# Influence of AFIR's charging station spacing requirement on heavy-duty vehicle electrification rate

Mattias Ingelström*[1] and Francisco J. Márquez Fernández[2]

[1]PhD student, Division of Industrial Electrical Engineering, Lund University, Sweden
[2]Associate Professor, Division of Industrial Electrical Engineering, Lund University, Sweden

## Short summary

The rapid progression of the electrification of road transport in Sweden requires effective research-based decisions on the location of charging infrastructure. The new European Union (EU) regulation for alternative fuel infrastructure (AFIR) specifies the maximum allowed distance between public fast-charging stations (FCSs) for heavy-duty trucks along the Trans-European Transport Network (TEN-T). The impact of these requirements is assessed using a novel method that places charging infrastructure according to the geographical distribution of the vehicles' energy needs. Our analysis shows that if charging infrastructure for road freight transport is placed based on the vehicles' charging needs the EU regulation will not be met, at least in certain areas. To follow the regulation would therefore result in the introduction of redundant stations, lowering utilisation and thereof profitability of FCSs. The paper recommends additional studies, e.g. the need for redundancy to create a trustworthy charging infrastructure.

**Keywords**: Agent-based modelling, charging infrastructure, electric freight transport, electric vehicles, transport decarbonisation, AFIR.

## 1 Introduction

On July 25th 2023 a new EU regulation, AFIR, Council of European Union (2019) was adopted as part of Fit For 55, Council of European Union (2023), the EU climate action package to reach climate neutrality. The regulation sets firm infrastructural requirements for member countries, specifying standards for minimum total installed power capacity at charging stations, lowest rated power of individual charging points, and minimum distance between stations along the TEN-T for both light and heavy vehicles. The TEN-T spans the most important transportation corridors in Europe, and consists of a core network and an extended comprehensive network. AFIR requires that heavy-duty transport should be able to charge every 60km along the core network and every 100km along the comprehensive from 2025.

Due to the novelty of AFIR, detailed assessments are limited. A techno-economic study, Ragon et al. (2022), finds that, at an aggregated level, the future charging need for all road transport in the EU is 80% higher than the proposed levels. This paper uses another method for evaluation of AFIR, based on a detailed multi-agent-based simulation and a detailed synthetic population representing Sweden's road goods transport. This approach was introduced in Bischoff et al. (2019), where the total charging need of both passenger cars and heavy-duty transport is evaluated for different combinations of both FCSs and electric roads systems (ERS).

This paper aims to assess the effect of setting different maximum distance requirements on the placement of FCSs for heavy-duty trucks in Sweden, assuming fully electrified road freight transport. As Sweden is not part of central Europe, most of the road freight either starts or ends in the country, as opposed to e.g., Germany which experiences a large share of transit transport. Furthermore, Sweden's geography, with large remote areas, suggests that assuming the same distance requirements for the whole country may not be the best alternative. The results in this paper provide detailed information regarding the impact AFIR will have on the electrification progress in Sweden. They will also open up for new discussions regarding the need for, and distribution of, Sweden's fast-charging infrastructure for heavy-duty road transport. These discussions can also be applied, largely, on all electrification of heavy-duty transport in the EU.

## 2 Methodology

***Synthetic population***

The synthetic population representing Swedish long-distance road freight transport originates from the model Samgods, an origin-destination matrix of goods transport from the Swedish Transportation Administration, Trafikverket (2020), which enables the creation of daily plans of simulation agents. Trips shorter than 300km are removed as they are less likely to be in need of on-route fast-charging, and more likely to charge at their destinations. The Samgods model contains information about the vehicle type used to transport each type of goods, making it possible to pair each individual trip to one out of four vehicle types. For each type, a battery capacity, a maximum speed and a specific energy consumption map dependent on the vehicle speed and slope of the road are defined. The battery capacity as well as the share of the total population corresponding to each vehicle type are shown in Table 1.

