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Exhaust and non-exhaust emissions from today's and future road transport: A simulation-based quantification for Berlin

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Abstract

The full decarbonization of the transport sector is one of the greatest challenges of the coming decades. In this study, both greenhouse gases and local air pollutant emissions are quantified for the today's situation (reference case), a full decarbonization scenario and a transition scenario. The quantification uses the Handbook Emission factors for road transport (HBEFA, version 4.1) and the simulation framework MATSim (Multi-Agent Transport simulation). In the today's situation, for an average car user who lives in Berlin, the CO_2 footprint amounts to 3.3 tons per year. In contrast, for an average car user who lives in the Greater Berlin area, including Berlin, the CO_2 footprint amounts to 4.9 tons per year. In the full decarbonization scenario, greenhouse gases are eliminated. Nevertheless, non-exhaust emissions are still present. In the full decarbonization case, PM10 is found to decrease by 13-15%, PM2.5 by 26-31% and Black Carbon by 63-68% compared to the reference case (year 2020). The applied simulation approach allows for a detailed investigation of further transition scenarios towards full decarbonization.

Keywords: decarbonization; emissions; electric vehicles; air pollution; agent-based simulation; non-exhaust emissions

1. Motivation and problem statement

Greenhouse gas emissions have continued to rise in the last decade (United Nations Environment Programme, 2019). The European Union is pursuing the goal of being climate-neutral by 2050. This includes the full decarbonization of the transport sector which is one of the greatest challenges of the coming decades (EC, 2019). For the year 2030, the European Union's target is to reduce greenhouse gas emissions by at least 40% compared to the year 1999. In a recent proposal by the European Commission, this target was even increased to 55% (https://ec.europa.eu/clima/policies/strategies/). The transport sector being responsible for around 19% of the greenhouse gas emissions in Germany in 2018 offers the potential to contribute to a significant reduction in greenhouse

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gases, e.g. by the use of battery electric vehicles (BEVs) instead of internal combustion engine vehicles (ICEVs) (BMU, 2020).

An increased share of BEV will not only reduce greenhouse gas emissions but also yield a reduction in local exhaust air pollutants, e.g. NO_x emissions. However, even if the goal of a fully decarbonized transport sector is achieved, some transport-related environmental effects will persist, e.g. traffic noise (Kaddoura et al., 2020) and non-exhaust emissions, e.g. Particulate Matter (PM). Non-exhaust air pollutant emissions result from the wearing down of brakes, tyres, and road surfaces as well as from the (re-)suspension of road dust (Grigoratos and Martini, 2014; INFRAS, 2019).

In several existing studies, various tools and emission factor databases are used to quantify transport-related emissions for the today's situation or for policy cases (Hülsmann et al., 2011; Ghafghazi and Hatzopoulou, 2014; Fernandes et al., 2014; Guzman et al., 2015; Washburn et al., 2016; Garcia-Castro et al., 2016; Kickhöfer and Nagel, 2016). Most of these studies do not explicitly consider the shift from ICEV to BEV or treat BEV as zero-emissions vehicles. In this study, both greenhouse gas and local air pollutant emissions are quantified for different BEV shares. Going beyond most existing studies, the focus lies in the detailed investigation of non-exhaust emissions in the case of a fully decarbonized transport sector and the transition phase.

The remainder of this paper is structures as follows. Sec. 2 describes the simulation-based emission computation methodology, Sec. 3 provides the results for the Berlin case study including a plausibility check of the results, Sec. 4 discusses the results in a wider context and Sec. 5 briefly describes the main findings and provides an outlook.

2. Methodology

For the computation of exhaust and non-exhaust emissions, the agent-based simulation framework MATSim (Multi-Agent Simulation, www.matsim.org) (Horni et al., 2016) and an existing calibrated transport model for Berlin, Germany (Ziemke et al., 2019) (release 5.4, 10% population sample) is used. In MATSim, each traveler is modeled as an individual agent that moves along the network and interacts with other agents, e.g. in the form of dynamic traffic congestion with spill-back. MATSim also provides a tool which allows for a detailed computation of greenhouse gas and air pollutant emissions based on the traffic situation (road type, speed level, traffic state), the vehicle type (in particular engine type) and the engine temperature (cold start vs. warm start). For the emission factors, MATSim's emissions module uses the Handbook Emission Factors for Road Transport (HBEFA) database (INFRAS, 2019). A detailed description of MATSim's emissions modeling approach is described in Kickhöfer (2016). In this study, emission factors are taken from the HBEFA version 4.1 for Germany (INFRAS, 2019).

