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Where to charge electric trucks in Europe - Modelling a charging infrastructure network

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Summary

Heavy-duty trucks account for 27% of the European greenhouse gas emissions in the transport sector. To decarbonize road freight transport, the European Union plans to build a fast charging network for trucks. This paper presents two scenarios, covering European highways with charging stations every 50 or 100 kilometers. For each location, the required number of charging points at 15% battery electric trucking is calculated individually. A third scenario takes into account the infrastructure ramp-up in 2025 and assumes a share of 5% battery electric trucking in a network with 100 kilometers distance. We define a network of 660 (100 kilometers distance) or 1,468 stations (50 kilometers distance). Depending on the scenario and the individual station, the number of charging points per station varies between 1 and 18 in 2030. The results help to design future charging infrastructure for electric road freight transport.

Keywords: charging, freight transport, fast charge, infrastructure, truck

1 Motivation

Road transport causes approximately one quarter of current European greenhouse gas (GHG) emissions. In turn, heavy duty trucks and busses account for 27% of road transport GHG emissions [1]. European Union (EU) legislation requires CO2 emissions from newly registered heavy-duty vehicles to be reduced by 30% in 2030 compared to current levels [2]. Analyses show that this in only possible when using zero emission vehicles (ZEV), i.e. electric or hydrogen powered trucks [3]. When comparing different options to electrify heavy-duty trucks (e.g. fast charging, overhead catenary or battery swap), fast charging seems to be the best option in the short term, mainly due to a comparatively scalable infrastructure [4]. Current research shows, that charging infrastructure is essential for the diffusion of battery electric trucks (BET) [5, 6]. Consequently, the EU plans to install a fast charging infrastructure for BET [7].

According to [8], charging infrastructure planning models can be divided into three groups: node-based, path-based, and tour-based models. In node-based models, a charging station covers a certain area or a certain part of a road. Therefore, a quite dense charging network with many charging points is modeled. In some cases, these

models are therefore referred to as coverage approach [9]. [10] shows a coverage approach to design an infrastructure for battery electric cars in Germany. [9] transferred the approach to BET in Germany.
In contrast, path-based models try to cover a maximum of passing traffic with a minimum of stations. For example, a Flow Refueling Location Model (FRLM), a prominent representative of this approach, places locations such that origin-destination-relations known in advance can be supplied with a minimum number of locations. These models haven been used to model charging infrastructure for battery electric cars in the USA [11] or in Europe [12]. However, due to the high computational effort, restrictions are usually made. For example, [11] clusters 4,486 regions to 196 regions. [13] transferred this approach to hydrogen powered trucks and combined the model with a capacity restriction to avoid unrealistic large stations.
Finally, a tour-based model considers individual driving profiles and locates charging stations such that they fit to the driving profiles. While the level of details increases from the node-based to the path-based to the tour-based model, the demands on the input data also increases. For the node-based approach, data from local traffic counts are sufficient. Path-based models require origin-destination relations. The tour-based models typically rely on journey logs. For example, [14] use driving trip data to model slow-charging infrastructure in the city of Columbus (Ohio, USA). For a deeper comparison of the models, refer to [8].

The aim of this paper is to design a public fast charging network for BET throughout Europe for the mid-term future (e.g. 2030) based on transport flows. We limit the analysis to the EU, extended by Great Britain, Switzerland and Norway (EU27+3). Since the proposal for the Alternative Fuel Infrastructure Regulation (AFIR) [7] suggests charging infrastructure at regular intervals along the European highway network, we follow [9] and apply a node-based approach and combine it with a queuing model. The queuing model determines the number of necessary charging points for a given share of BET for each charging station.

The paper is structured as follows: First, we present relevant input data and the methodological approach. Afterwards, section 3 contains the results. Finally, we discuss some critical aspects in section 4.