Table 1: Truck population characteristics and distribution

| Vehicle type | Battery size [kWh] | Share of population [%] |
|---|---|---|
| Medium duty 3.5-16 tonnes | 180 | $< 1$ |
| Medium duty 16-24 tonnes | 300 | 7 |
| Heavy duty 25-40 tonnes | 400 | 37 |
| Heavy duty 40-60 tonnes | 500 | 56 |

Transforming annual goods transport data to daily transportation plans requires specific timing information which is not present in the original Samgods model. To overcome this, real-life data provided by truck manufacturers, consisting of arrival times of long-haulage transport trips for different vehicle types is used. The procedure is described in Figure 1.

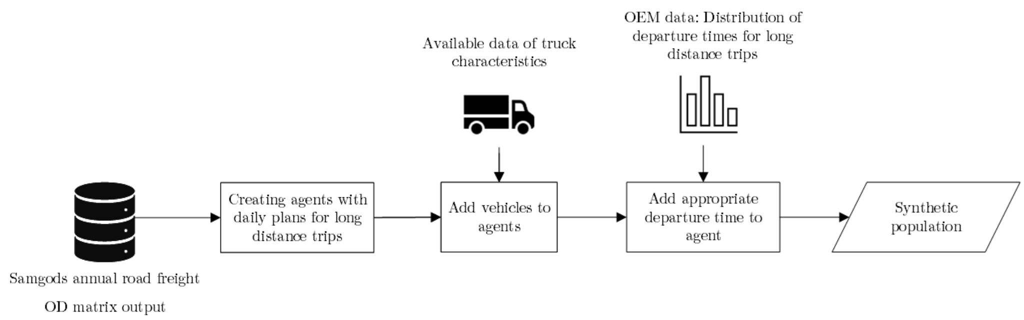



Figure 1: Processing of the annual road freight transport to a synthetic population.

***Simulation workflow***

The synthetic population is simulated using the multi-agent-based simulation tool MATSim, Horni et al. (2016). In MATSim, daily plans of the agents are iteratively processed, traversing the agents along the Swedish road network. Each agent's plan is optimised with regards to minimisation of travel time and finding appropriate charging options, mitigating the risk of the agent's vehicle's battery running out. In the MATSim mobility simulation, each agent will get the chance to find an FCS along its route. Either when the battery level, its State of Charge (SOC), reaches a random value between 15-40% or after driving 4.5 hours to comply with EU driving time regulations, a charging event at the closest FCS is added to the agent's plan. To give agents the possibility to try out different charging stations along their routes, a number of iterations (15) are run, and in each iteration 20% of the synthetic population is allowed to replan, changing the SOC value at which they start looking for an FCS. Thus, each agent will likely find the best FCS along its route, increasing the likelihood of an agent completing its trip, never having an empty battery. This is defined as a successful completion of a trip.

To identify candidate fast-charging infrastructure locations, the places with high concentration of Unmet Charging Needs (UCNs) need to be analysed. UCNs arise when an agent reaches 20% SOC and therefore needs to charge not to deplete their battery. The full simulation environment, shown in Figure 2, comprises an additional algorithm placing fast-charging infrastructure based on UCN. As the study focuses on the impact from AFIR, this algorithm only places FCSs along the TEN-T, and the simulation runs until there are no UCN remaining along the TEN-T. Consequently, some trips in the simulation will be impossible to electrify as they will require additional charging outside TEN-T.

