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Public fast charging infrastructure for battery electric trucks—a model-based network for Germany

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Abstract

Globally, road freight accounts for 40% of the CO_2 emissions in the transport sector, mainly from heavy-duty vehicles (HDVs). All the major truck markets have introduced fuel efficiency regulations for HDV, and the more ambitious regulations require the introduction of zero-emission HDV, for which battery electric trucks (BEVs) are a promising candidate. However, frequent long-distance trips require a dense public high-power charging network if BEV are to meet today's operating schedules in logistics. Here, we develop a model for public BEV high-power fast-charging that uses widely available traffic count data as input and combines this with on-site queueing models. We apply the model to Germany and obtain a fast-charging network where average waiting times do not exceed 5 min. For 15% BEV in the truck stock and 50% public charging, the model shows 267 charging locations, each with 2–8 charging points per location, for a dense network with 50 km distance between charging locations. We calculated 142 charging locations with 2–13 charging points for a wider network with 100 km distance between locations. Our results help to design future charging infrastructure for electric road freight transport.

1. Introduction

Globally, the transport sector is one of the largest emitters of energy-related CO_2 emissions. Its share in global emissions was approximately 22% in 2015, and this has continue to rise since then. Road freight vehicles account for 40% of direct CO_2 emissions in the transport sector worldwide (IEA 2017). In 2018, road freight transport in Germany caused 47.9 million tonnes CO_2 emissions, which corresponds to 6.3% of total German CO_2 emissions (UBA 2020). Heavy-duty vehicles (HDVs) with a gross vehicle weight (GVW) above 12 tonnes are of special interest, as they are responsible for about 70% of the CO_2 emissions in road freight transport (Gnann *et al* 2017). In 2019, the European Union (EU) passed a regulation to reduce the CO_2 emissions of newly sold HDV by 30% until 2030 (EU 2019). To comply with this target, truck manufacturers will have to sell 4% to 22% zero-emission vehicles (ZEVs) [battery electric vehicles (BEVs) or fuel cell electric vehicles] in 2030 (Breed *et al* 2021).

BEV operate without emitting local CO_2 emissions and are therefore considered ZEVs (EU 2019). All major truck manufacturers have announced their intention to sell battery electric trucks without an additional combustion engine (BEV) within the next few years. Due to typical daily mileage of 500 km and more (KiD 2010), public charging infrastructure for BEV will be necessary.

Previous studies have analysed the applicability of BEV from an economic perspective. An overview is given in Kluschke *et al* (2019a). Mareev *et al* (2018) showed that, from a techno-economic perspective, BEV are already viable in some scenarios. They took 2113 'average rest area(s) with charging infrastructure for trucks' (Mareev *et al* 2018, p 16) into account in their calculation to cover all parking areas in Germany. However, they did not conduct a detailed local demand assessment or sizing.

Based on this, Liimatainen *et al* (2019) used Finland and Switzerland as an example and showed that charging infrastructure, together with other factors such as battery size, has a major impact on the technical electrification potential of truck fleets, but did not determine the amount of charging infrastructure needed.

Based on truck trip data, Whitehead et al (2021) identified up to ten public charging locations in South East Queensland for short-haul trucks. However, they did not consider public charging on long-haul trips.

To the best of the authors' knowledge, the literature does not provide any estimation of public charging infrastructure for BEV trucks in Germany.

From a methodological point of view, there are two main approaches to modelling the rollout of charging infrastructure along motorways, both of which are known from modelling infrastructure for cars. On the one hand, distributing infrastructure as evenly as possible guarantees maximum geographical coverage. On the other hand, positioning infrastructure at locations with high charging demand enables high utilization of the charging sites (Reuter-Oppermann et al 2017). We refer to the latter perspective as a demand-oriented approach and the former as a coverage-oriented approach.

Early studies using a demand-oriented approach followed a p-median model to find the optimal location for a police station in a road network, a switching station in a communications network (Hakimi 1964) or optimal locations for facilities (ReVelle and Swain 1970). The objective of this approach is to minimize the average weighted distance from each node to the selected locations. However, applying this approach to refuelling stations means they are mainly located where citizens live (Capar and Kuby 2012). Therefore, later studies (e.g. Hodgson 1990, Berman et al 1992) focused on locating refuelling stations by maximising the passing flows without double counting. This approach is known as a flow-capturing location model (FCLM). Instead of residential locations, the fundamental units of demand in an FCLM are the individual trips or traffic flows through a network. To take multiple stops due to range limitation into account, Kuby and Lim (2005) extended the FCLM to the flow refuelling location model (FRLM). Subsequent extensions improved the computing time (e.g. Lim and Kuby 2010, Capar et al 2013) and transferred the approach to other regions (e.g. Kuby et al 2009, Jochem et al 2016). In order to be able to calculate an FRLM covering Europe, Jochem et al (2019) reduced the optimization problem by ignoring traffic flows with fewer than 5000 cars per year. He et al (2019) used an FRLM to calculate a fast-charging network for the United States of America. They used flows between 4486 regions and clustered them to 196 regions to reduce complexity. Rose and Neumann (2020) and Rose et al (2020) subsequently transferred the approach to HDVs and generated a hydrogen refuelling station infrastructure for Germany. The demand-oriented approach requires an extensive data basis in the form of traffic flows. Traffic flows are mainly available from traffic count surveys, but not in the origin-destination form required by the FRLM. Obtaining origin-destination data is very time-consuming and in some cases almost impossible (Whitehead et al 2021). In addition, the model is still computationally intensive and relies on significant simplifications, especially when applied to large areas.

The coverage-oriented approach, on the other hand, uses a heuristic to determine the charging locations with the aim of geographical coverage and is therefore significantly less intensive computationally. Funke and Plötz (2017) and Funke (2018) positioned charging locations for battery electric cars along German highways and used local traffic volumes to size the locations by applying queueing theory. As a heuristic, this approach does not provide an optimal solution in terms of the minimum number of charging locations. Based on one scenario for Germany, Reuter-Oppermann et al (2017) showed that a coverage-oriented approach with 100 km distance between locations almost doubles the number of charging locations, but at the same time significantly reduces the average number of charging points per charging location. A coverage-oriented charging network can thus reduce drivers' anxiety of not reaching a charging station, as shown by Spöttle et al (2018) for passenger cars. This should be even more relevant for trucks, as detours or additional charging breaks, which can arise when minimizing infrastructure, are only accepted to the limited extent of about 15 min (Kluschke et al 2019b).

In summary, the demand-oriented approach computes the minimum number of charging stations, but requires high-resolution traffic flow data and considerable computational power. The coverage-oriented approach works with widely available local traffic volumes, but does not provide a minimum solution.

Another aspect is the dimensioning of the charging infrastructure in terms of number of chargers per location. For passenger cars, queueing models have been used with different location models. Hosseini and MirHassani (2015) used a recharging location model with queues to identify optimal electric vehicle (EV) charging positions via a heuristic. Yang et al (2017) introduced an optimization approach to minimize the number of charging locations and charging points for a taxi fleet. Funke (2018) combined queueing theory and a coverage approach to design a charging infrastructure for electric cars in Germany. Huang and Kockelman (2020) used a network equilibrium model with queues to develop a charging network for Boston, which is cost-optimal for the infrastructure owner.