2 Data, methods, scenarios

2.1 Data and assumptions

To model a charging infrastructure for Europe, we require the traffic volumes on the European highway network. Modeled European traffic flows [15] serve as our basis. The dataset represents an update of the truck traffic flows published in the European Transport policy Information System (ETIS) project [16] and contains projections between NUTS3[1]-regions in Europe. The dataset contains only transports between NUTS3-regions. Inner regional traffic is not included. However, inner regional traffic is not relevant for public fast charging infrastructure on the highway network. In the following, we refer to the truck traffic flows in the dataset as long-haul traffic. The underlying road network contains 17,435 nodes that are connected with 18,447 edges. In some sections, we add additional nodes to ensure a maximum distance of 10 km between two nodes. The nodes serve - simplified - as potential station locations in this paper. For each edge and node, it is known how many vehicles pass it per year in 2010, 2019, and 2030. Figure 1 shows the traffic volume in Europe 2030 according to [15]. Within this paper, we filter the updated ETIS dataset and focus on the international E-road network in Europe.

Additionally, we derive a cumulative annual mileage of 162,397 million km in 2019 and 215,042 million km in 2030 for long-haul traffic on roads in the EU, including Switzerland, Norway, and Great Britain from [15]. Simplified, we assume 188,719 million km in 2025.

[1] *Nomenclature des unités territoriales statistiques.* Level 3: small regions, large cities

