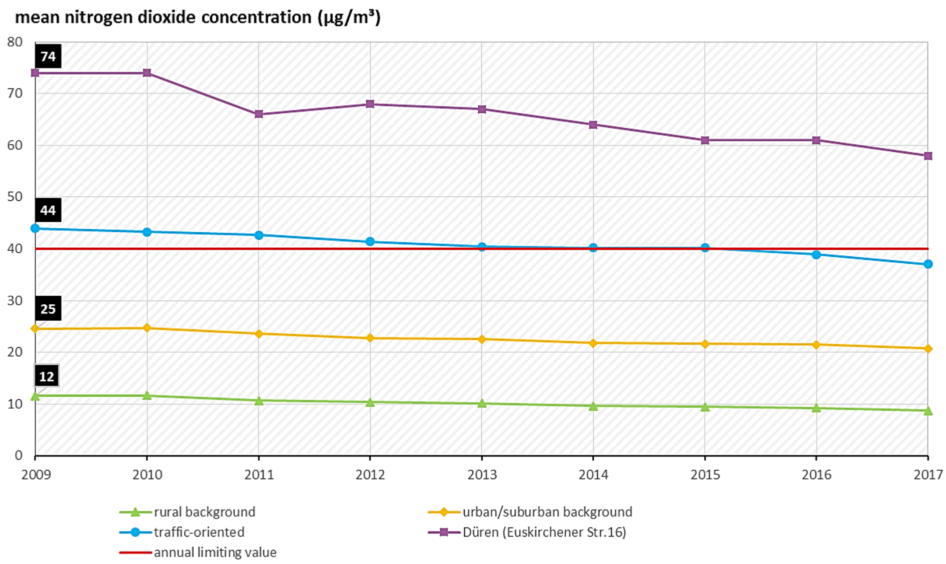

Fig. 3 Development of NO_2 annual average values in comparison between Düren and the national average at different measuring stations [own visualization based on UBA 2018, LANUV 2018]

4. Methodology for the estimation of NO_x-saving potential through the development of CIS

The methodology that will be developed during the course of this project for the estimation of the NO_x saving potential is based on the general idea that firstly, the transport performance of potentially substitutable conventional vehicles around future CIS is determined in order to, in a second step, calculate the NO_x emissions that can be reduced with the help of an emission model. The saving potential will be calculated for each spatial resolution level of the postal code five-level areas in Düren (see figure 5).

In order to generate input data for the estimation method of the NO_x-saving potential, different data sources and methods are used. The data sources include, inter alia, the traffic model for the region of Aachen, which was developed by the ISB between 2010 and 2016, and the site selection model for electric CIS (STELLA), which has been developed by the ISB since 2014 and is currently being further developed as part of various projects [Brost et al. 2018]. Furthermore, specific data from those employers who set up CIS within the project eMIND will be used. Such data include, for example, the mileage of the company fleet or source-destination connections of the employers.

4.1. Methodic procedure

The estimation of the saving potential of NO_x through the development of CIS is based on the development of three case distinctions and their comparison (see figure 4). In a first step, case ZERO will be developed, which shows the status quo of the current traffic volume with the current fleet composition and the resulting NO_x emissions. In a second step, case ONE will be formed in which expected future developments in the composition of the vehicle fleet will be incorporated. Especially the electrification of the drive train of the vehicles (BEV and PHEV) will be analyzed. The development of this vehicle market is, among other things, considering the local promotion of electromobility by the expansion of the CIS in Düren. Based on these modified input data, the emission burden of case ONE is recalculated. The third case, case ONE VALID, is used to validate the assumptions made in the previous steps. For this purpose, the charging data flowing back from the established CIS is analyzed with information about the user groups and type of use.
Within the project, the calculation of case ZERO (status quo) has already been carried out since the beginning of the project. Initial, as yet uncalibrated, estimates of changes in NO_x emissions are being made in case ONE. Charging data for calibration (ONE VALID) is not yet available as the CIS is currently being set up.