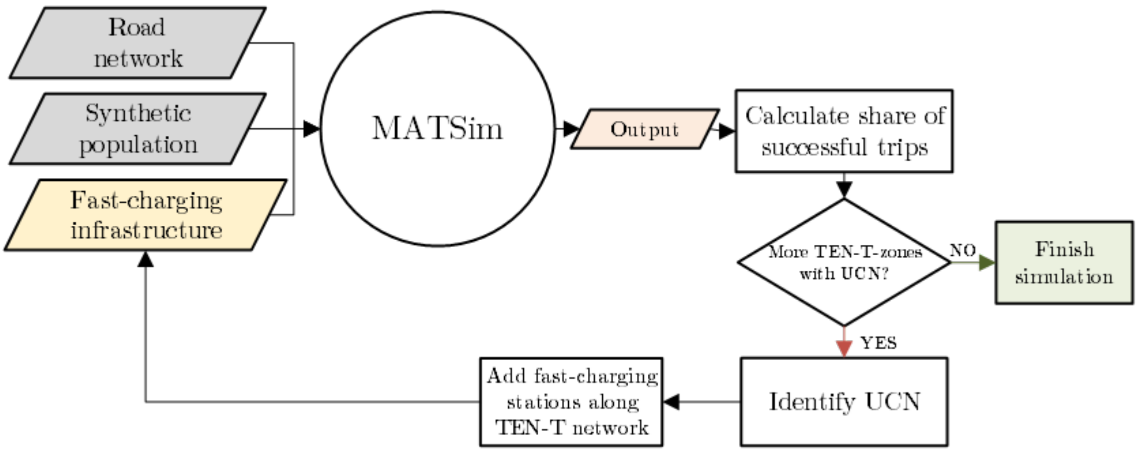
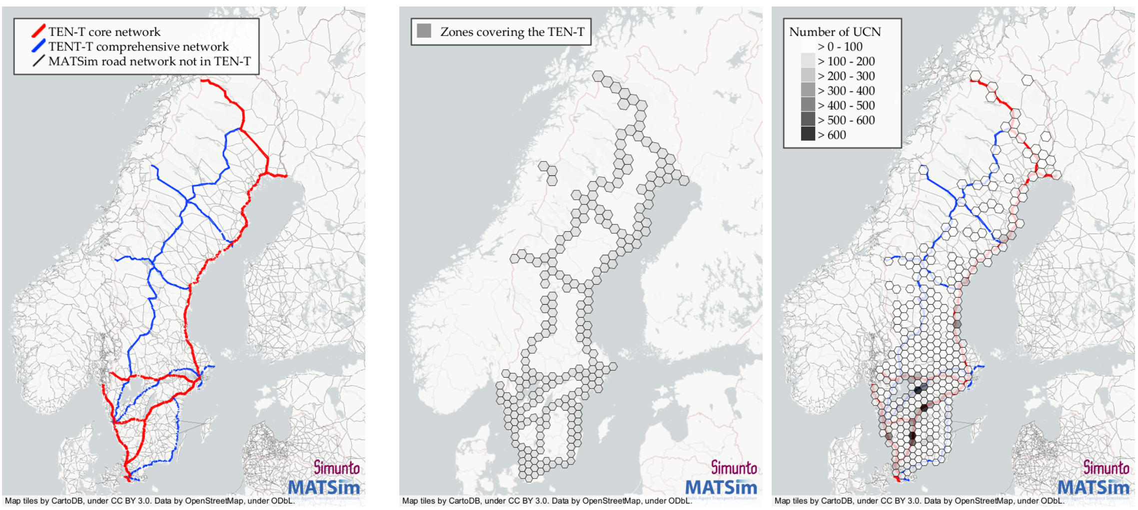



Figure 2: Simulation workflow, showing the iterative process of adding FCSs until no more UCN is encountered along the TEN-T.

From the road network, regular hexagonal zones of equal area are generated. Within these zones, the locations and total number of UCNs are recorded. Another set of hexagonal zones is generated, only covering the TEN-T. These zones represent all potential locations for fast-charging infrastructure. The full procedure is shown in Figure 3.




(a) (b) (c)

Figure 3: (a) shows the TEN-T, as well as the additional road network used in MATSim. (b) shows an example of generated hexagonal zones covering the TEN-T, i.e., candidate locations of FCSs. (c) shows the distribution of UCNs along the full road network, with no added fast-charging infrastructure.