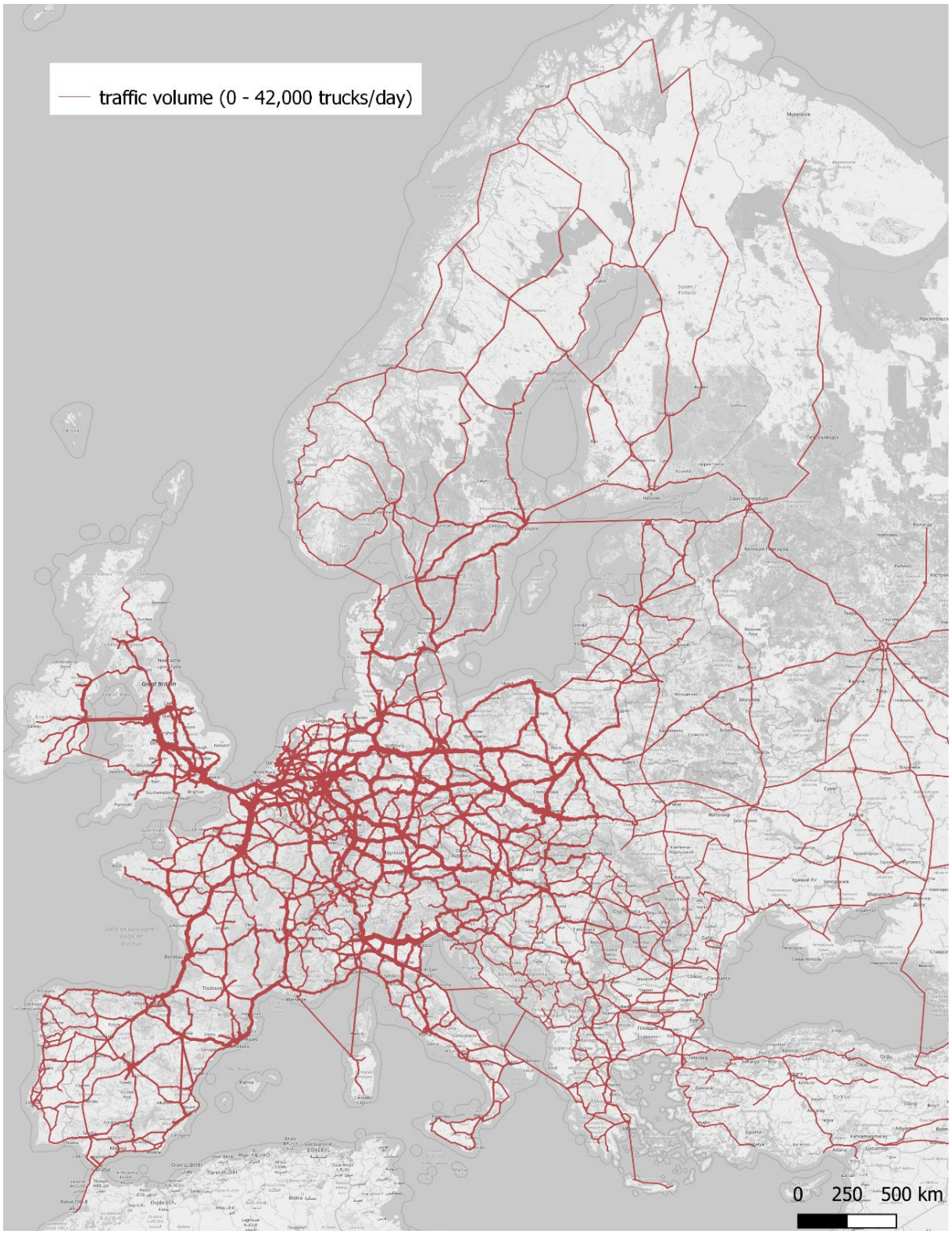

Figure 1: Traffic volume in Europe 2030. Own illustration, based on [15]. Background: OpenStreetMap

As shown in [9], and based on the automated traffic census in Germany [17], we assume that a maximum of 6% of the daily charging events happen in the most trafficked hour of the day. For this hour, the average waiting time should not exceed 5 minutes, according to experts from the automotive industry [18]. Thus, the charging process of 30 minutes can be carried out within the mandatory break of 45 minutes after 4.5 hours of driving, including 10 minutes buffer. Therefore, a recharge for approximately 300 km is required each time [9].

We assume that 25% of the charging events occur on public fast charging infrastructure. This means that, on average, half of the BET use public infrastructure and, for these trucks, every second charging process takes place publically. However, this assumption comes with a high level of uncertainty. As shown in [9], the required number of charging points increases approximately linearly with the share of public charging events. Table 1 sums up the most important parameters.

Table 1: Input parameters for infrastructure calculation

Parameter	Abbreviation	Value	Reference
Cumulative annual mileage	$AM_{HDV,EU27+3}$	188,719 Mio. km (2025) 215,042 Mio. km (2030)	Own calculation, based on [15]
Range in 4.5 h	$range_{BET}$	300 km	[9]
Share of public charging	CE_{public}	25%	Own estimation, based on [9, 18]
Average charging time		30 min	[9]
Average waiting time	W_q	5 min	[9]
Share of daily charging events in most trafficked hour		6%	[9]

In the following, we will focus on three scenarios: First, we will design a startup network for 2025. Within the startup network, we assume 5 % of the annual mileage being electrified ($BET_{share} = 0.05$), following [3] and expert opinion [18]. Additionally, we assume a distance of $d_{avg} = 100\ km$ between the charging locations. This is slightly more than the EU's proposal with 60 km [7]. Second, we will design an expansion network for 2030 that will densify the startup network to 50 km. The BET_{share} will grow to 15%. Third, we will design a widemeshed network for 2030 with a distance of 100 km and a BET_{share} of 15%. Table 2 sums up the most important information.

Table 2: scenario definition

Scenario	Targeted year	d_{avg}	BET_{share}
Startup	2025	100 km	5%
Expansion	2030	50 km	15%
Widemeshed	2030	100 km	15%

2.2 Methods

The methodological procedure is divided into two steps: First, the charging locations and the number of charging events at every location are determined. Second, the number of charging points for every location is calculated. Both steps are described shortly in the following. For a more detailed description, compare [9].

2.2.1 Determine charging locations

According to the coverage approach described in [9], every single road of the network graph is traversed successively according to a predefined scheme. Within the E-road network, there are two major groups: odd numbers indicate roads that run from north to south, whereas even road numbers run from east to west. Each of these roads is processed one after the other in ascending order, along the previously defined direction of travel.