The aim of this paper is to design a high-power fast-charging network for BEV (>12 t GVW) in Germany for the medium-term future, e.g. around the year 2030. Due to the limited availability of truck flow data, we use a coverage approach and adapt this to the specifics of truck traffic.

This approach is in line with the proposal for the Alternative Fuel Infrastructure Regulation, which indicates the need for a dense charging network for trucks and mandates charging locations at regular intervals along the main road network (European Commission 2021). Similar to the car sector, a high utilization rate

Table 1. Comparison of manual (BAST 2017) and automated (BAST 2019) traffic census.

	Manual traffic census	Automated traffic census
Census year	2015	2018
Counting stations	2549	846
Temporal resolution	Daily (one average value per station)	Hourly (8760 values per station)
Counted vehicles	>3.5 t GVW	Semi-trailer trucks and trailer trucks
Geo-coordinates	Not included	Included

is necessary to make operating the charging network as attractive as possible to the provider (Muratori *et al* 2019). We use traffic count data to model the hourly arrival rate of trucks at each charging station. Considering an acceptable mean waiting time, the use of queueing theory ensures the minimum number of charging points at each location and thus a high utilization rate.

To the best of the authors' knowledge, this study is the first to consider the regional distribution of charging infrastructure for BEV in Germany using a coverage-oriented approach. This is also the first time that queueing theory has been applied to the dimensioning of charging locations for battery electric trucks.

This paper is structured as follows. Section 2 gives an overview of our data, our scenarios, and our methodological approach. Sections 3 and 4 present and discuss the results. We close with a summary and suggestions for further research in section 5.

2. Data and method

2.1. Data

This section describes the two types of relevant data used for the analysis. First, geographical traffic counting data to determine the locations of charging sites. Second, technical data of heavy-duty electric trucks to scale the size of the charging sites.

2.1.1. Traffic volume and geographical distribution

Our study focuses on HDV with a GVW above 12 t driving on motorways. In total, such HDV covered 23.5 billion km on German motorways in 2015 (Wietschel *et al* 2017). Assuming a 30% growth in traffic volume by 2030 (BMVI 2016), our calculations are based on a traffic volume of 30.5 billion km in 2030. If only working days are taken into account, this results in a daily mileage of 97.5 million km.

Two data sources provide information regarding HDV traffic volumes in Germany. While the automated traffic census (BAST 2019) provides hourly values for 846 counting stations, the manual traffic census (BAST 2017), carried out in 2015, contains a daily average value for 2549 counting stations. The latter correspond to an average counting station distance of approximately 5 km along the 13 000 km of motorways in Germany. Due to the higher counting station density, the manual traffic census is used for the distribution of charging locations. The geo-coordinates of the counting stations were added manually based on the location description in the dataset. The automated traffic census, on the other hand, is used to determine the distribution of traffic over the day and the associated station dimensioning (cf section 2.2.3).

Table 1 contains the most important information regarding the manual and the automated traffic census. Figure 1 shows all the counting stations in the manual traffic census, the potential charging location sites. (Please note that the A36 motorway is not included in the counting data, as, until recently, it was included in the national road network as the B6.)

2.1.2. Vehicle assumptions

To calculate the energy required at the charging locations, technical assumptions for the vehicles are necessary. The battery size needs to ensure a typical driving time of 4.5 h. A speed limit of 80 km h^{-1} exists for trucks on German motorways, but the actual speed driven varies between different motorway sections (Löhe 2016). The average speed is therefore lower than 80 km h^{-1}. Expert consultations with the HoLa consortium, which plans to build the first megawatt chargers as well as the associated vehicles (HoLa 2021) revealed that the commercial vehicle industry assumes an average truck speed of 60–70 km h^{-1}. This corresponds to driving 300 km in 4.5 h. To consider a buffer, we assumed a total range of 333 km as we expect fast charging to be possible up to 90% state of charge in the medium-term future (Figenbaum 2019). There are different estimates regarding the energy consumption of BEV-HDV [e.g. (Moultak *et al* 2017, Wietschel *et al* 2017, Kühnel *et al* 2018)]. We assumed an optimistic development and 1.2 kWh km^{-1}. The assumed charging time is 30 min as this is a good match to the compulsory 45 min break of the driver after 4.5 h of driving. In addition to the actual charging time, we assumed an average waiting time of 5 min. At present, it is not known whether these times can be met, but demonstration projects are planned to show whether recharging can take place within the compulsory breaks