Initially, all agents' daily plans are processed without the possibility to add charging activities. This way, it is possible to map UCNs and place charging infrastructure accordingly. While it is possible to add infrastructure solely based on the first simulation results, this will neglect the dynamic effects caused by adding charging infrastructure. When a new FCS is added, agents will adapt their routes in an attempt to successfully reach their destinations without depleting their battery. Thus, an evolving charging infrastructure will alter the distribution of UCN. Due to time constrains, it is not feasible to add one FCS at a time, even though it would be optimal. An alternative is to add 5 charging stations per simulation. The method of adding an FCS based on UCN is described in Figure 4

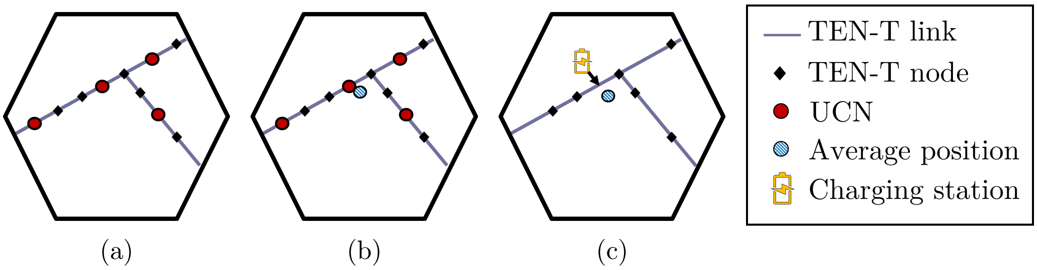



Figure 4: Fast-charging infrastructure placement. In (a), the UCNs are identified and the 5 zones of highest UCN intensity are chosen. (b) calculates the average coordinate of the UCNs and (c) places an FCS at the nearest TEN-T link.

***Scenarios***

The maximum distance within two adjacent hexagons is shown in Figure 5. With the hexagon's side s, the maximum distance $d_{max}$ can be calculated to $\sqrt{13}\,s$. This will be the maximum Euclidean distance between two FCSs in two adjacent hexagons, given that both are having UCNs. Although the actual travelled distance may be longer than the Euclidean distance, as the charging stations will be placed along the TEN-T, the difference is assumed to be negligible. The distance between two hexagon centroids, $d_c$ $(=\sqrt{3}s)$ is used to analyse the homogeneity of UCN within a hexagon. If the distance between adjacent FCSs is close to $d_c$ it indicates that the UCNs are evenly spread in those zones.

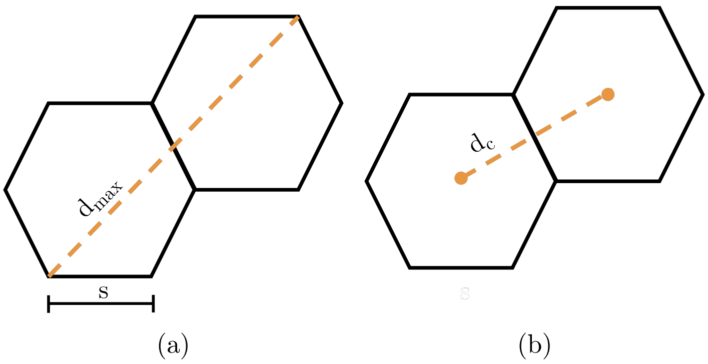



Figure 5: (a) shows the maximum distance between two vertices and (b) the distance between the centroids of two adjacent hexagons.