Every node in the network is a potential charging location. Locations are positioned at regular intervals. Equation 1 shows this approach, where CL_L is a bivariate variable indicating whether infrastructure is built in L or not. $d_{CL,L}$ indicates the distance between the last positioned charging location and location L. d_{avg} defines the distance between two charging stations in the network.

$$CL_L = \begin{cases} 1, if & d_{CL,L} \geq d_{avg} \\ 0, else & \end{cases} \quad (1)$$

Afterwards, the total number of daily public charging events in the EU27+3 CE_{EU27+3} is calculated as follows:

$$CE_{EU27+3} = \frac{BET_{share} * (AM_{HDV,EU27+3}/313)}{range_{BET}} * CE_{public} \quad (2)$$

BET_{share} stands for the share of BET on the total cumulative annual mileage $AM_{HDV,EU27+3}$ of all heavy duty trucks. The annual mileage is divided by 313 to derive daily mileage, excluding Sundays. $range_{BET}$ refers to the range that a truck can cover in 4.5 hours of driving. This corresponds to the maximum driving time, before a mandatory break is required. Finally, we multiply with the share of charging events on public infrastructure CE_{public}.

Finally, the expected daily public charging events have to be allocated to individual charging locations. For this purpose, the maximum traffic volume in the area in front of and behind the location is calculated and compared with the total maximum traffic volume of all locations. The number of trucks in both directions is considered together. Equation 3 describes the calculation of the daily charging events at each realized charging locations. $MAX_{CL_{i-0.5}}^{CL_{i+0.5}}(TV_j)$ describes the maximum traffic volume of all subsection j on half the distance between the realized charging location i and the realized station before this location ($CL_{i-0.5}$) and half the distance to the subsequent location ($CL_{i+0.5}$). The individual maximum traffic volume is set in relation to the sum of all maximum traffic volumes of all realized stations.

$$CE_{CL_i} = CE_{EU27+3} * \frac{MAX_{CL_{i-0.5}}^{CL_{i+0.5}}(TV_j)}{\sum_{CL} MAX_{CL_{i-0.5}}^{CL_{i+0.5}}(TV_j)} \quad (3)$$

2.2.2 Dimension charging locations

The calculation of the number of charging points per location is based on queueing theory. For the peak hour, we assume 6% of the daily charging events of one location, as described above. The system is designed for this size. We stick to the Kendall notation (*A/S/c/d/k/m*), to define the queueing system. To define the arrival process *A*, we assume Poisson-distributed arrivals [19], with the average arrival rate $\lambda = CE_{CL_i} * 6\%$. The inter-arrival times are therefore exponentially distributed (Markovian Distribution M). This means *A* = M. With regard to the service process *S*, [19] show that a General distribution G with normally distributed service times fits quite well. The average number of customers served per period is defined by μ. For example an average charging time of 30 min results in an average service rate μ = 2 trucks/hour. The number of service units *c* - charging points - shall be calculated. For *D*, *k*, and *m*, we assume the default values. The queue's discipline *d* follows the First-In-First-Out principle. This means that the trucks are served in the order of their arrival. The number of customers waiting in the queue *k* is assumed to be infinite. The same applies to the number of customers in total. Therefore, we define an M/G/c queueing system. Since exact solution for the mean waiting time of M/G/c systems are not known, the mean waiting time is approximated, according to [20]:

$$W_q^{M|G|c} = \frac{C^2 + 1}{2} W_q^{M|M|c}. \quad (4)$$

C is defined as the variation coefficient of the distribution of the service times, i.e. the standard deviation (5 min) divided by the mean value of the service time distribution (30 min). This formula is used with the waiting time of the original M/M/c system, given in equation 5:

$$W_q^{M|M|c} = \frac{1}{1-\rho}\frac{1}{c\mu}\frac{(c\ \rho)^c}{c!}\left((1-\rho)\sum_{n=0}^{c-1}\frac{(c\rho)^n}{n!}+\frac{(c\rho)^c}{c!}\right)^{-1} \quad with \quad p=\frac{\lambda}{c\mu} \tag{4}$$