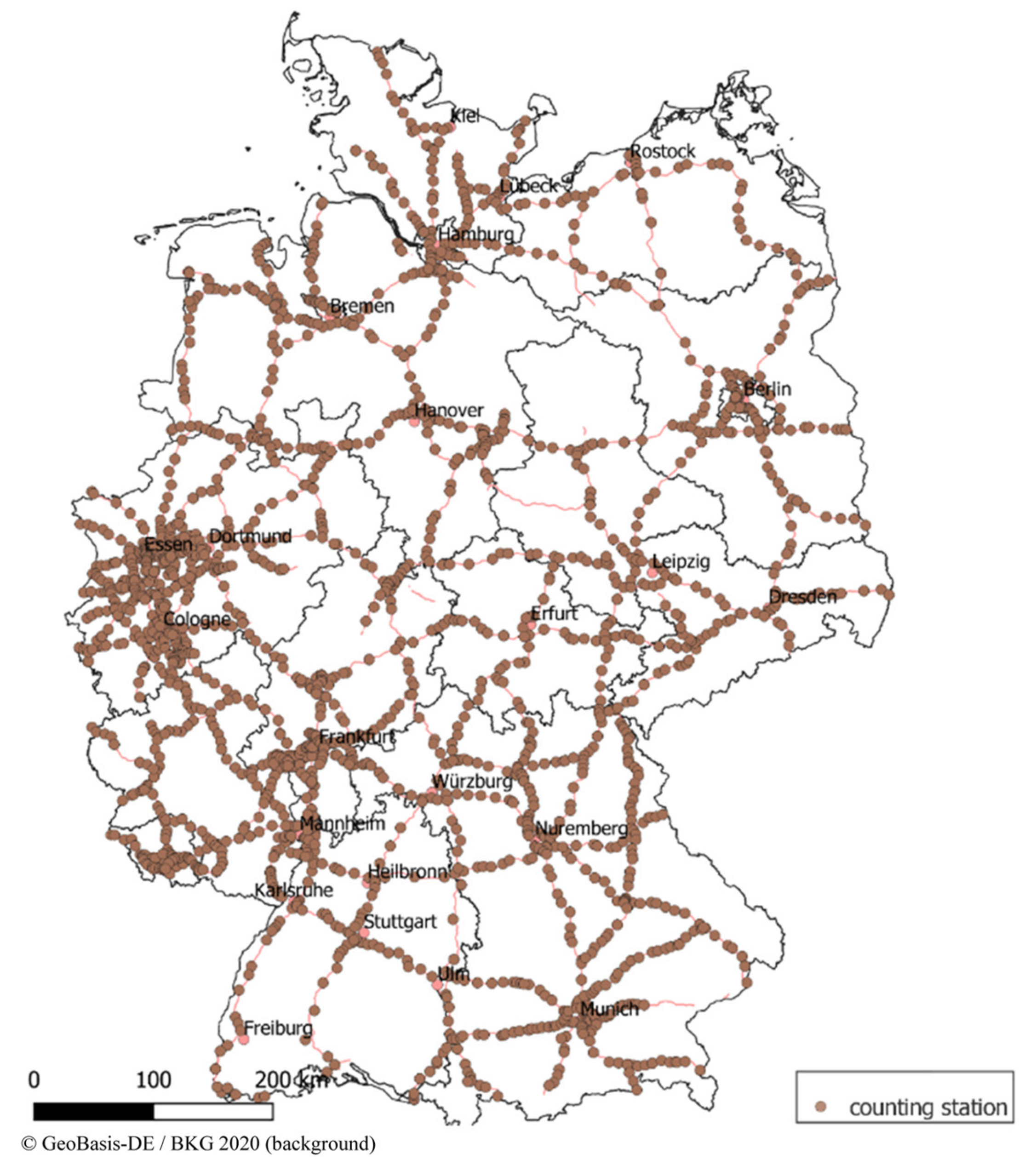


Figure 1. Counting stations in the manual traffic census (BAST 2017).

(HoLa 2021). Therefore, we used sensitivity analyses to test the influence of these parameters on the necessary infrastructure. However, longer break times and thus longer times for HDV tours are usually not accepted by transport companies (Kluschke *et al* 2019b). The required charging power of approximately 720 kW on average and 1 MW peak power (HoLa 2021) corresponds to a tripling of today's charging power from the 350 kW commonly available for passenger car chargers. According to commercial vehicle manufacturers, this will be possible in the medium-term future and will be evaluated in pilot projects [e.g. (HoLa 2021)]. Table 2 sums up the most important vehicle parameters.

2.1.3. Scenario description

We designed a charging network for a stock diffusion of 15% battery electric trucks in all HDV in Germany. This complies with the expected necessary share of zero-emission HDV of 11% in 2030, calculated from the current EU fleet CO_2 targets for trucks (Breed *et al* 2021). After discussions with representatives of truck manufacturers and haulage companies (HoLa 2021), we assumed that 50% of charging takes place at public charging infrastructure along motorways. This is a rather generous estimate. Finally, our study distinguished two networks. In the first scenario, 'wide meshed network', the distance between two charging locations is approximately 100 km. In the second 'close meshed network' scenario, this distance is about 50 km. This estimation follows the European Commission's proposal of a maximum of 60 to 100 km between charging

Table 2. Technical parameters vehicle[a].

Parameter	Value
Electric energy demand (kWh km^{-1})	1.2
Range (km)	333
Useable battery size (kWh)	400
Assumed mileage in 4.5 h (km)	300
Average charging power (kW)	720

[a]Source: own assumptions, based on (Moultak *et al* 2017, Wietschel *et al* 2017, Kühnel *et al* 2018) and expert evaluation within HoLa (2021).

Table 3. Scenario assumptions[a].

Parameter	Value
Charging time (min)	30
Average waiting time (min)	5
BEV share (%)	15
Share of public charging along motorways (%)	50
Distance between stations (km)	50 or 100

[a]Source: own assumptions and expert evaluation within HoLa (2021).

points (European Commission 2021). Table 3 shows the most important assumptions. Since they are subject to uncertainty, they were varied within the sensitivity analysis.

2.2. Method

We used a three-step approach to design a high-power fast-charging network for BEV. The first step determines the charging locations. The second calculates the number of charging events based on traffic flow. The third step is a queueing model to determine the number of fast charging points at each charging location to meet local demand.

2.2.1. Positioning of charging locations

Each of the 2549 counting points represents a possible charging location. Following Funke (2018), the charging locations are positioned along motorways, taking into account the target distance between charging locations. To guarantee a countrywide network, locations are distributed along all the motorways in Germany. Following the course of each motorway, each counting station is a potential charging location. If the distance to the last charging location exceeds the defined distance between two charging locations (50 or 100 km), a new location is introduced. Equation (1) shows this procedure. The next counting point along the respective motorway is checked in the same way until the end of the motorway is reached.

$$\mathrm{CL}_L = \begin{cases} 1, & \text{if } d_{\mathrm{CL},L} \geqslant d_{\mathrm{avg}} \\ 0, & \text{else} \end{cases} \tag{1}$$

CL_L charging location at location L, $d_{\mathrm{CL},L}$ distance between the last positioned charging location or the beginning of the motorway and location L, d_{avg} defined distance between two charging locations.

The European Commission requires a charging network to operate across borders (European Commission 2021). To take cross-border traffic and motorway junctions into account, we followed a slightly different procedure for the first and last charging location of each motorway. The distance to the end and the start of the motorway is half of the defined average distance (i.e. 25 or 50 km instead of 50 or 100 km). In the close meshed network scenario, this means HDV can find a charging location 25 km before and 25 km after the border. The average distance is still 50 km.

Motorways with a total length of less than 25 km, typically urban motorways, are not considered for charging locations. This reduces the total number of charging locations. Urban traffic typically charges on private infrastructure, while long-distance vehicles pass charging points on major motorways.

2.2.2. Calculating the number of charging events

To design the locations, the number of charging events at the location is required. We first calculated the daily public charging events in Germany and then distributed them according to the traffic volume, as described in Funke and Plötz (2017). Since public charging occurs as a trip interruption, we assumed that the number of local charging events increases with local traffic volume, i.e. the number of charging events is proportional to the number of trucks per hour on the motorway segment under consideration. For this purpose, first we determined the daily kilometres driven by electric HDV in Germany, based on the daily mileage of all HDV and the assumed share of electric vehicles. Then we divided the result by the typical trip distance covered in 4.5 h (maximum driving time) and thus obtained the number of Germany-wide charging processes. For the dimensioning, we only considered the charging processes on public infrastructure. Equation (2) shows the calculation of the daily charging events in Germany.

$$\mathrm{CE}_{\mathrm{GER}} = \frac{\mathrm{BEV}_{\mathrm{share}} * \mathrm{traffic}_{\mathrm{GER,daily}}}{\mathrm{range}_{\mathrm{BEV,trip}}} * \mathrm{CE}_{\mathrm{public}} \tag{2}$$

$\mathrm{CE}_{\mathrm{GER}}$ daily charging events in Germany, $\mathrm{BEV}_{\mathrm{share}}$ share of BEV in fleet (%), $\mathrm{traffic}_{\mathrm{GER,daily}}$ daily mileage of HDV (GVW $>$ 12 t) in Germany (km), $\mathrm{range}_{\mathrm{BEV,trip}}$ assumed mileage in 4.5h (km), $\mathrm{CE}_{\mathrm{public}}$ share of charging events on public infrastructure (%).