By altering $d_{max}$, scenarios of varied fixed spacing between FCSs are recreated. To fairly compare the scenarios, the maximum charging power that can be installed per zone (i.e. per FCS) is limited, based on the number of zones. Hence, the total charging power that can be installed, all FCSs included, is limited to the same value in all scenarios. Data regarding power capacity distribution in Sweden is classified, making it impossible to create well-grounded assumptions. Nonetheless, the method is designed to easily implement caps of varying installed power capacities based on this type of data. In this study, FCSs are assumed to be connected to the medium-voltage grid, and a limit of approximately 0.3 MW/km along the TEN-T is considered, ensuring that all scenarios has the possibility to install the same amount of total charging power. The resulting assumptions are seen in Table 2.

Table 2: Scenario definitions

| $d_{max}$ | Number of zones along TEN-T | Maximum installed charging power per zone [MW] |
|---|---|---|
| 15 | 848 | 6 |
| 30 | 470 | 10 |
| 45 | 318 | 15 |
| 60 | 228 | 20 |
| 90 | 153 | 30 |
| 120 | 110 | 42 |
| 150 | 86 | 54 |

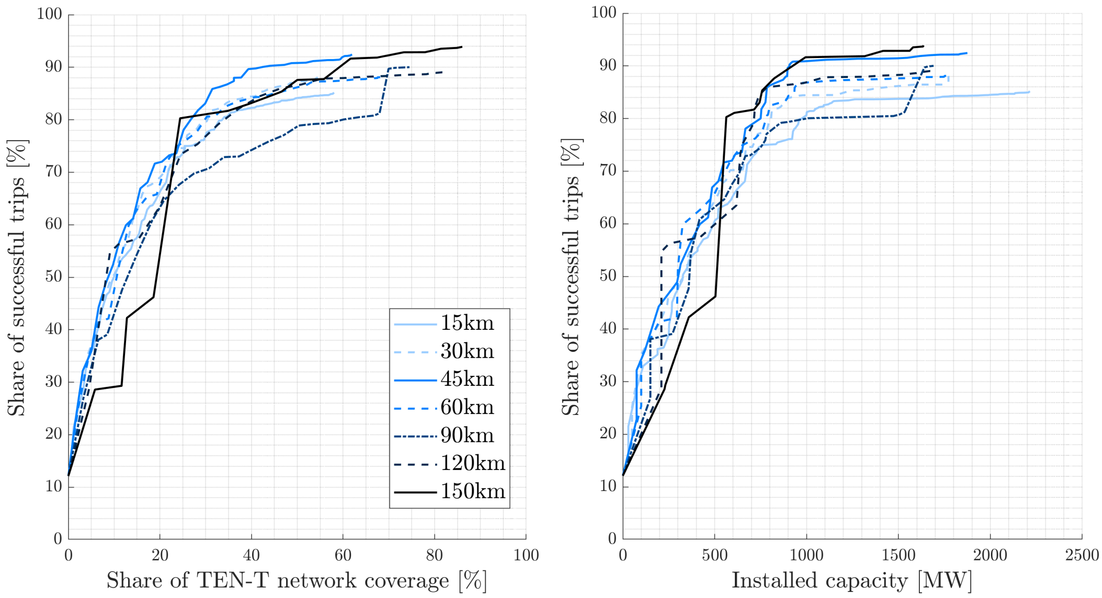
## 3 Results and discussion

The results contain detailed data regarding the number of successful trips, evaluation of charging station performance and the geographic distribution of the charging stations. Figure 6a shows the fraction of freight transports that can be successfully electrified as a function of charging infrastructure coverage along the TEN-T. From the results, it is also possible to determine the total required installed capacity, $P_{installed}$, to meet the charging need, as shown in Equation 1. For each FCS, the maximum number of simultaneously charging vehicles at any given point in time is obtained, denoted as $N_{v,i}$, and then multiplied with the rated power per charging point, $P_{rated,i} = 1$ MW. The results are shown in Figure 6b.

$$P_{installed} = \sum_{i=1}^{N_{stations}} N_{v,i} \cdot P_{rated,i} \tag{1}$$

Given a total installed capacity, the differences between scenarios are connected to the differences in utilisation of the FCSs. Except for one scenario, $d_{max}$= 90km, chargers installed after 700-800 MW are added at a very low utilisation, which indicates that they could be more efficiently added outside of the TEN-T to reach a higher utilisation.