Finally, we calculate the maximum average arrival rate λ that allows for an average waiting time of 5 minutes for all possible numbers of charging points c. For each location, we compare the local average arrival rate $\lambda = \ CE_{CL_i} * 6\%$ to the arrival rates with different c. Afterwards, we can choose the number of charging points c for each location so that the average waiting time is less than 5 minutes.

3 Results

Figure 2 and Figure 3 show the distribution of the charging locations in the EU27+3. For the startup network and the widemeshed network with a distance of 100 km, we receive 660 charging locations. For the expansion network with 50 km distance, we count 1,486 charging locations. There is more than a doubling, since very short sections as well as peripheral areas also receive charging locations in the closer network.

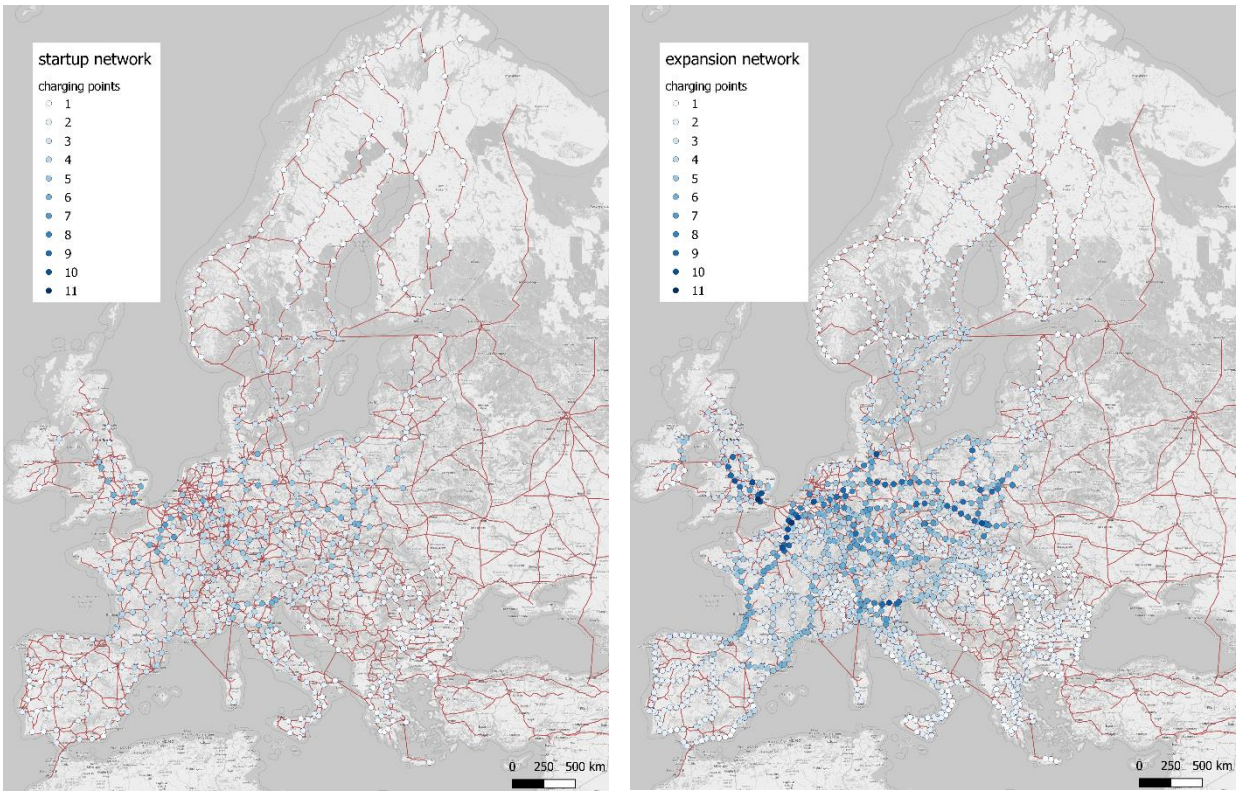

Figure 2: Location of 660 charging locations in the startup network and 1468 charging locations in the expansion network. Background: OpenStreetMap

