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Modelling a capacity-constrained public charging infrastructure network for electric trucks in Germany

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Executive Summary

CO_2 emission standards in the European Union necessitate the introduction of zero-emission trucks. Battery electric trucks are one promising alternative to diesel trucks. However, a public fast charging infrastructure is necessary for operation. Existing charging infrastructure models do not contain restrictions regarding the maximum size of a single charging location, leading to unrealistically large locations. Here, we integrated a capacity constraint derived from the available parking lots and applied the resulting model to 236,000 origin-destination traffic flows. Considering a vehicle range of 300 km, we identified 124 optimal charging locations with approximately 12,000 charging points in Germany. Hence, our locations are still quite large, but feasible from the perspective of available parking space. Without the capacity constraint, 42 charging locations could serve Germany.

Keywords: BEV (battery electric vehicle), freight transport, heavy-duty, infrastructure, truck

1 Motivation

European Union (EU) legislation mandates that CO_2 emissions from newly registered heavy-duty vehicles have to be reduced by a least 30% by 2030 compared to 2019 [1]. This will require up to 22% of newly registered heavy-duty vehicles to be zero-emission vehicles, i.e. battery-electric or hydrogen powered vehicles [2]. For the diffusion of battery-electric trucks (BET), the available charging infrastructure is of decisive importance [3, 4]. Therefore, the European Commission plans a charging infrastructure ramp-up in the member states of the EU [5]. At the same time, public parking areas for trucks are already scare today. For example, Germany lacks more than 23,000 parking lots for trucks [6].

Infrastructure modelling can be divided into three streams: node-based, path-based, and tour-based models [7, 8]. Node-based models locate facilities - i.e. charging locations - to meet the demand of neighbouring nodes - i.e. vehicles with a need for charging. Combining a node-based model with queuing theory, [9] distribute charging locations for battery electric trucks in the EU. They define a network of 660 to 1,486 charging stations with up to 18 charging points per station for 2030. In total, [9] derive approximately 5,000 megawatt charging points (megawatt charging system - MCS). However, since local traffic volumes at regular nodes in the road network are used, any information about individual trips is lost. In contrast, path-based models are based on traffic flows within a network. They try to cover a maximum of passing traffic with a minimum of stations. To do this, they use the information about the distance the vehicles have already travelled at any position in the network. For example, a flow-refuelling location model (FRLM), a subset of path-based models, has been used to model charging infrastructure for battery electric cars in the USA [10]. [11] applied this approach to fuel cell trucks and added a capacity restriction that prescribes a maximum dispensing quantity per station. [12] shows that the node-capacitated flow-refuelling location model (NC-FRLM) proposed by [11] can - under unfavourable conditions - result in vehicles refuelling more energy than they can transport. No adjustments have been made by [12], since a redefinition would significantly increase the computational effort. Finally, tour-based models rely on individual driving profiles. Typically, journey logs with multiple paths per vehicle serve as input. Due to the high data and computational effort, these models are typically used for small fleets and limited areas. For example [13] use driving profiles to model a slow-charging infrastructure for cars in the city of Columbus (OH, USA). Based on simplified synthetic trip chains and legal requirements, The approach of [14] can also be considered as a tour-based model .Based on simplified synthetic trip-chains and legal requirements, [14] calculate necessary truck stops. They find 9,000 MCS charging points and about 40,000 overnight charging points (combined charging system - CCS) suitable to serve Europe in 2030. Charging stations can be found almost everywhere along European highways. This is consistent with findings from [15] which show that today trucks park almost everywhere.

In summary, estimates for a future dense fast charging infrastructure for BET exist. However, to the authors' knowledge, there is no estimate regarding the minimum number of charging locations needed to enable long-distance electric trucking. Yet, this knowledge is important to support the required rapid market diffusion of BET.

The aim of this paper is to design a minimum public fast charging network for battery electric trucks in Germany, taking limited parking capacities into account. For this purpose, we enhance the NC-FRLM and combine it with a queuing model.

We thus extend the existing literature by content-related and methodological aspects. First, we consider actually available parking capacities for recharging stations for battery electric trucks. Second, we improve the approach from [11] and ensure that a maximum amount of energy can be recharged that fits into the battery.