This level of electrification is mainly affected by two factors. First, the FCS location and its vicinity to the UCN, which will be altered for each scenario. Second, the capability for each FCS to meet the total UCN which is controlled by the maximum installed charging power per zone. Smaller zones result in FCS located nearer the UCN they are addressing, but will feature an FCS with lower power capability. Having available data regarding electrical grid limitations is key to create better assumptions of FCS capability. As seen in Figure 6, there are significant differences between scenarios. However, some trends can be analysed. The difference between the scenarios, especially when focusing on the first 30% of the TEN-T that is electrified, shows that the distance between FCS has a significant impact on the early electrification. Placing the first 5% of charging stations nearer to the actual demand could lead to a 15% increase in electrification progress, when comparing the shorter distances (15-45km) to the longest one of 150km. At 30% of chargers added, between 60-80% of road freight transport can be electrified. All scenarios manage to electrify around 90% of long-distance road transport without covering the TEN-T fully. This shows that there is still a significant need to place FCSs outside the TEN-T and that covering all TEN-T will result in unnecessary FCSs - at least from a charging needs point of view.



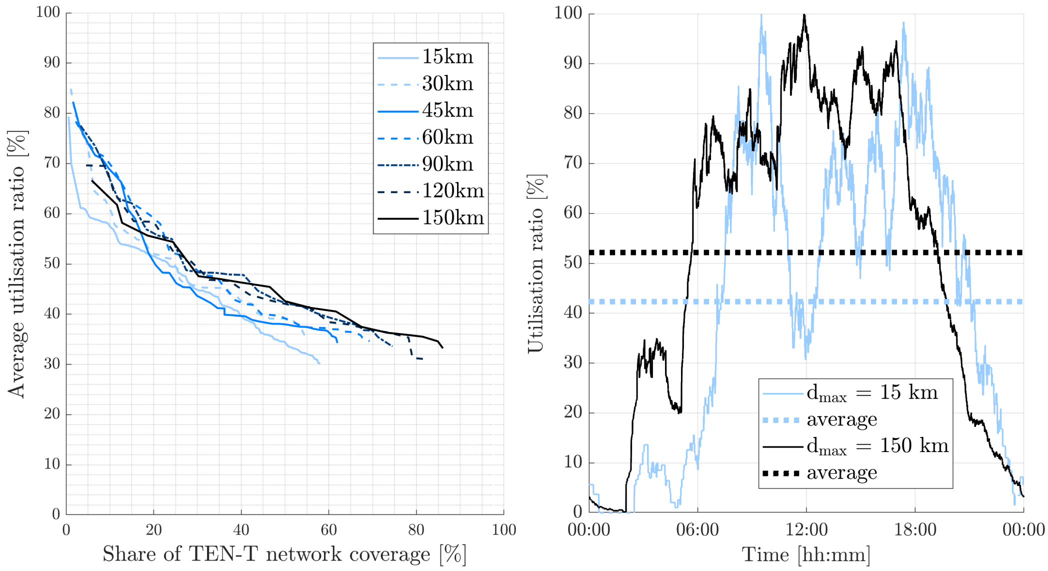

(a) (b)

Figure 6: (a) shows the electrification progression as the number of FCSs are added to the TEN-T and (b) shows the progression varies in relation to the installed capacity.

As the maximum installed charging power per zone is limited, scenarios allowing closer spacing will have the possibility to add more stations at a lower installed capacity, i.e. with fewer charging points, which increases the risk of not finding a free charger once you get to the FCS. This is probably the reason for the flattening of the share of successful trips in relation to the installed capacity for $d_{max}$= 15km. To be able to accommodate a high number of case studies, the number of iterations was kept low. Although the solution converges for the initial phases with few FCSs, a sensitivity analysis of the number of iterations is needed. From these results, close spacing between FCS might be at a disadvantage in comparison to scenarios with fewer and larger FCSs. However, the benefit of using close spacing is that the FCSs are placed closer to the actual charging demand.