In this study, emissions are only computed for the passenger car mode; emissions related to other modes of transportation or demand segments such as freight traffic are neglected. Furthermore, vehicles are only differentiated by their engine type; for the vehicle size and further engine parameters, emission factors are based on average numbers for the year 2020. In the reference scenario, the vehicle engine types are randomly distributed based on the vehicle composition provided by the HBEFA (51.27% for petrol, 46.28% for diesel, 1.14% for bi-fuel LPG/petrol, 0.39% for bi-fuel CNG/petrol, 0.57% for Plug-in Hybrid petrol/electric, 0.01% for Plug-in Hybrid diesel/electric, 0.33% for electric). Note that the latest numbers published by the German Federal Motor Transport Authority for the end of the year 2020 are slightly different (65.2% for petrol, 31.2% for diesel, 0.7% for bi-fuel LPG/petrol, 0.2% for bi-fuel CNG/petrol, 2.1% for Plug-in Hybrid, 0.6% for electric) (KBA, 2021). Nevertheless, following the HBEFA numbers allows for an improved consistency with emission calculations for future fleet compositions provided by HBEFA.

In various simulation experiments, for different shares of randomly selected car users, the vehicle type is changed to a BEV. In this study, the agents' trajectories and travel decisions are kept constant. That is, there are no changes in destination, mode, time and route choice throughout the different simulation experiments. The source code to run the emission analysis as well as the Berlin model data is openly available.[1]

[1] see https://github.com/matsim-scenarios/matsim-berlin/ branch "airPollutionByEngineType", commit ID daefc73, 13 January 2021

3. Results

3.1. Aggregated analysis

In Tab. 1, aggregated emission values are given for different emission components and vehicle compositions. The simulation results for an average working day are multiplied by a factor of 365 to obtain yearly numbers. That is, in this study, differences between working days and weekend days are neglected.

Table 1: Aggregated emissions in tons per year caused by the passenger car sector. Numbers are given for the emissions by Berlin residents (Berlin) and the entire population in the Greater Berlin area.

Additional BEVs	0% (reference case)		50% (transition)		100% (full decarbonization)	
Emissions caused by residents of...	Berlin	Greater Berlin	Berlin	Greater Berlin	Berlin	Greater Berlin
Particulate matter <10μm (PM10)	254	1,052	237 (-7%)	974 (-7%)	220 (-13%)	897 (-15%)
Particulate matter <2.5μm (PM2.5)	133	501	116 (-13%)	424 (-15%)	99 (-26%)	347 (-31%)
Black Carbon (BC)	27	108	18 (-33%)	72 (-33%)	10 (-63%)	35 (-68%)
Nitrogen oxides (NO_x)	3,645	17,228	1,812 (-50%)	8,618 (-50%)	0 (-100%)	0 (-100%)
Carbon dioxide (CO_2)	1,452,744	6,141,413	721,684 (-50%)	3,075,374 (-50%)	0 (-100%)	0 (-100%)

Numbers for the entire population in the Greater Berlin area are significantly larger compared to the emissions by Berlin residents only (see Tab. 1, column "Berlin" vs. column "Greater Berlin"). In the reference case, only 21-27% of all emissions in the Greater Berlin area are emitted by Berlin residents. In the reference case, the CO_2 emissions caused by Berlin residents' amount to 1.45 tons per year, whereas, for all residents in the Greater Berlin area, the CO_2 emissions are 6.14 tons per year. In the model, there are 2.80 million residents in the Berlin area and 4.91 million residents in the entire Greater Berlin area. That is, for Berlin residents, the average CO_2 emission is 0.52 tons per year. And for residents in the Greater Berlin area, including Berlin, the average CO_2 emission is 1.25 tons per year. Note that these numbers refer to the total number of residents, including those people who do not use the car mode. If the emissions are put in relation to the number of car users, or more precise, residents who use the car mode on an average working day, the CO_2 footprint increases. For a car user who lives in Berlin, the average CO_2 emission amounts to 3.34 tons per year and for a car user who lives in the Greater Berlin area, including Berlin, the average CO_2 emission amounts to 4.91 tons per year.

Analyzing the emissions caused by Berlin residents reveals that in the full decarbonization scenario, PM10 emissions are reduced by 13%, PM2.5 by 26% and BC by 63% compared to the reference case (year 2020). Non-exhaust emissions still amount to a total of 220 tons PM10, 99 tons PM2.5 and 10 tons BC per year.