2 Data and methods

In the following, we present the datasets and the most important assumptions for our modelling. Afterwards, we show our methodological approach.

2.1 Data

The calculation of a charging network for battery-electric trucks relies on origin-destination-data for trucks in Europe. An updated version of the ETISplus data - a project that modelled traffic flows in 2010 - serves as basis [16]. The dataset covers 1,675 regions all over Europe and 1.5 million origin-destination paths. In accordance with [9], we assume a maximum electric range of 300 km, suitable for 4.5 hours of driving. This corresponds to the maximum driving time in Europe before a mandatory break of 45 minutes is required. Paths that are shorter than 300 km do no need to be recharged and are therefore not relevant for public fast charging infrastructure. The paths that need to be recharged are shown in Figure 1, based on 2030 data from [16]. In accordance with [17] and to keep the problem solvable, we only consider flows that are served at least once a week (>50 trucks/a). This reduces the number of paths in Europe from 1.4 million and 172 billion vehicles kilometres travelled to 374,000 flows and 156 billion kilometres travelled. For Germany, we receive 236,000 flows. While keeping more than 90% of the vehicles kilometres travelled, we significantly reduced the number of flows.

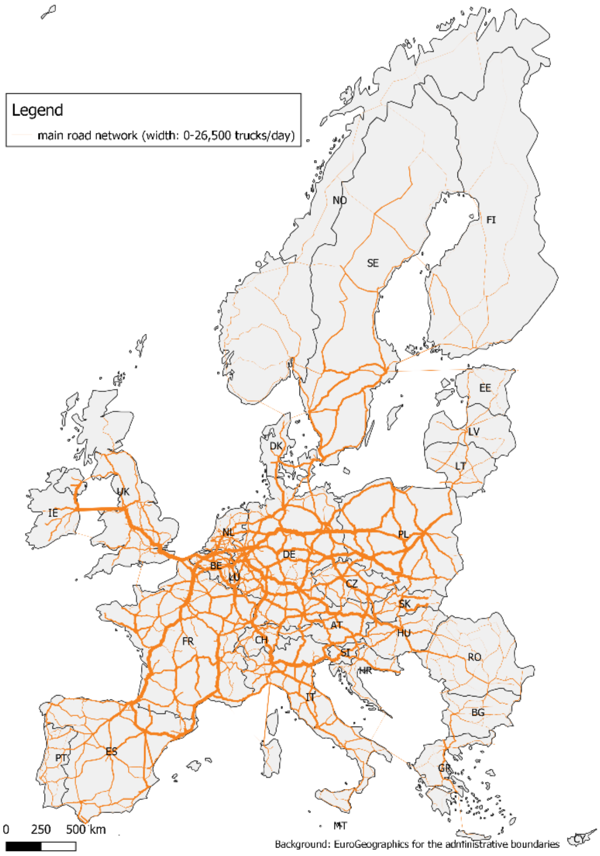

Figure 1: Europe-wide traffic flows longer than 300 km, based on [16]

Regarding the parking capacity, the Autobahn GmbH, the operator of the German highway infrastructure, provided data on the availability of truck parking areas. The maximum hourly throughput of vehicles at parking areas is derived from the parking capacity using queuing theory. For the queuing model used, please refer to [9]. in accordance with [9], we assume an average charging time of 30 min, an average waiting time of 5 min, and a peak traffic of 6% of the daily traffic in the peak hour of the day.

Finally, we assume a maximum electric range of 300 km, suitable for 4.5 hours of driving. Trucks can recharge at origin and destination and start fully charged. As mentioned, fast charging can be done within 30 minutes (megawatt charging). For our calculation, we also expect all truck traffic to be battery-electric in the long term.

2.2 Methods

The modelling consists of two steps. First, we calculate a Europe-wide charging network. Second, we calculate a charging network for Germany, taking the available parking areas as an additional constraint into account.