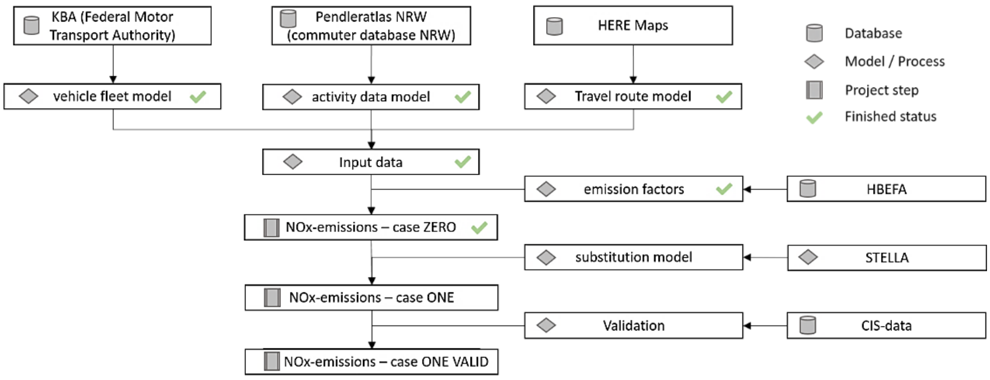

Fig. 4 Structure of the methodological procedure
[own visualization]

The actual estimation of NO_x emissions is based on the combination of two data-packages: emission factors and traffic performance. The Emission Factors (EFs) describe the emitted mass (g) of NO_x per driven distance (km) depending on the type of vehicle and the traffic situation. The basis for their determination is, as stated in Chapter 2, HBEFA, which calculates the desired EFs either as weighted averages of EFs (per vehicle category), or as EFs per particular technology, per fuel type or per segment [Colberg et al. 2005]. The basis for the determination of the specific traffic performance is formed in a first approximation by the commuter relations, their vehicle fleet composition as well as their chosen routes. In further steps, this first approach is to be expanded by the volume of traffic for other purposes, such as purchasing, as well as through traffic.

4.2. Estimation of traffic performance based on commuter links and fleet composition

Information extracted from the “Pendleratlas NRW” [IT.NRW 2019] is used to analyze the commuter relations of the city of Düren. This contains data on the place of residence and place of work of employees subject to social security contributions. By setting up the CIS on the operational areas of individual employers in Düren, employees, as well as the fleets, can also be addressed as part of the group of "commuters". Therefore, these were put into focus in a first analysis step. To derive the typical traffic behavior of commuters, the results of the study "Mobility in Germany 2017" (MiD 2017) [infas et al. 2019] were used. From this nationwide questioning of households on their everyday traffic behavior, the routes with the purpose "to work" were analyzed in more detail. In a first step, it was validated whether an assumption of the places of residence and places of work from the Pendleratlas NRW can be used as source and destination places of work. The validation was carried out by means of a comparison of the distributions of the path lengths of the working routes from the MiD and the distances routed on the road network between the local centers of work and residence from the Pendleratlas NRW. The results of the distributions are shown in table 2.

Table 2. Distribution of work distances according to distance classes
[own visualization based on infas et al. 2019, IT.NRW 2019]

distance	MiD 2017 [%]	Pendleratlas [%]
≤ 9 km	50.0	53.5
≤ 19 km	75.0	77.0
≤ 47,5 km	95.0	94.9

The distribution of the route lengths for the purpose of work from the MiD and the commuters of the Pendleratlas NRW almost coincide, proving that the places of residence from the Pendleratlas NRW can be chosen as the source of the commutes. In order to distribute the destinations spatially in Düren, various destinations within the city by the choice of four centers of gravity on the spatial resolution of the postal code 5 level areas (PLZ5-level) were chosen, as shown in figure 5. The basis for these destinations is data from the traffic model for the region of Aachen. Relevant commuter relationships were included in the calculation, in which at least 35 commuters from one municipality commute to Düren. This considers 96% of the commuters, who distribute to 69 of the 207 communities from which people commute for work to Düren. A visualization of the commutator relationships considered to be relevant is shown in figure 5.