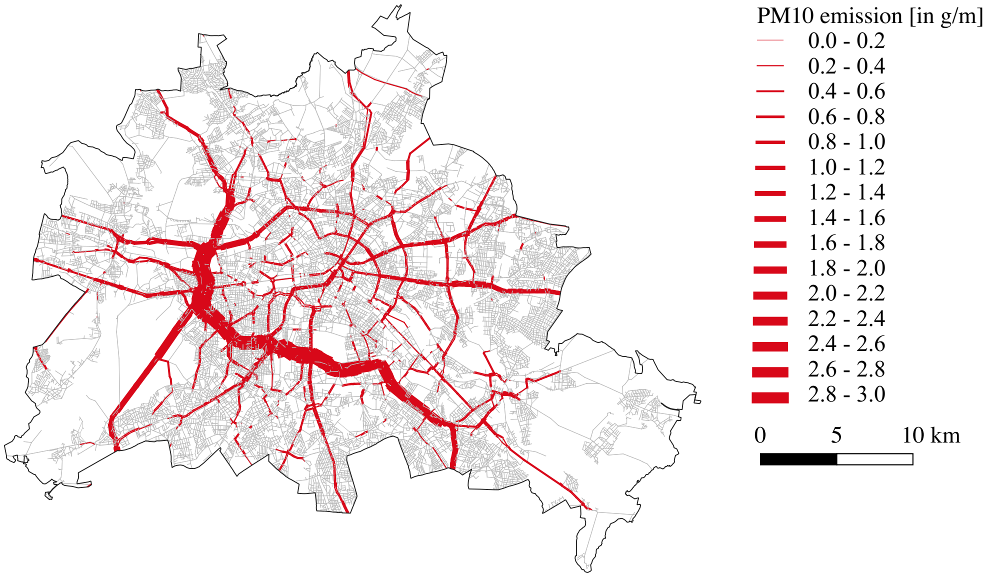
NO_x and CO_2 emissions are reduced proportionally to the share of electric vehicles: 50% for the transition and 100% for the full decarbonization scenario.

3.2. Spatial analysis

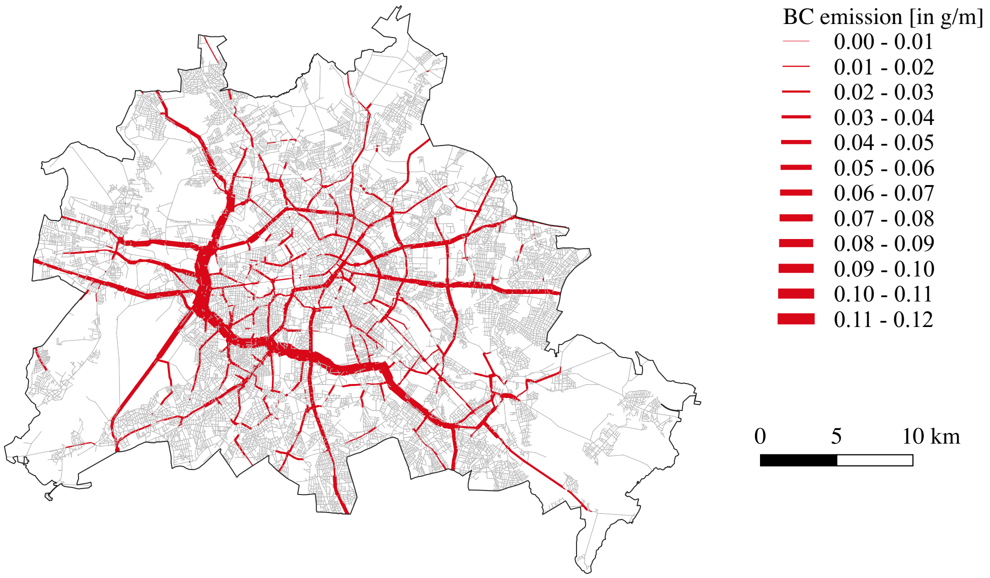
Fig. 1 depicts the daily non-exhaust emissions in gram per road length (meters) in the full decarbonization scenario. The highest emission levels are observed along the main roads, in particular the inner-city motorway. In the reference case (not shown), the spatial distribution looks similar but absolute emission levels are slightly higher.