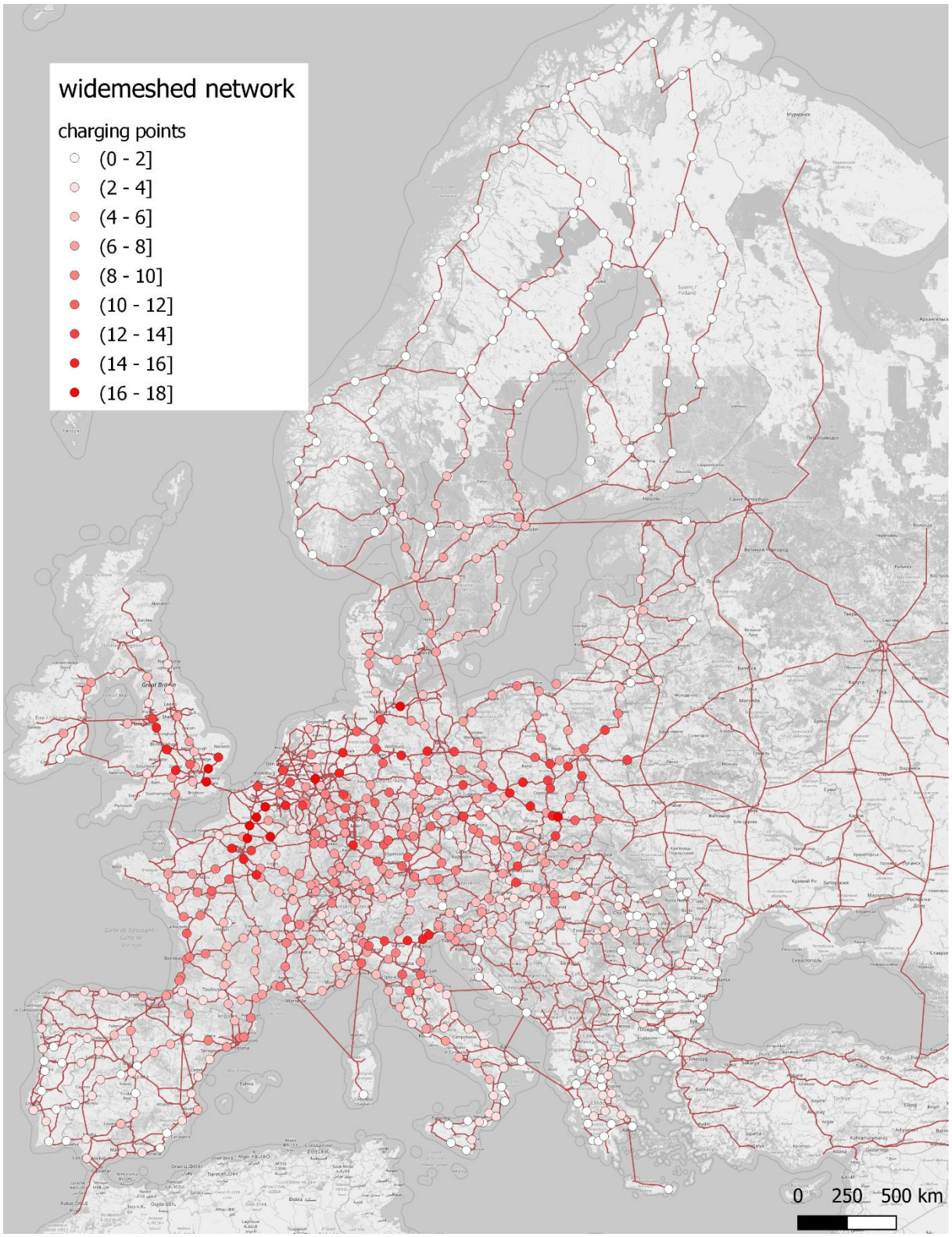

Figure 3: Location of 660 charging locations in the widemeshed network. Background: OpenStreetMap