The European charging network is calculated as a flow-refuelling location model (FRLM). The objective function of the mixed-integer optimization model minimizes the number of necessary charging locations. Constraints ensure that locations are positioned so that no vehicle has to travel more distance than the maximum range. The mathematical formulation follows [11] and [18].

$$\min \sum_{i \in N} z_i \tag{1}$$

s.t.

$$\sum\nolimits_{i \in K_{i,j}^q} z_i \geq y_q, \qquad \forall q \in Q, a_{j,k} \in A_q \tag{2}$$

$$\sum\nolimits_{q \in Q} f_q y_q \geq s \sum\nolimits_{q \in Q} f_q \tag{3}$$

$$y_q, z_i \in \{0,1\}, \qquad \forall q \in Q, i \in N \tag{4}$$

Set and indexes

A_q	Set of all directional arcs on a shortest path q, sorted from the origin to the destination
$K_{i,j}^q$	Set of all potential nodes that can refuel the arc $a_{j,k}$ in A_q
N	Set of all nodes in the modelled network
Q	Set of all origin-destination pairs
i, j, k	Indices, indicating nodes
q	Index of origin-destination pairs
$a_{j,k}$	Index of a directed arc from node j to node k

Parameters

f_q	Vehicle flow at path q
s	Share of recharged vehicle flows, in our modelling always 1

Decision variables

y_q	=1 if the flow on path q is recharged, 0 otherwise
z_i	=1 if a charging location is built at node i, 0 otherwise

The objective in equation (1) minimizes the number of public fast charging locations $z_i$at all node i in the network. As shown in equation (2), a path can be recharged ($y_q = 1$) if there is a charging infrastructure for each arc $a_{j,k}$ of the path. For each arc $a_{j,k}$ outside the initial range of the vehicle, a candidate set $K_{i,j}^q$ is computed that contains all recharging possibilities to pass the arc $a_{j,k}$. The path can be recharged if every candidate set contains at least one location z_i that is realized. Finally, equation (3) ensures that a certain share s of all vehicle flows f_q can be realized. In this paper, we assume that all flows have to be realized.

For the capacity-constrained German charging network, only trips that take place at least partially in Germany are considered. For multi-country paths, the distance from the origin or the last charging location before the German border to the first charging location or the destination after the German border is considered. The mathematical formulation is shown in the following:

$$\min \sum_{i \in N} z_i \tag{5}$$

s.t.

$$\sum\nolimits_{i \in K_{i,j}^{q_s}} x_{i_{q_s}} \geq 1, \qquad \forall q_s \in Q, a_{j,k} \in A_{q_s} \tag{6}$$

$$\sum\nolimits_{q_s \in Q} f_{q_s} x_{i_{q_s}} \leq c_i z_i, \qquad \forall i \in N \tag{7}$$

$$\sum\nolimits_{i \in N} x_{i_{q_s}} \leq l_{q_s}, \qquad \forall q_s \in Q \tag{8}$$

$$x_{q_s}, z_i \in \{0, 1\}, \qquad \forall q_s \in Q, i \in N \tag{9}$$

Set and indexes

A_{q_s}	Set of all directional arcs on a shortest path q_s, sorted from the origin to the destination
$K_{i,j}^{q_s}$	Set of all potential nodes that can refuel the arc $a_{j,k}$ in A_{q_s}
N	Set of all nodes in the modelled network
Q	Set of all origin-destination pairs
i, j, k	Indices, indicating nodes
q_s	Index of origin-destination pairs. Extended to identical origin-destination pairs for each subset. Flows are split, if the vehicle flow exceeds the capacity of a single parking space.
s	Index, indicating a subset of a path q
$a_{j,k}$	Index of a directed arc from node j to node k

Parameters

f_{q_s}	Vehicle flow at path q_s
c_i	Capacity restriction in node i
l_{q_s}	Number of maximum stops to drive path q_s

Decision variables

$x_{i_{q_s}}$	=1 if the flow on path q_s is recharged at node i, 0 otherwise
z_i	=1 if a charging station is built at node i, 0 otherwise