3.3. Emissions plausibility check

In this section, the CO_2 emissions in the reference case are checked for plausibility using travel survey data for Berlin. SrV survey data Ahrens et al. (2009) for the year 2008 which was used to calibrate the applied Berlin model Ziemke et al. (2019), reports for an average working day 3.1 trips per person and 6.0 kilometers per passenger car trip (trips < 100 km) and a passenger car trip share of 29.6%. For a population of 3.416 Mio. residents in Berlin (year 2008), this yields a total of 18.81 Mio. vehicle-kilometers per day by passenger cars. Using an emission factor of



(a) Particulate matter <10μm (PM10) emissions



(b) Black Carbon (BC) emissions

Fig. 1: Daily emissions in gram per meter (road length) in the full decarbonization scenario caused by the entire population; Simulation-based computation based on the HBEFA version 4.1; only taking into consideration the passenger car sector

181.887 gram per vehicle-kilometer (average emission category and fuel type based on HBEFA 4.1, Germany, year 2020) and multiplying daily numbers by 365, this yields a total of 1,248,582 tons CO_2 per year.

Using averages from the more recent SrV 2018 survey (3.5 trips per day, 9.5 km per passenger car trip < 100 km, passenger car trip share of 18.4%) (Gerike et al., 2018) and 3.669 Mio. residents, total daily vehicle-kilometers amount to 22.45 Mio. and the emissions are 1,490,424 tons CO_2 per year (181.887 gram CO_2 per vehicle-kilometer). The simulation-based computation for the reference case and Berlin population (see Tab. 1, column "Berlin") is approximately at the same lower level compared to the survey-based plausibility check. Possible reasons for the minor differences may be explained by the higher level of detail in the applied simulation approach, in particular the differentiation in emissions factors provided by the HBEFA and the temporally and spatially disaggregated travel demand. Note that real-world emission levels caused by the Berlin population may be different due to differences in traffic patterns between weekdays and weekend days. Here, in both the simulation-based computation and the plausibility check, numbers for an average working day are multiplied with a factor of 365 to obtain yearly emission levels.

4. Discussion

The simulation-based emission computation only accounts for passenger cars. Emissions caused by other vehicles, such as freight vehicles are neglected. Passenger cars may be used in a different context and may be ascribed to the private sector or the commercial sector. The SrV traffic survey which is used for the applied transport model (Ziemke et al., 2019) as well as the plausibility check (see Sec. 3.3) contains parts of the commercial traffic sector, in particular trips which are carried out by residents (Gerike et al., 2020, page 9). With regard to the private traffic sector, the SrV survey data covers all trips carried out by residents (Gerike et al., 2020, page 9). To get an intuition about all CO_2 emissions caused by the entire road traffic sector, an investigation of the freight traffic is necessary. Since the integration of freight traffic is still a required extension of the applied transport model, the additional emissions by freight traffic are estimated based on the available data sources. The GVP (PTV/TCI, 2009) provides aggregated numbers for the different transport sectors in Berlin. For the computation of CO_2 emissions, vehicle-kilometers by category are taken from PTV/TCI (2009, Fig. 52, page 67) and multiplied with 365 to move from an average working day to annual numbers. The emissions factors in gram per vehicle-kilometer are approximated as follows: 182 for passenger traffic, 209 for small freight vehicles (less than 3.5 tons), 475 for medium freight vehicles (3.5 - 12 tons) and 713 gram per vehicle-kilometer for heavy freight vehicles (> 12 tons). The resulting emissions by sector are shown in Fig. 2 and should be considered as a rough approximation based on aggregated model data from PTV/TCI (2009).

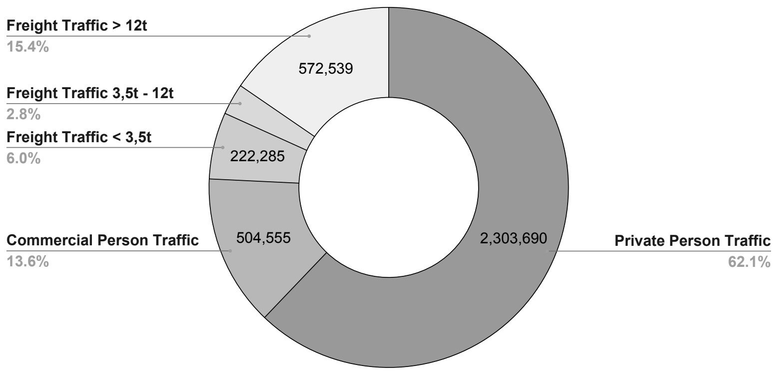


Fig. 2: Rough approximation of CO_2-emissions by segment in tons per year based on the vehicle-kilometers provided in PTV/TCI (2009) for Berlin