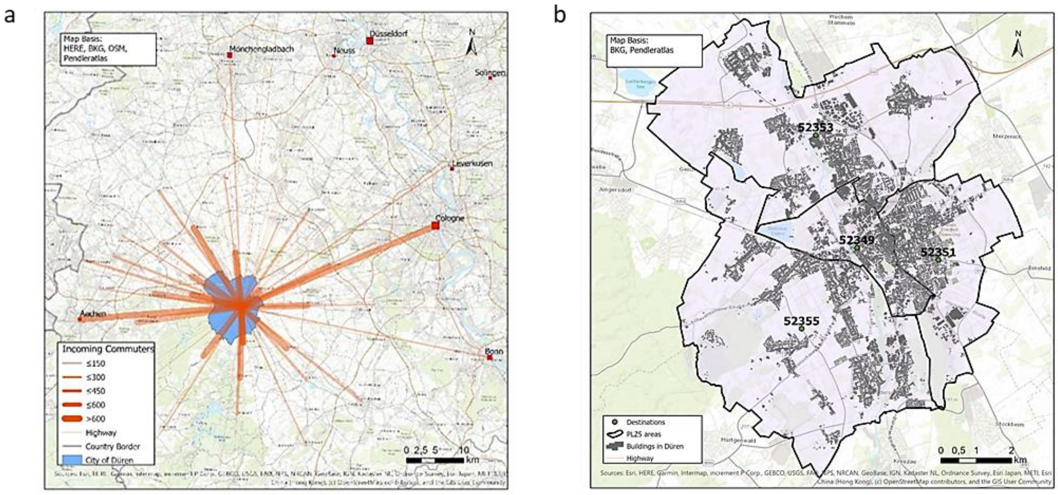

Fig. 5 (a) origins and amount of commuter traffic into the city of Düren;
(b) spatial resolution of the postal code five-level areas (PLZ5-level) in the city of Düren
[own visualization]

Since the CIS set up within the project eMIND is intended to make it accessible to the public even outside the business hours of the companies and thus make charging possible for other user groups, the outgoing commuters of the city of Düren were also considered. For them, it was assumed that they can use the built CIS at night to recharge their vehicles instead of a private charging option. Thus, the transition from a conventionally powered vehicle to an electric vehicle is made possible for this group of people, resulting in additional savings of NO_x emissions. Assuming the same commuter relationships that were defined as relevant, the 69 municipalities were also used as the basis for the commuter relations between Düren and the surrounding communities. As a simplification, the first methodical approach was also based on the assumption that the way back home from work corresponds to the way forward. Thus, as far as blurring is concerned, there are only two-dimensional path relationships for the path with the attraction "work".

Based on the number of incoming and outgoing commuters, the resulting number of vehicles is determined with the aid of a modal split and considering a vehicle occupancy rate, which move for the purpose of "work" on the named relations. Two different approaches are available for the conversion from the number of commuters to the number of vehicles: Either the already calculated resulting number of vehicles from the traffic model for the region of Aachen or the characteristic values from the MiD 2017 [infas et al. 2018] can be used. The distribution of the routes to the different traffic modes from the traffic model for the region of Aachen was calibrated with the MiD from the year 2008 [infas et al. 2008]. In order to decide whether the resulting number of vehicles can be used from this model, the modal split parts of the motorized private transport (MPT) as a driver from the MiD 2008 and the MiD 2017 were compared with each other for different distance classes (see table 3). As a result, it appears that the mobility patterns have changed and the MiD 2008 seems regarding the motorized private transport for the purpose "to work" outdated. Thus, based on the results of the MiD 2017 vehicle shares of 40% to 75% were selected depending on the distance of the trip (see table 3).

Table 3. Derived as well as selected share of MPT[1] as a driver from different sources for the purpose of travel "to work" [own visualization based on infas et al. 2019]

Distance class	MiD 2008 [%] [infas et al 2010]	MiD 2017 [%] [infas et al 2019]	Selected vehicle share [%]
≤ 5 km	45.1	38.3	40.0
≤ 10 km	75.1	63.9	65.0
> 10 km	78.0	75.1	75.0

[1] Motorized private transport (MPT)

In the next step, the calculated vehicles of each relation are divided between the individual vehicle categories. The vehicle number and category were obtained from the KBA (Federal Motor Transport Authority) as of January 1, 2018 [KBA 2018] and used for the calculation at the municipal level. These data include all vehicles registered in Germany (registered, allocated license plates) in accordance with the Vehicle Approval Regulation. From this data, only diesel or gasoline-powered vehicles were considered for further methodical development, accounting for 97.8% of the vehicles in the study area. The missing 2.1% of the vehicles use other fuel types, to which only partial information about the emission of pollutants in HBEFA can be found or whose plausibility is difficult. The individual vehicle shares per municipality were then linked to the respective commuter shares.

In order to obtain conclusions about the traffic performance as input parameter for the estimation method of the NO_x-saving potential on the basis of the distribution of the commuter link, information about the proportions of the traveled roads and their categories has to be determined. For this purpose, the entire road infrastructure per postal code area was differentiated with regard to its road category (federal highway, out-of-town, inner-city). Thus, information about the traveled route length and road category is available, when a commuter passes through a specific postcode area. Therefore, the total distance traveled per road category, postcode and source/destination municipality is determined.