With regard to the geographical distribution of the charging points, there is a concentration on Central Europe (e.g. France and Germany). The traffic generated by the ports in the Netherlands, Belgium and Germany is of great interest for the dimensioning of charging locations. The surrounding countries (e.g. Norway, Sweden, Finland, Greece, Italy, and Spain) are equipped with smaller locations that cover the whole area.

The startup network consist of 1,697 charging points at 660 locations. This means that an average charging location includes 2 - 3 charging points in 2025 (mean = 2.57, median = 2). Assuming a tripling of electric traffic (BET_{share} 5% versus 15%) and a densification of the network from 100 km to 50 km, the average charging location has still 3 charging points (mean = 3.25, median = 3). However, the largest station contains 11 charging points instead of 7. We refer to this scenario as expansion network. In total 4,778 charging points are needed in this scenario. Figure 4 (a) shows the change in the required number of charging points from the startup network to the expansion network. In less than 2% of all charging locations, between 2 and 4 charging points are removed. These are typically locations nearby areas with high traffic, such as ports, where a new charging location is opened closer to the high traffic location. If the network is not densified, 3,679 charging points are required, as shown in the widemeshed network. However, the individual charging locations will be significantly larger. An average charging location is equipped with 5 - 6 charging points (mean = 5.57, median = 5). The biggest charging location consists of 18 charging points. Figure 4 (b) shows the distribution of charging points among the individual charging locations for all scenarios.

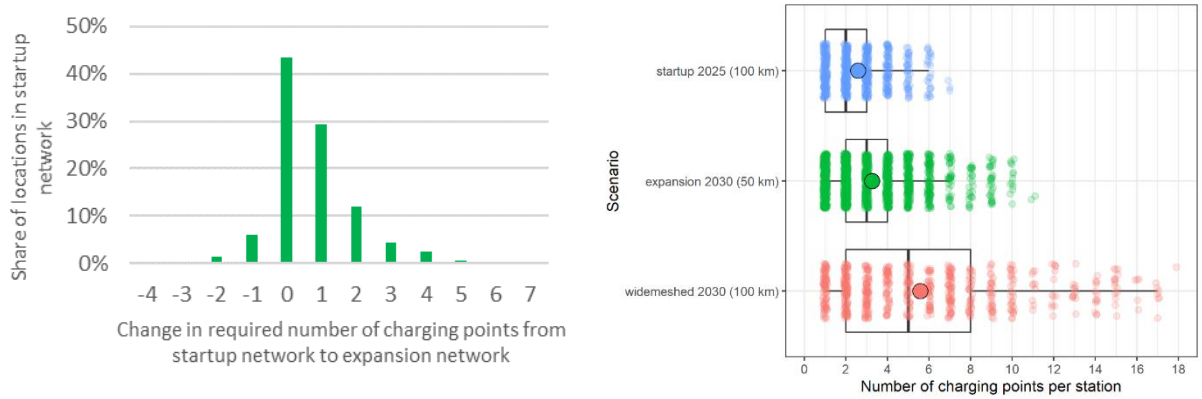

Figure 4 (a): Change in number of charging points from startup network to expansion network

Figure 4 (b): Boxplot of charging points per location for all scenarios (right)

Since our model relies on assumptions, Figure 5 shows a sensitivity analysis for BET_{share}, CE_{public}, and $range_{BET}$. We varied the parameters by +- 50%. An increase in BET_{share} or CE_{public} by 50% increases the number of charging points from 4,778 to 6,211. This means the number of charging points increases by 30%. The same effect can be observed when reducing BET_{share} or CE_{public}. A reduction of $range_{BET}$ by 50 % leads to an increase of charging points from 4,778 to 7.581. An increase of $range_{BET}$ by 50 % reduces the number of charging points to 3,813.