Subsequently, we distributed the nationwide charging events to the realized locations according to the maximum volume of traffic in the served section. First, we calculated the maximum traffic volume along the motorway section served by a single charging location. Then we related the maximum traffic volume of each individual location to the maximum traffic volume of all locations, thus determining the share of Germany-wide charging processes. Equation (3) illustrates the distribution of Germany-wide charging events.

$$\mathrm{CE}_{\mathrm{CLr}_i} = \mathrm{CE}_{\mathrm{GER}} * \frac{\mathrm{MAX}_{\mathrm{CLr}_i-1}^{\mathrm{CLr}_i}(\mathrm{TV}_j)}{\sum_{\mathrm{CSr}} \mathrm{MAX}_{\mathrm{CLr}_i-1}^{\mathrm{CLr}_i}(\mathrm{TV}_j)} \tag{3}$$

$\mathrm{CE}_{\mathrm{CLr}_i}$ daily charging events at realized charging location i, $\mathrm{CE}_{\mathrm{GER}}$ daily charging events in Germany, $\mathrm{MAX}_{\mathrm{CLr}_i-1}^{\mathrm{CLr}_i}(\mathrm{TV}_j)$ maximum daily traffic volume (both directions) on one of the sections j between realized charging location i (CLr_i) and the realized location before this location ($\mathrm{CLr}_i - 1$) $\sum_{\mathrm{CSr}} \mathrm{MAX}_{\mathrm{CLr}_i-1}^{\mathrm{CLr}_i}(\mathrm{TV}_j)$ sum over the determined maximum daily traffic volumes of the sections of the realized charging locations.

2.2.3. Defining the number of charging points per charging location—queueing model

The design of the charging location, i.e. the number of charging points per charging location, is based on the mathematical queueing theory (see Adan and Resing (2017)). Queueing theory is an established field of mathematics, which indicates how many counters are necessary in a system to maintain a given average waiting time for a given arrival rate and service time. In the application presented here, we assumed an average waiting time of 5 min; the number of counters corresponds to the number of charging points per location. The arrival rate results from the daily flow of BEV traffic, and the service time from the charging time.

A queueing system is characterised by three components: arrival process, service process, and waiting (Salazar 2020). First, the arrival process describes how customers arrive in the system and the distribution of their arrival. Second, the service process is determined by the number of counters and the number of queues. The distribution of service times is also part of the service process. Third, waiting refers to the rule used by a counter to select the next customer from the queue when the counter finishes serving the current customer. Here, we assumed that customers are served in the order of their arrival ('first-in, first-out').

We followed the standard Kendall notation for queueing models. The standard notation system for classifying a queueing system is $A/B/c/k/m$ with the probability distribution for the arrival process A, the probability distribution for the service process B, the number of counters c, the maximum number of customers k allowed in the queueing system, and m stands for the maximum number of customers in total. In our case, k and m can be assumed to be infinite.

It is plausible to assume Poisson-distributed arrivals for rapid charging of electric trucks, with the average arrival rate derived directly from the number of battery trucks (Gnann *et al* 2018). The Poisson distribution describes the number of events that occur at a constant rate in a fixed time interval (Johnson *et al* 2005). The average number of arrivals per period is denoted by λ. For example, an average arrival rate of $\lambda = 4$ trucks h^{-1} means that, on average, four trucks arrive per hour, but sometimes fewer and sometimes more. The waiting time between the arrivals of the vehicles then follows a Markovian distribution M.

The average number of customers served per period (i.e. average service rate) is μ. For example, an average charging time of 30 min, results in an average service rate of $\mu = 2$ trucks h^{-1} per counter. In the case of charging BEV trucks, the service times are approximately normally distributed, i.e. there is a typical charging time with variations around it. Therefore, the service time follows a general distribution G. In the literature, Markovian distributions are sometimes used for fast charging, too. However, Funke (2018) and Gnann *et al* (2018) show that $M/G/c$ systems correspond better to the real distribution of service times than $M/M/c$ systems.

We therefore used an $M/G/c$ queueing model. Exact solutions for the mean waiting time of $M/G/c$ systems are not known, but an approximate formula is available, an extension of the Pollaczek Khinchine formula (cf Funke 2018). The mean waiting time $W_q^{M/G/c}$ of an $M/G/c$ system can be approximated by the mean waiting

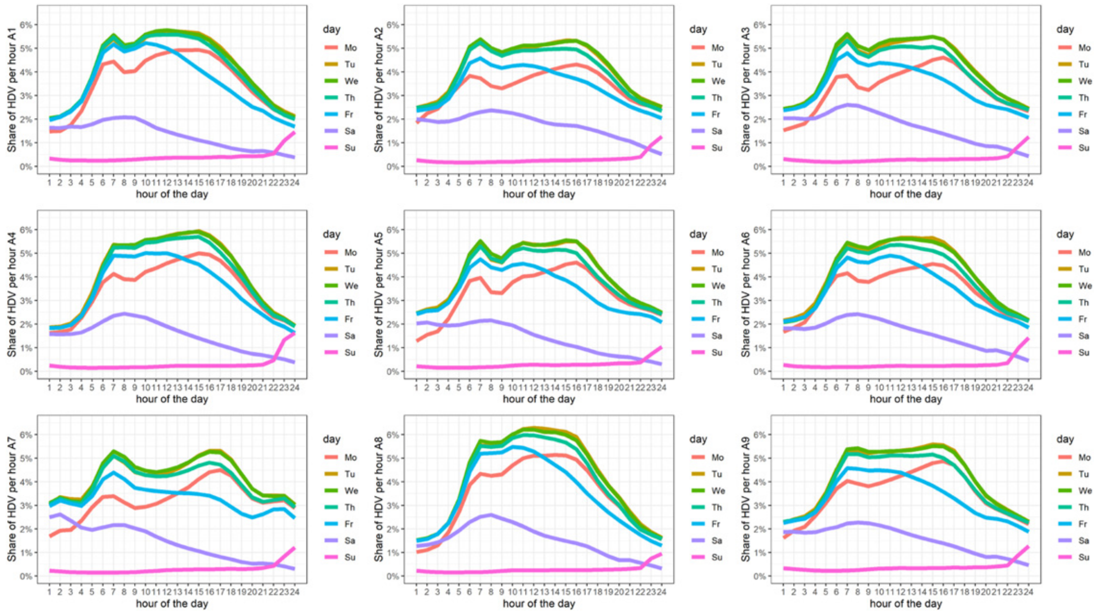


Figure 2. Share of HDV per hour and day along the top nine motorways in Germany.