By multiplying the travel distance with the previously determined vehicle proportions of the communities, the traffic performance of each vehicle type can be determined. After an aggregation of the traffic performance per vehicle type and road category at the PLZ5 level, the total emissions according to Formula 1.1 are determined by multiplication with the emission factors from HBEFA.

$$(1.1) \quad E_{NOx}(X) = \sum_i \sum_j (EF_{NO_x,i,j} * \sum_k (D_{i,j,k}(X)))$$

With *E = Total NO_x-emissions per PLZ5-area*
X = PLZ5-area
EF = HBEFA-Factor
D = vehicle kilometres
i = traffic situation
j = vehicle type
k = commuter relation

In accordance with the procedure described above, for case ZERO, current emissions from Düren's commuter traffic with the conditions previously presented were determined in Table 4. The basis of the routes or vehicle kilometers routed by means of the software ArcGIS is the assumption that the commuters choose the fastest route to get to their destination.

Table 4. Total daily vehicle kilometers of the commuters and Emissions per PLZ5 area [own visualization]

Postcode 5 area	**Vehicle kilometers**		**Emissions**
(PLZ5)	Diesel (km)	Gasoline (km)	(g)
52349	19 433	23 265	15 173
52351	43 757	53 710	31 153
52353	139 768	157 036	110 376
52355	39 798	55 142	28 094
∑	**531 909**		**184 796**

Considering the driving purpose-specific car occupancy rate for the purpose "work" from the MiD 2017 [infas et al. 2019] in the amount of 1.17, the average NO_x emission is for the examination area under the above conditions 0.30 g/Pkm. In comparison, based on the model results of TREMOD 5.82, UBA [2018c] estimates the average emissions of individual means of transport nationwide for cars to be 0.34 gNO_x/Pkm. The general conditions under which the value was calculated from the TREMOD model cannot be further analysed due to the lack of public accessibility and the missing description of the published source. Nevertheless, it can be used as a plausibility measure for the self-determined value of NOx emissions in the city of Düren. Furthermore, a model-typical underestimation of emissions assuming the mapping of real values by TREMOD occurs (see chapter 2). Due to the same order of magnitude as TREMOD and the accessibility of the method HBEFA will be further used to estimate the NO_x emissions in the city of Düren.

5. Outlook

The approaches presented serve as the basis for the development of a method for estimating the potential for reducing NO_x pollution by modeling the substitutable transport performance of conventionally powered vehicles by electric vehicles. Similarly, the initial research questions will address both the spreading and use of electric vehicles by encouraging the development of LIS among employers, as well as the connection between the promotion of electromobility (in this case through the development of charging infrastructure) and the local reduction of air pollution through collected data sets of the charging behavior at the built charging infrastructure.
The previous methodological approaches and first results presented in this paper currently refer to a very limited user group (commuters) as well as to the analysis of a specific driving purpose (residential work). These limitations were chosen for the initial approaches to develop and test the method. Extending the method to other user groups (e.g. company fleets), driving purposes (e.g. purchasing) and taking into account through traffic and the question of what influence the spread of local charging infrastructure in Düren has on the fleet composition and mobility behavior of these persons is within the scope of further research of the eMIND project by September 2022. Further work will mainly focus on updating the HBEFA 3.3 to HBEFA 4.1, which was only available during the processing phase but provides more detailed information on vehicle classes and traffic situations, as well as the creation of case ONE and case ONE VALID. The current work in Case ONE is a small-scale forecast on the development of the vehicle fleet in Düren and the surrounding regions relevant to the different destinations, which is dedicated in particular to penetrating the market with electric vehicles and the question of which electric vehicle models will be used. The development of case ONE VALID requires data on the charging behavior of the charging stations built in the project, which are currently being planned or under construction. When deriving the inferences of the charging data on the use and spread of electromobility, it must be taken into account that the charging infrastructure will probably not satisfy the complete charging needs of individual users, but they also recharge at other charging points – regardless of whether in private, semi-public or public areas. In addition, findings from the analysis of charging data from other research work of the institute can be consulted.
After completion of the investigations concerning the Düren pilot area, it is intended to carry out an assessment of the transferability of the methodological approaches at national level.

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