The utilisation ratio is the ratio between the average and the maximum number of vehicles connected to a specific station at any given time. The average utilisation ratio is thus the average value for all FCSs. In Figure 7, it is evident that smaller stations are more volatile in terms of utilisation and are therefore more dependent on being placed where the need is. This is illustrated in Figure 7b, where two FCSs in the final configuration for scenarios $d_{max}$= 15km and $d_{max}$= 150km are compared. Both are the stations with the median charging activity and thus representative FCSs in each scenario. Larger hexagonal zones result in larger FCSs with many charging points agglutinating the charging needs of many vehicles. Smaller stations, however, have a more uneven utilization, since there are competing stations nearby.

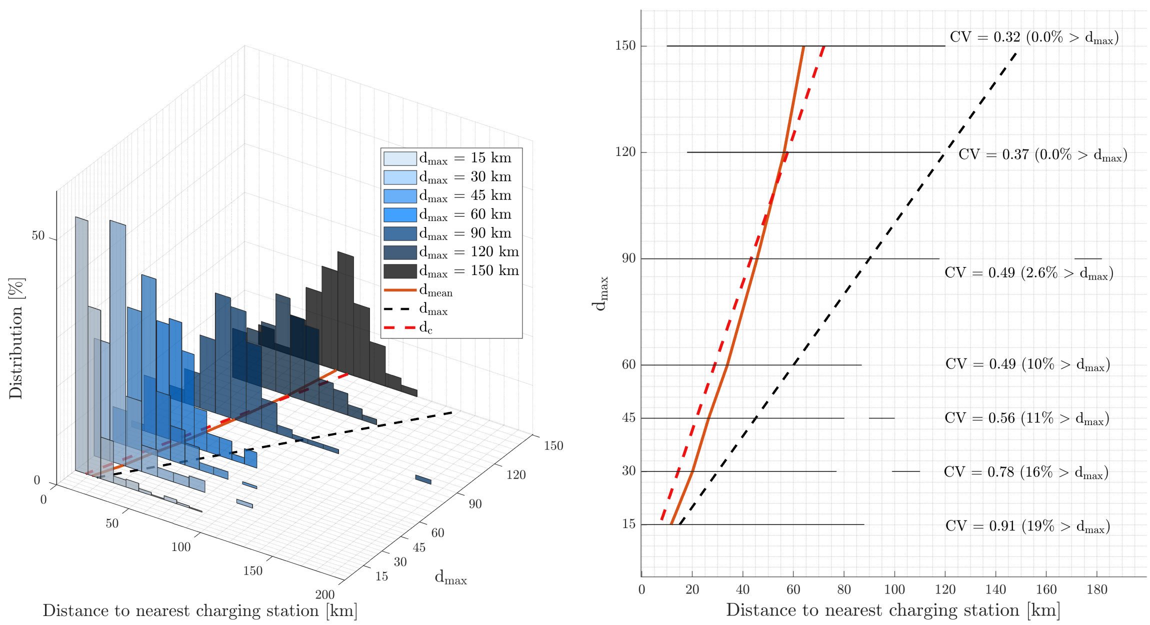
In Karlsson & Grauers (2023), charging utilisation ratio is investigated using agent-based modelling along one highway in Sweden, finding that the resulting utilisation ratio of 30% is both reasonable and profitable.




(a) (b)

Figure 7: Development of the average utilisation ratio of all FCSs for the different scenarios (a) and a detailed study of representative FCSs for scenario $d_{max}$= 15km and $d_{max}$= 150km.