Again, equation (5) minimizes the number of charging locations z_i. As indicated by [19] and [12], a capacity-constrained infrastructure modeling needs to know the charging location of each vehicle. Therefore, $x_{i_{q_s}}$ indicates if a flow q_s is recharged at node i. Again, equation (6) ensures that every arc $a_{j,k}$ of a path is drivable. Equation (7) limits the number of charging events at a node i to the capacity of the node. The capacity c_i is calculated using the available parking lots to calculate the number of vehicles that can be served in the peak hour. For the actual calculation, the queuing theory approach described in [15] is used. Finally, equation (8) defines the maximum number of charging stops during one origin-destination-tour. The maximum number of stops for a path q_s is calculated according to equation (10). Since the capacity constraint in combination with the vehicle range might lead to additional charging stops, we allow for one additional stop. The additional stop may be necessary if the distance between two stops is significantly shorter than the vehicle range, for example because no charging facility can be provided at a suitable distance or it is fully occupied by other vehicles and can't be expanded due to the capacity constraint.

$$l_{q_s} = \left\lfloor \frac{distance_{q_s}}{range_{BET}} \right\rfloor + 1 \qquad \forall (q_s \in Q) \cap (distance_{q_s} > range_{BET}) \tag{10}$$

l_{q_s}	Number of maximum stops to drive path q_s
$distance_{q_s}$	Length of path q_s
$range_{BET}$	Vehicle range within one driving session of 4.5 h

Again, the objective function minimises the number of charging locations. Compared to the FRLM presented above, the constraints additionally ensure that no more charging points are established at any charging location than there are parking lots available. We refer to this formulation as capacitated flow-refuelling location model (CFRLM).The capacity constraint significantly complicates the problem, since for each vehicle not the possible charging locations, but the actually used charging locations have to be determined. Therefore, we use 8 processors and 256 GB of memory to solve the problem. The implementation is done in Python 3.10, integrating CPLEX 12.6 via Pyomo.

3 Results

First, we present the results for the FRLM for Europe. Second, we present the results for the CFRLM for Germany.

As shown in Figure 2, 339 charging locations in Europe allows for Europe-wide truck traffic. In order to keep the computation time reasonable, we accept a solver tolerance of 5%. Theoretically, the optimal solution could be 323 charging locations. Along roads with few junctions, for example in Norway, Sweden, or Finland, charging locations have the maximum possible distance of 300 km. If the road network is dense, for example in the centre of Europe, it is more efficient to place charging locations at highway junctions or intersections. One location may serve two roads, if built at a junction. However, the model does not know whether it is possible to build a charging infrastructure at those junctions.

In the background, the relevant daily traffic volume (>300 km, >= 50 trucks/a) is plotted. It can be clearly seen that the traffic volume has no influence on the density of the charging infrastructure. For example, there are heavily trafficked roads in Poland with a similar distance between charging stations as rarely travelled roads in Norway or Sweden.

The result from the FRLM outside Germany serves as minimum charging infrastructure for cross-border traffic in the CFRLM. For example, there is a charging location in the South of Denmark. Therefore, neither the FRLM nor the CFRLM position a charging location nearby the German-Danish border in Germany. However, the 42 charging locations of the FRLM in Germany are not part of the CFRLM charging network.