Still, the total amount of road traffic CO_2 emissions in Berlin with 3,707,093 tons CO_2 per year is in the same range as official emission statistics for Berlin (Amt für Statistik Berlin-Brandenburg, 2019) with 3,846,000 tons CO_2 per year. Therefore, the numbers provided in PTV/TCI (2009) seem plausible. As shown in Fig. 2, 62% of the CO_2 emissions in Berlin are caused by the private transport sector and 38% by the commercial traffic sector (commercial person traffic and freight traffic). Regarding the vehicle type, 76% of the CO_2 emissions are caused by passenger cars (private and commercial sector) and 24% of all CO_2 emissions are caused by freight vehicles.

Comparing these numbers with the simulation-based results in Sec. 3 reveals that CO_2 emissions caused by person traffic (commercial and private sector) in PTV/TCI (2009) are much higher. The difference is explained by different spatial references. In contrast to the simulation approach and the SrV-based plausibility check where travel characteristics only refer to Berlin residents, the GVP (PTV/TCI, 2009) refers to all trips that start or end in Berlin. Furthermore, in the simulation-based computation and plausibility check, only trips below 100 kilometers are taken into consideration, whereas in PTV/TCI (2009), all trip distances are considered. Assuming the Commercial person traffic which is already included in the model and the SrV plausibility check only forms a small fraction of the total commercial traffic and assuming that 25% of the private person traffic in PTV/TCI (2009) is ascribed to trips by non-residents (commuters, tourists, etc.), the CO_2 emissions in the different computation approaches are considered as roughly at the same level.

5. Conclusion and outlook

In this study, both greenhouse gases and local air pollutant emissions are quantified for the today's situation (reference case), a full decarbonization scenario and a transition scenario. The quantification uses the Handbook Emission factors for road transport (HBEFA, version 4.1) and the simulation framework MATSim (Multi-Agent Transport simulation). The presented methodology allows for a detailed investigation of the transition towards a fully decarbonized transport sector. The agent-based simulation approach allows for a vehicle-specific consideration of the engine type.

In the today's situation (reference case), Berlin residents are responsible for 1.5 million tons CO_2 emissions per year (passenger car sector). In contrast, car traffic related CO_2 emissions by residents in the Greater Berlin area amount to 6.1 million tons. For a car user who lives in Berlin, the average CO_2 emission amounts to 3.3 tons per year and for a car user who lives in the Greater Berlin area, including Berlin, the average CO_2 emission amounts to 4.9 tons per year.

Decarbonizing the transport sector provides a great potential to reduce emissions. Nevertheless, in the full decarbonization scenario, non-exhaust emissions are still present: PM10 is only reduced by 13-15%, PM2.5 by 26-31% and BC by 63-68% compared to the reference case. Further measures are required for a greater reduction of these non-exhaust emissions. Besides the most obvious one (reducing the vehicle-km driven), emissions might be reduced by e.g. using lighter vehicles, reducing speed limits, or developing and introducing new brake, tyre and/or road technologies in order to reduce the tyre wear.

In future research, the fleet distribution of the reference case and the transition state will be improved by accounting for sociodemographic attributes, the income, the home location and the travel behavior, e.g. number of trips and trip distances. Also, emission levels will be computed for various transition scenarios based on different assumptions regarding which parts of the population are most likely to switch from ICEVs to BEVs. On the one hand, residents with their own parking space or garage could relatively easily install a charging station and are more likely to switch to a BEV. On the other hand, those people may be less aware of the environment and thus less willing to switch to BEVs. In the transition phase, prioritizing the replacement of vehicles with the highest absolute emission levels seems to be a good approach. Transport policies in the form of incentives, pricing or prohibitions must be designed to overcome economic and social obstacles and thereby lead to the desired change in behavior of individuals or companies.

For an improved investigation of a city's transport related emissions, more detailed travel data is required, in particular for the commercial transport sector where only a small fraction of travel demand is contained in the established traffic surveys. A further next step is to incorporate the entire commercial sector into the transport model and compute emission levels for all transport sectors, including freight transport, and to investigate decarbonization policies in the commercial transport sector.

In future research projects, emission dispersion will be simulated and resulting concentrations will be compared against limit values for Germany, typically given in $\mu g/m^3$ (39. BImSchV, n.d.).

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