time $W_q^{M/M/c}$ of a comparable $M/M/c$ system (Funke 2018)

$$W_q^{M/G/c} = \frac{C^2 + 1}{2} W_q^{M/M/c}. \tag{4}$$

Here, C is the variation coefficient of the distribution of service times, i.e. the quotient of the standard deviation and the mean value of the service time distribution. Since we used normally distributed service times with a pronounced peak, $C < 1$, and the average waiting time in the $M/G/c$ system is shorter than in the $M/M/c$ system. Since we assumed that drivers will recharge after about 4.5 h of driving, they will have similar amounts of energy to charge. Specifically, we assumed a standard deviation of 1/6 of the mean energy charged in the following, i.e. $C = \frac{5}{30} = 1/6$. This approximation formula is used together with the exact results for the mean waiting time of $M/M/c$ systems to design charging stations, i.e. $W_q^{M/M/c} = \frac{1}{1-\rho} \frac{1}{c\mu} \frac{(c\rho)^c}{c!} \left((1-\rho) \sum_{n=0}^{c-1} \frac{(c\rho)^n}{n!} + \frac{(c\rho)^c}{c!} \right)^{-1}$ according to (Adan and Resing 2017). Here, $p = \frac{\lambda}{c\mu}$ describes the occupation rate per counter.

The average waiting time of 5 min does not imply that all users wait exactly 5 min. In fact, there is a distribution of waiting times. For the example of an average arrival rate of $\lambda = 4$ trucks h^{-1} and a charging time of 30 min, i.e. an average service rate of $\mu = 2$ trucks h^{-1}, $c = 4$ charging points are needed to stay below 5 min average waiting time. With $c = 4$, it is 1.3 min and with $c = 3$, it is 6.8 min. The average waiting time of less than 5 min is achieved in this example by the fact that the vast majority of trucks (approx. 83%) do not have to wait at all, a few (8%) wait up to 5 min or between 5 and 15 min (7%), and very few (2%) wait longer than 15 min.

The procedure for designing the individual location is as follows: the number of BEV trucks per day determines the average hourly arrival rate λ in trucks h^{-1} for peak traffic during peak hours or the daily average. In the traffic data, the average number of heavy trucks per day is available at the manual traffic counting stations. These can be distributed over the day using the hourly data from the automatic traffic count data. The automatic traffic count contains the number of heavy trucks per hour for all hours of a year. Figure 2 shows the daily distribution of heavy trucks as a percentage of trucks per hour by weekdays compared to the total number of trucks for the A1 to A9 motorways. Since a percentage share is necessary for the model to calculate different BEV scenarios, the share of the average traffic volume is considered here. To be more precise, the annual average of the daily traffic volume of all Tuesdays in HDV/day is compared with the average number of HDV per hour and weekday. For each motorway, the average is calculated for all counting points of the motorway.

A clearly increased volume can be seen at all motorways, especially on Tuesdays to Thursdays, as well as a morning and an afternoon peak. In addition, the volume of traffic on working days does not approach zero at night, but falls to one half or one fifth of the daily peak.

Based on the proportions of daily traffic volumes each hour, the following assumptions were made for the daily average and peak hour to design the locations. The peak is about 6% of the daily traffic volume across the motorway and is used as the peak portion when designing the locations. For the daily mean, we assumed

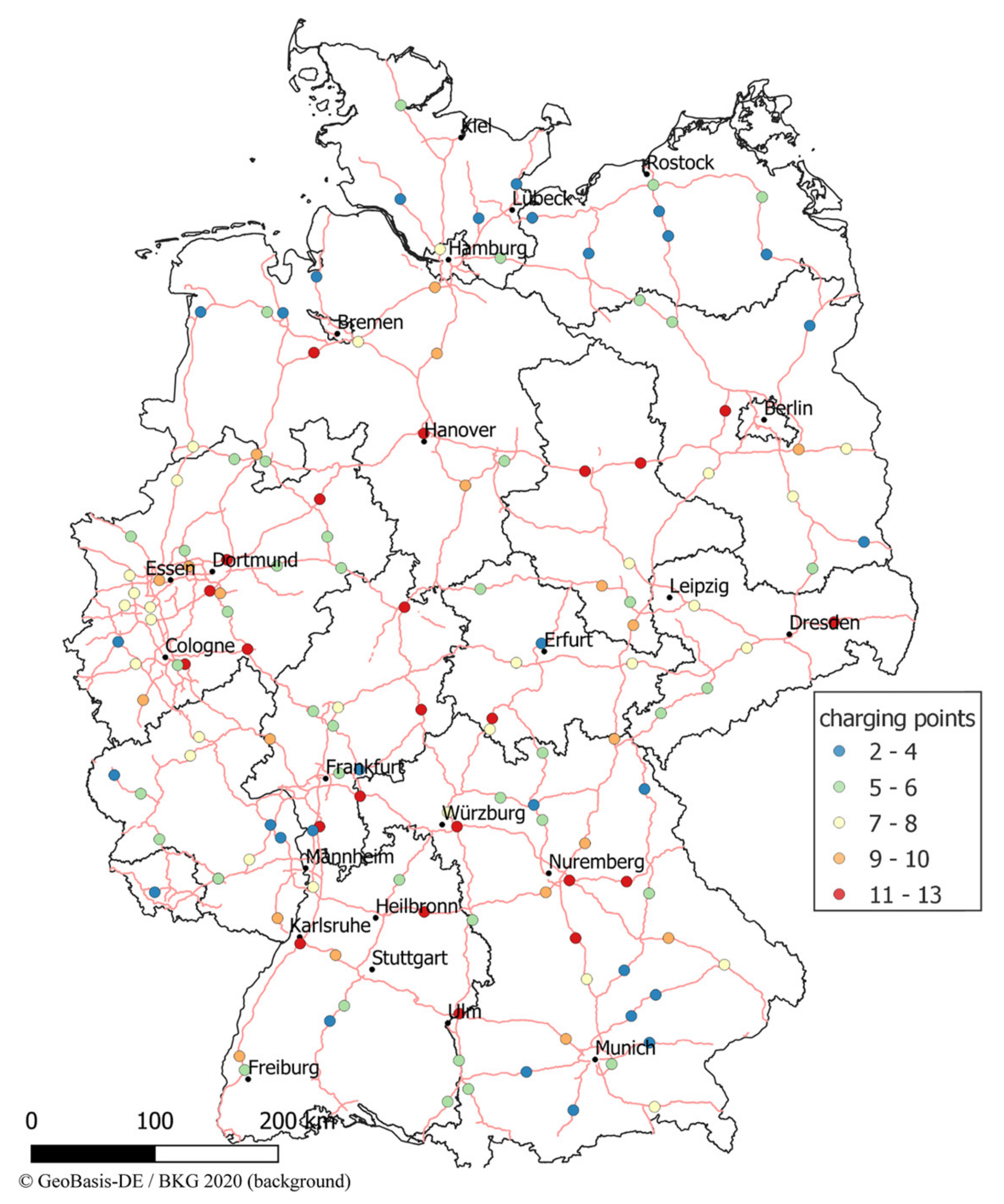
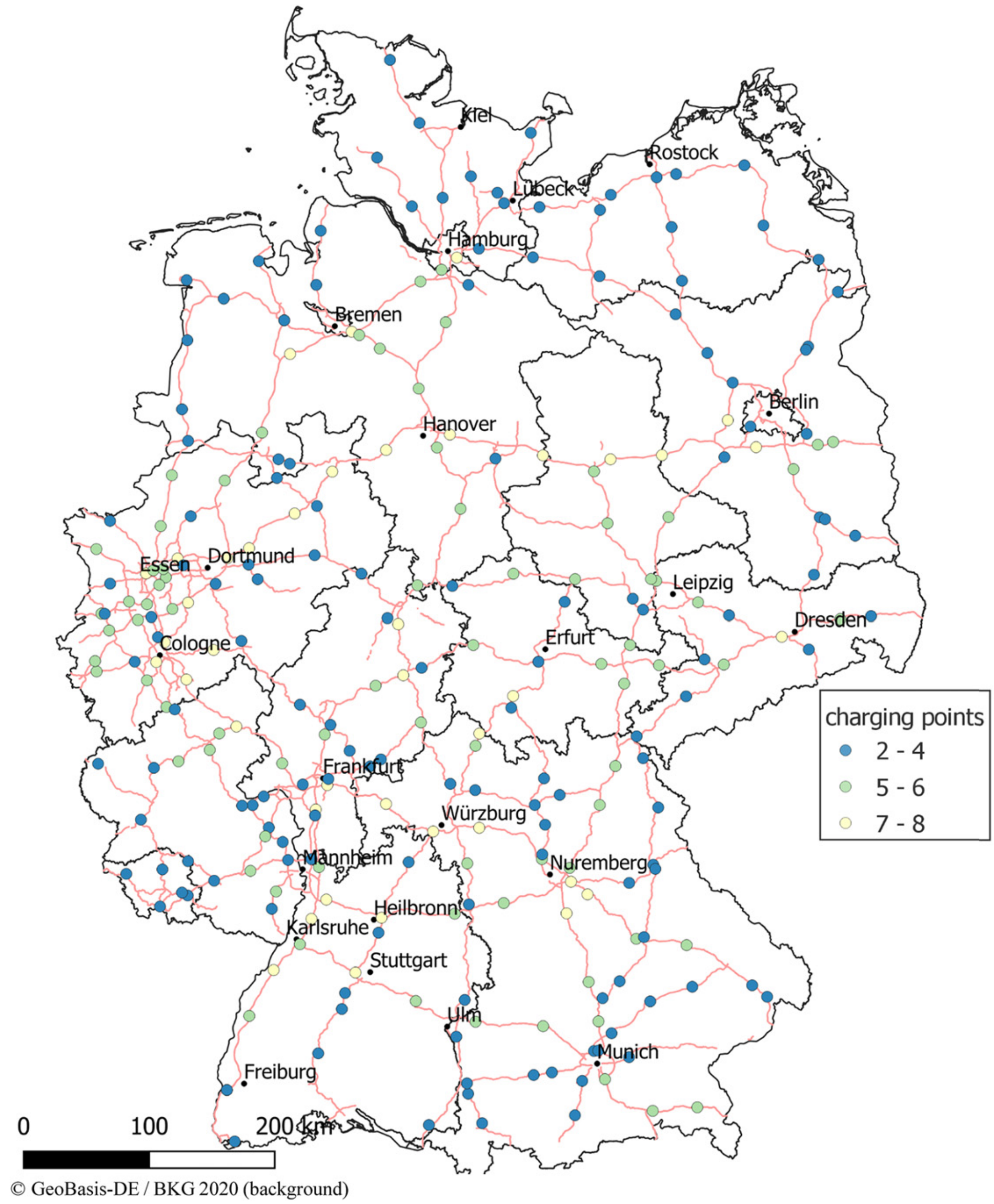