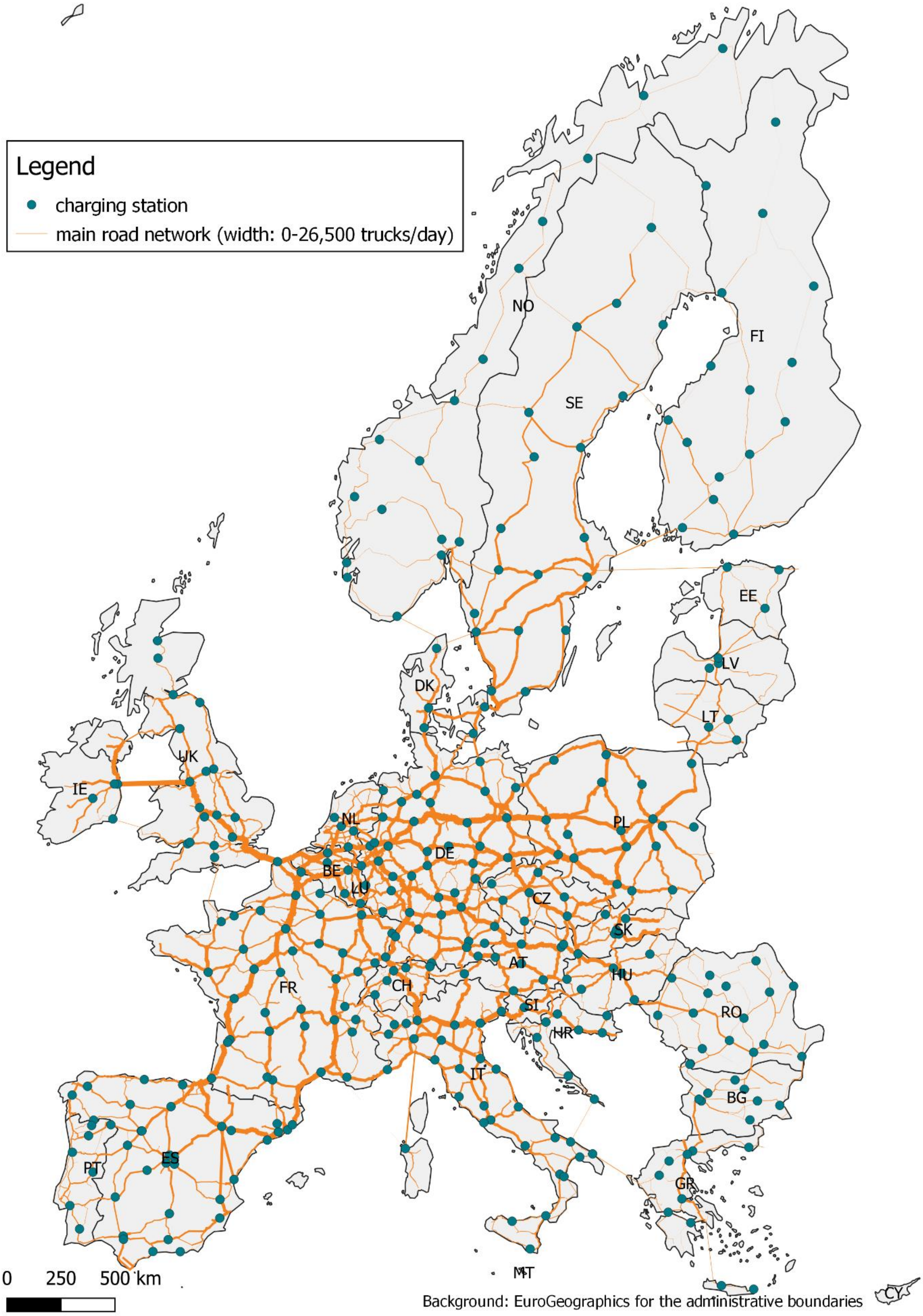

Figure 2: European charging locations, according to the FRLM

Figure 4 shows the results of the CFRLM in Germany. For comparison, the FRLM solution is plotted as blue dots in the same figure. In total, the charging network consists of 124 charging locations. Since the computational effort is quite high, the solver tolerance is set to 15%. Therefore, the best-case solution could also be 106 charging locations. However, this is still 2.5 times more than the solution in the FRLM.

Even with the introduction of the capacity restriction, large locations continue to be part of the solution. While the smallest location contains two charging points, the largest location consists of 334 charging points. Figure 3 shows how many charging locations with a certain size are build. However, we clustered the parking locations from the Autobahn GmbH to the next point in the road network, as long as the distance is less than 2 km. This means that some charging locations contain multiple parking areas. For example, the largest location with 334 charging points includes four different parking areas. In total, the CFRLM calculates 12,323 charging points. The median charging locations contains 83 charging points. On average, a charging station contains 99 charging points.