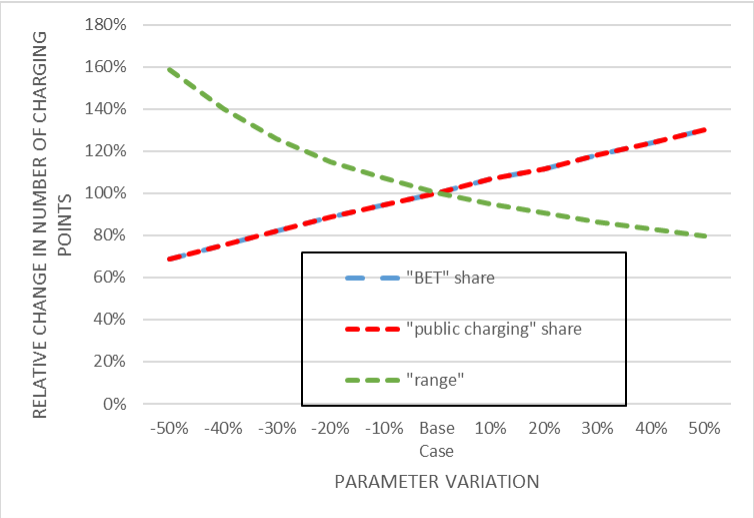

Figure 5: Sensitivity analysis for the expansion network

4 Discussion and Conclusion

The results shown in this paper rely on different assumptions and data sources. As shown in Figure 5, the number of charging points heavily rely on these assumptions. Therefore, the assumptions should be further investigated and validated in the future. In contrast to previous work [9] , the traffic volume used here is based on synthetic road freight transport flow data [15]. On the one hand, this significantly improves the results, since regional traffic that is unlikely to use public fast charging infrastructure is not included in the dataset. On the other hand, the dataset itself relies on significant simplifications, e.g. in terms of resolution, scaling, and non-consideration of multi-stop-tours. From a scientific perspective, additional data sources, such as driver logbooks, should be integrated to better reflect actual driving behavior. From a planner's perspective, activities at local rest areas should be observed, to validate the model results.

Additionally, the model itself comes with some limitations. First, the location selection does not take into account the suitability of the location for a charging area. Aspects such as parking area availability or the power grid connection are not part of the analysis. The locations are intended as representatives for the particular highway section, not as a defined location. However, the model gives a good impression of the general distribution of charging locations as well as the total number of charging points required. As part of the model development, location details could be integrated up to a certain level in the future. However, a planner will evaluate the local conditions in the targeted area in detail. Second, the model is based on the assumption that charging processes are distributed equally to traffic volumes. This assumption seems plausible, but should be verified in the future, for example with driving logbooks or with data from parked vehicles. Third, the differentiation between public fast charging in the mandatory break and public slow charging is highly simplified and can only be modeled as part of CE_{public}. At this point, path-based or tour-based models are better suited. However, these models are associated with significantly higher computational effort and a high demand on data availability.

In conclusion, a dense fast-charging infrastructure for heavy-duty trucks is essential for the successful electrification of road freight transport. The EU is currently defining the legal framework to create a corresponding network. This paper gives a first insight, how a fast-charging network in Europe with charging stations at regular intervals might look like. Our results indicate a demand of approximately 700 to 1,500 charging locations with up to 4,800 charging points in total. In addition, the paper shows that even in an early stage of market, large locations with more than ten charging points are required. Given the EU's targets for the CO_2 reduction of newly sold vehicles in 2030, technical issues should be clarified, path decisions should be made, and construction projects should be initiated.

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