Figure 3. Location of 142 fast-charging locations with a mean distance of 100 km and peak traffic—wide meshed network.

an equal distribution over all hours of the day, i.e. 1/24 = 4.2% of the daily traffic volume. This percentage is multiplied by the total number of charging events CE_{CLr_i} on the specific motorway segment per day, obtained from the traffic count data and the assumption of 15% BEV trucks in the total truck stock. The average service rate is $\mu = 2$ trucks h^{-1} at 30 min average charging time, i.e. approx. 720 kW average charging power. For each charging location, we calculated λ from the traffic data and chose the smallest c that complies with the 5 min waiting time condition. That is, we determined the smallest number of charging points c at the given charging location, such that the average waiting time is less than 5 min.

3. Results

The results are divided into three subsections: the first refers to the geographical distribution of charging locations within Germany. The second describes the dimensioning of the individual charging stations. The third presents some sensitivity analyses to obtain a deeper insight into critical parameters.



© GeoBasis-DE / BKG 2020 (background)

Figure 4. Location of 267 fast-charging locations with a mean distance of 50 km and peak traffic—close meshed network.

3.1. Fast charging locations

Figure 3 shows the distribution of charging locations in the wide meshed network (100 km distance). The network consists of 142 charging locations in total and covers all motorways throughout Germany. Due to the denser motorway network in south-west Germany, the concentration of charging locations is slightly higher there.

Figure 4 depicts the close meshed network (50 km). This network contains 267 charging locations. Since charging infrastructure is not included at the beginning and end of each motorway, halving the average distance does not result in doubling the number of charging locations.

At motorway junctions, the distance between two locations can be closer than 50 or 100 km, as the model treats motorways independently and the start and end of motorways separately. For example, the model creates a location on the A5 motorway near the city of Freiburg (southwest Germany) in the wide meshed network, 50 km before the end of the motorway at the Swiss border. At the same time, the model has positioned a location 10 km further North. This location is about 100 km away from the next charging location, near Karlsruhe. Since the A5 motorway is electrified from North to South, this effect occurs at the southern end of the motorway, near the Swiss border.