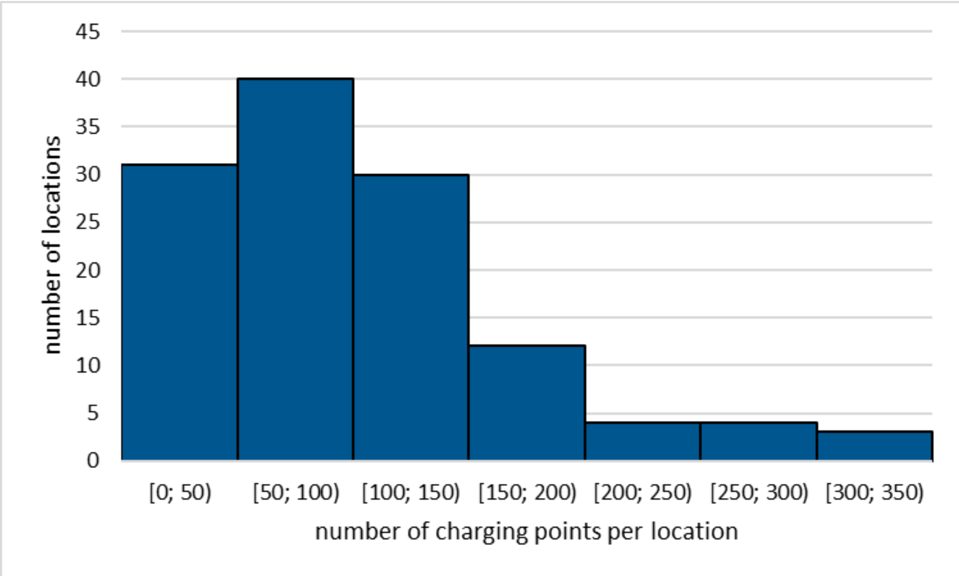

Figure 3: Distribution of charging points to charging locations

In contrast to the FRLM, the CFRLM positions large stations with low distance at highly trafficked routes. For example, large charging stations are built along the A2 highway from the Netherlands - via Dortmund, Hanover, and Berlin - to Poland. This is one of the most trafficked long-haul corridors from the ports in the Netherlands to Eastern Europe. Another example is the transit route from the Netherlands - via Cologne and Frankfurt - to Austria. On this route, there are also large charging locations at short distances. In comparison, less frequented routes, for example from Lübeck via Rostock to Poland, are equipped with few and comparatively small charging locations. In such sections, the CFRLM network density is quite similar to the FRLM.