Figure 8 shows the distribution of the distances from each FCS to its nearest station. Figure 8b, shows key statistic values e.g., the average distance, $d_{mean}$, and the corresponding centroid-to-centroid distance, $d_c$, for each scenario. If FCSs would be placed in all zones and $d_{mean} = d_c$, that would imply that the UCN is uniformly distributed within each zone, leading to all FCSs placements near the zones' centroids. The results show that the average UCN is fairly uniform. The coefficient of variation (CV) indicates how much the UCN is deviating from uniformity. For shorter spacing, this deviation increases because of FCSs being placed near the actual demand. If the UCN is met with greater precision, as is the case with closer spacing, it results in some zones not needing an FCS. This explains the increase of stations placed outside of $d_{max}$.




(a) (b)

Figure 8: (a) shows the distance distribution of FCSs for each scenario. (b) shows the comparison of $d_{mean}$ and $d_c$ as well as the CV and the percentage of FCSs placed outside of $d_{max}$.

## 4 Conclusions

Although the AFIR requirement of 60km seems favourable to support a rapid electrification of heavy-duty transport, this study shows that there are possibilities for improvement. Placing FCSs closer to UCNs can lead to more rapid electrification. Even though UCN in Sweden is generally evenly distributed, there is a significant share that is not. Hence, covering the TEN-T evenly with FCSs leads to the addition of unprofitable stations. The results show that it could be favourable to install smaller stations in an early electrification phase as the stations are well placed, but that larger stations have a higher resilience to changes in utilisation ratio which greatly affects the efficiency and profitability of an FCS.

The paper also stresses the importance of making Swedish electric grid data to some extent available for researchers. This data would add another dimension to the study and would remove uncertainties in the assumptions.

## Acknowledgements

This work is funded by the Swedish Innovation Agency, Vinnova (2021), within the project E-Charge: system demonstration of electrified long-haul trucks, Lindholmen Science Park (2021). Moreover, the industrial expertise and data provided by the project partners is gratefully acknowledged.

## References


Bischoff, J., Márquez-Fernández, F. J., Domingues-Olavarría, G., Maciejewski, M., & Nagel, K. (2019). Impacts of vehicle fleet electrification in sweden – a simulation-based assessment of long-distance trips. In *2019 6th international conference on models and technologies for intelligent transportation systems (mt-its)* (p. 1-7). doi: 10.1109/MTITS.2019.8883384

Council of European Union. (2019). Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC. *OJ*, *L 198*, 202–240. (http://data.europa.eu/eli/reg/2019/1242/oj)

Council of European Union. (2023). Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU. *OJ*, *L 234*, 1–47. (https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559)

Horni, A., Nagel, K., & Axhausen, K. (2016). Multi-Agent Transport Simulation MATSim. London: Ubiquity Press. (License: CC-BY 4.0) doi: http://dx.doi.org/10.5334/baw

Karlsson, J., & Grauers, A. (2023). Agent-based investigation of charger queues and utilization of public chargers for electric long-haul trucks. *Energies*, *16*(12). Retrieved from https://www.mdpi.com/1996-1073/16/12/4704 doi: 10.3390/en16124704

Lindholmen Science Park. (2021). *E-charge.* Retrieved 2023-02-22, from https://www.lindholmen.se/en/project/e-charge

Ragon, P., Mulholland, E., Basma, H., & Rodríguez, F. (2022). A review of the AFIR proposal: public infrastructure needs to support the transition to a zero-emission truck fleet in the European Union.

Trafikverket. (2020). *Representation of the swedish transport and logistics system in samgods v. 1.2* (Tech. Rep.). https://bransch.trafikverket.se/contentassets/ab220f9016154ef7a8478555560bb280/2020/representation_report_20200615.pdf. (Online)

Vinnova. (2021). *E-Charge: System demonstration of electrified long-haul transports.* Retrieved from https://www.vinnova.se/en/p/e-charge-system-demonstration-of-electrified-long-haul-transports/