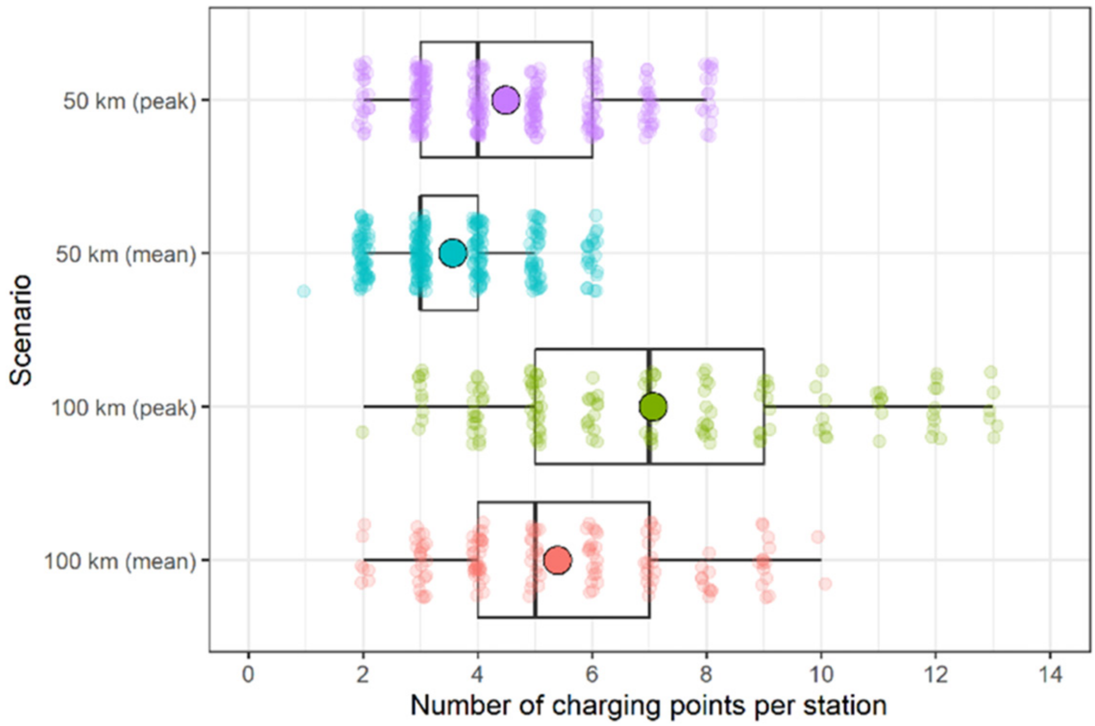


Figure 5. Box plot of charging points per location in the close meshed network (50 km) and the wide-meshed network (100 km) for mean and peak configuration.

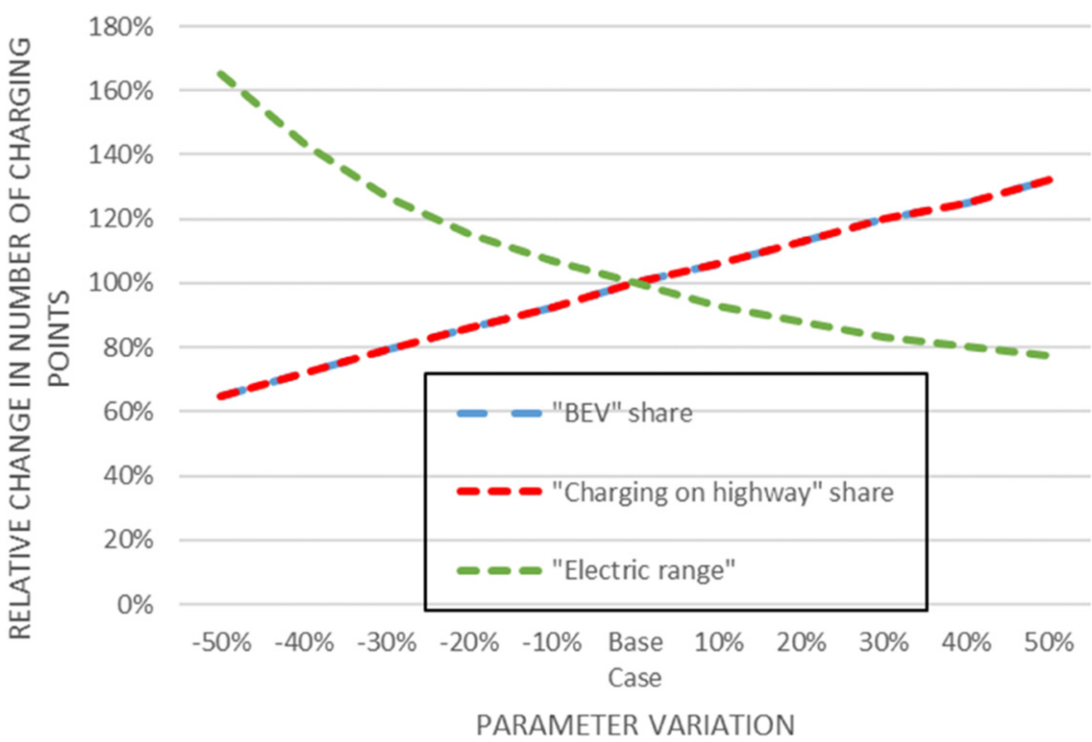


Figure 6. Sensitivity analysis for a close meshed network with peak traffic.

A small distance between two locations can also occur near motorway intersections. For example, there are two locations northwest of the city of Leipzig (eastern Germany) less than 5 km apart in the close meshed network. One of the locations belongs to the A9 motorway, one to the A14. Similar situations occur on parallel motorways, e.g. North of Mannheim (southwest Germany) in the wide meshed network (A5 and A67).

No electrification takes place on short motorway sections, as these are explicitly excluded by the model algorithm. This applies especially to short urban motorways and connecting sections, such as motorway A114 from the center to the North of Berlin.

3.2. Number of charging points per location

Locations were designed to ensure mean waiting times below 5 min for mean daily traffic. The wide meshed network (100 km) consists of 765 charging points, or 5.4 charging points per charging location on average. The two largest locations contain ten charging points. In the close meshed network (50 km), the number of charging points increases to 950. This corresponds to 3.6 charging points per charging location. If the total number of charging points is considered, the wide meshed network is therefore more efficient.

As described in section 2.2.3, the number of charging points depends on the choice to serve peak traffic or average daily traffic. If the locations serve peak traffic, the number of charging points increases to 1198 in the close meshed network (50 km) and to 1003 in the wide meshed network (100 km). This represents an increase of 26% and 31%, respectively. Figure 5 shows the distribution of charging points per charging location in both networks and for mean and peak configurations as a box plot together with the number of charging points per location for the individual locations as small circles.

3.3. Sensitivity analysis

Since BEV for long-haul trucking are not yet available, the calculations come with some uncertainties and estimates. This includes the electric range, the share of public charging on motorways, and the share of BEV as a proportion of total road freight traffic. To assess the impact of these uncertainties, figure 6 shows a sensitivity analysis for those parameters. Originally, we assumed 15% of the vehicles are BEV with 50% charging on motorways. Furthermore, we assumed a typical range of 300 km. We varied the original values by up to +/− 50% (original value ∗ 1.5 or original value ∗ 0.5). If the considered values change, the number of charging locations would remain the same while the number of charging points would change. As described in the methodology, the number of German-wide charging events has no influence on the selection of charging locations, but the sizing of the individual locations relies on the number of charging events. Increasing the electric range leads to a decrease in charging events and charging points. Conversely, increasing the BEV share or the share of charging on motorways leads to an increase in charging events and charging points. Figure 6 shows these changes for a close meshed network.

Another uncertainty is the time required for recharging. Since 30 min charging time seems optimistic from today's perspective, we considered an average charging time of 60 min in the sensitivity analysis. While the number of charging locations remained constant, the number of charging points increased to maintain the 5 min average waiting time. Taking the peak configuration as a starting point, the number of charging points in the close meshed network (50 km) increased from 1198 to 2121, slightly under-proportionately to the charging time. In the wide meshed network (100 km), the number of charging points increased from 1003 to 1857, with a maximum of 26 charging points at one location.