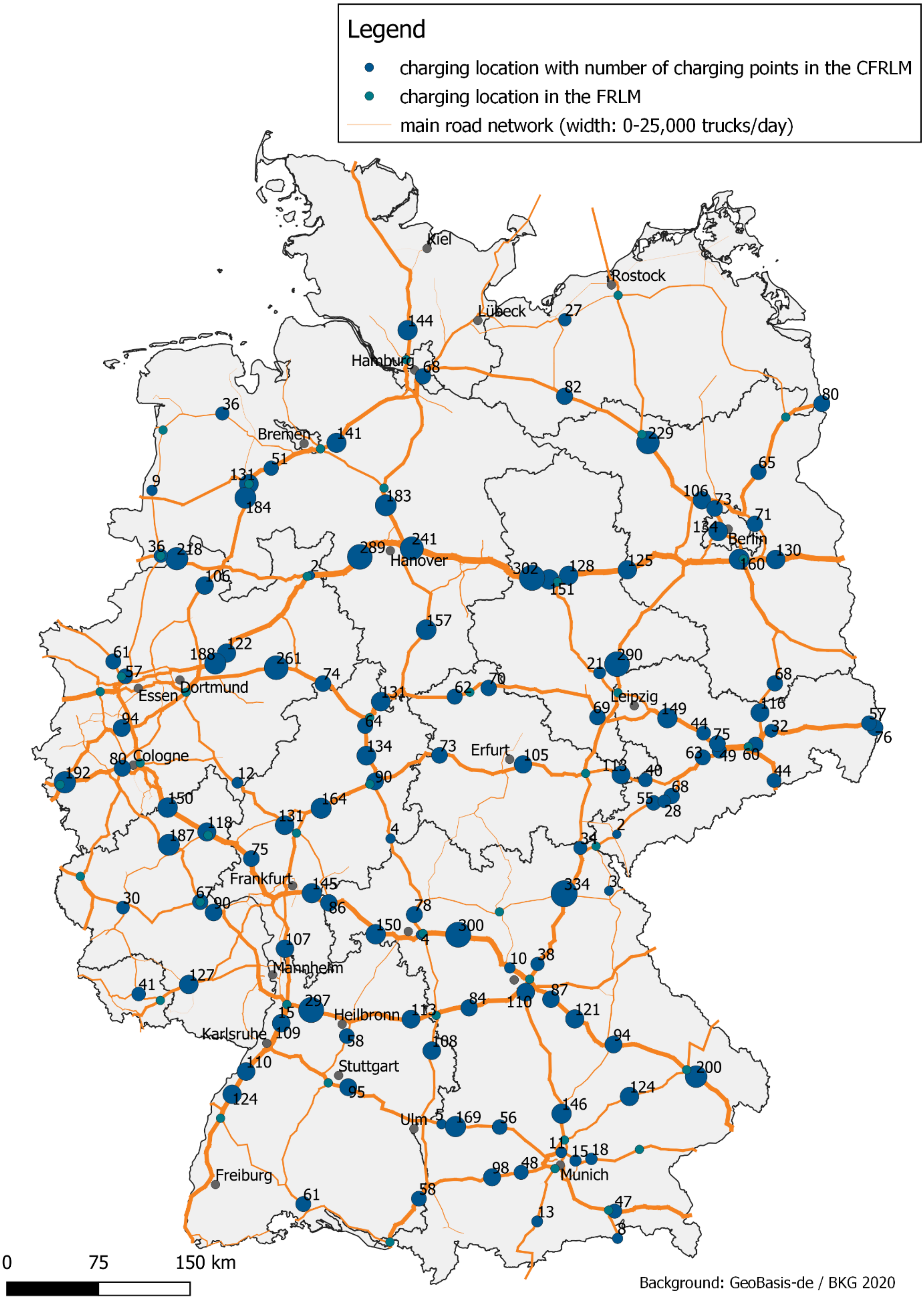

Figure 4: Distribution of charging locations in Germany according to the FRLM (green) and the CFRLM (blue)

4 Discussion

This paper applies a capacity-constrained FRLM (CFRLM) to a dataset with more than 200,000 traffic flows and includes real-world parking capacities. The capacity constraint more than doubles the required number of charging locations in Germany, compared to an uncapacitated FRLM. However, the results are still dependant on the input parameters, the assumptions, and the methodological approach. Regarding the input parameters, the modelling relies in synthetic origin-destination paths. Therefore, multi-stop-tours are taken into account as multiple single paths. Depending on the routing, the charging behaviour may differ. For example, additional charging events might be necessary, if the time between two trips is too short to recharge at the depot. Alternatively, public charging events can be skipped, if the combination of paths allows shorter distances between depots. The range of the vehicles may also change in the future. Regarding the assumptions, the potential usage of all parking lots as charging points is probably too optimistic. For example, the grid connection may also limit the number of vehicles that can be recharged at one location. This will likely result in additional locations. Regarding the methodology itself, the introduction of the capacity constraint comes with high computational demand. However, the results show that this additional effort, compared to an FRLM, allows significant knowledge gains. It should be noted, that optimality in the sense of a minimum number of locations is not necessarily optimal for the logistics provider. For example, a tighter network can offer additional resilience, such as in the event of traffic jams that lead to unplanned earlier stops.

In summary, the CFRLM shows a good starting point for local planners to identify highly relevant charging locations and to draw a basic picture of the future infrastructure. However, due to the given uncertainties, the evaluation of specific locations should include further information from additional sources.

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Presenter Biography

Daniel Speth studied Industrial Engineering and Management at the Karlsruhe Institute of Technology (KIT). His master thesis dealt with European CO2-legislation for passenger cars and its implications on market diffusion of alternative fuel vehicles. Since 2019, he is a researcher at the Fraunhofer Institute for Systems and Innovation research in Karlsruhe, Germany. Areas of work are the modelling of market diffusion for electric vehicles with a special focus on heavy-duty vehicles, their infrastructure, and the implications on the energy system.