Since the accepted average waiting time of users is still subject to uncertainty today, we also varied this parameter and doubled the average waiting time to 10 min. For the close meshed network (50 km) and peak configuration, the number of charging points then decreased from 1198 to 1089. The number of charging points in the wide meshed network (100 km) decreased from 1003 to 934. In both networks, doubling the average waiting time thus led to an average reduction of approximately half a charging point per location.

4. Discussion

The discussion is divided into two sections. The first sections refers to the assumptions and their influence on the results. The second section discusses the method and its limitations.

4.1. Assumptions influencing the results

The results presented here apply to Germany and represent a situation that might occur around 2030. Since the framework conditions for the use of trucks and charging infrastructure apply throughout the EU, the approach can be transferred to other EU countries. This relates to the targeted network density of 50 to 100 km or the mandatory breaks of 45 min as key assumptions of our modelling.

The model presented here relies on charging time assumptions. The charging time depends on different parameters that are still uncertain today. This includes the achievable average charging power. In turn, the charging power required depends on the driving time per stint, the average speed, and the energy demand per km. If these values exceed the assumed parameters or if the required charging power cannot be achieved, the charging time would increase. In the model, this has an almost linear effect on the required number of charging points, as shown by the corresponding sensitivity analysis. Future analysis should therefore validate the relevant parameters, for example, by prototyping or simulation.

The average waiting time is also subject to uncertainty. In order to avoid downtimes in addition to the mandatory 45 min break after 4.5 h of driving, we assumed 5 min average waiting time. In most cases, the charging process can be completed within the mandatory break. The actual acceptance of longer breaks remains a subject for further research. However, as shown in the sensitivity analysis, varying this parameter has only a small impact on the charging infrastructure.

Counting station data as a basis for station dimensioning is easy to understand and easily accessible. However, this approach comes with a relevant limitation. Compared to traffic flow data, the actual charging demand remains uncertain and needs to be estimated. This is done using the parameters 'BEV share' and 'charging on motorway share'. The sensitivity analysis showed that these parameters have an almost proportional impact on the demand for charging points. This may lead to an overestimation of charging demand in urban areas with a high share of regional traffic, and an underestimation on long-distance corridors. Until recently, traffic flow data for Europe, which are needed to cover long-haul transport, were not publicly available. However, newly published datasets, such as Speth *et al* (2022), could further improve future analysis.

4.2. Methodology and its limitations

In the model, all counting stations serve as potential charging locations. In reality, it cannot be assumed that every counting station is available as a location with unlimited capacity. Charging stations must be allocated to nearby parking areas. The results presented here can serve as orientation and estimation. The actual site selection depends on further factors, such as the available parking area or the possible electricity grid connection, and must be assessed individually for each location. Future models could consider these aspects in more detail, for example, by introducing capacity limits. However, for the actual selection of a specific site, they will also remain a simplification. Future models could also include costs into the assessment, although the cost parameters also depend on local conditions. To sum this up, local characteristics, such as parking area availability, connection to the electricity grid or local infrastructure costs, can all influence the exact siting of a charging location. The networks described here are therefore subject to uncertainty. They outline an overall picture for Germany, but are not intended to provide recommendations for the exact location of a site.

Another simplification concerns the shortened distance at the beginning and end of motorways to ensure cross-border traffic. As described in the results, in some cases, stations may be too close to each other. From an operational perspective, it needs to be verified whether both stations are required or whether a small deviation from the specified distance could save one station. Future modelling could consider this aspect by setting a minimum distance between stations. Although only a cross-border solution will be successful in the medium-term, one might argue that the focus during early market diffusion should be on domestic traffic. The results presented show a medium-term target around 2030 for two possible network configurations. In particular, the close meshed network does not build on the wide meshed network; any stepwise expansion remains a subject for further research.

Unlike an optimization model, the coverage approach cannot guarantee the minimum number of charging stations. Nevertheless, it has other advantages: (1) the input data requirements are comparatively low. While an FRLM requires a complete set of transport flows, the coverage approach works with counting station data. (2) The coverage approach is not computationally demanding, while the optimization approach for the entire vehicle fleet of a country relies on significant simplifications to render the problem solvable. (3) The coverage approach meets the user's demand to reach a charging station quickly at any time. This is even more valid for trucks, where detours or additional recharging stops beyond the usual mandatory breaks are unlikely to be accepted. Nevertheless, both approaches could be pursued and combined in the future. The FRLM designs a network, which makes all routes drivable with very few stations. The coverage approach shows networks enabling convenient use by many vehicles.

5. Conclusion

In summary, we show two possible networks for fast-charging infrastructure for electric HDV in Germany. Recharging can take place during the mandatory break of 45 min after 4.5 h of driving. Using a coverage approach, a close meshed network (50 km distance) and a wide meshed network (100 km distance) were designed to electrify 15% of the HDV in Germany. The close meshed network consists of 267 charging locations and up to 1198 charging points. The wide meshed network contains 142 charging locations with up to 1003 charging points in total. The resulting maps do not pinpoint exact locations of future charging infrastructure, but give an impression of a possible German network and provide local planners with an initial assessment of local demand. In terms of total network costs, the close meshed network has more charging points and should therefore be more expensive (basic costs for space allocation per location plus the grid connection and charging stations with costs increasing roughly linearly with the number of charging points). However, the close meshed network also offers a higher quality of service due to its higher density. Operators can be expected to start with larger distances between charging stations and then increase the density over time.

With regard to future research, we identified especially the following areas to overcome current limitations: (1) the assumptions regarding charging behaviour should be validated as soon as possible, as they form the basis for the usability of BEV in long-haul transport. (2) The data availability on traffic volumes should be improved to allow methodological adjustments. This includes filtering by regional and interregional traffic to avoid overestimation in urban areas. The generation of European origin-destination matrices would also enable the use of optimization models. (3) The consideration of other aspects, such as local parking capacity, available electricity, or local construction costs could further refine the results.

Our findings have several implications for policy and industry decisions. They show that the currently discussed European objectives require several hundred fast-charging stations along the German motorway network. Along highly utilized routes, the charging stations have to be equipped with up to 13 charging points, even in an early market stage. The government, as the entity responsible for public infrastructure, needs to prepare the corresponding infrastructure installation. Charging station operators must prepare for installation and evaluate the economic viability of potential locations. The power grid operators must provide the corresponding capacities. The varying size of the locations necessitates the development of market mechanisms that ensure economic operation of the charging locations as well as full-coverage expansion. The EU should ensure that the infrastructure ramp-up is accompanied by increasing penetration of battery electric trucks. The upcoming revision of the regulation to limit the CO_2 emissions of newly sold HDVs (EU 2019) provides a suitable opportunity. The rollout of infrastructure and electric HDV should be combined and jointly managed in order to match demand and supply and ensure capacity utilization of the new infrastructure.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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