From technology comparison to corridor allocation: modelling charging alternatives for battery-electric freight vehicles

Wanrong Hu[1], Denissa Sari Darmawi Purba[1], Yusak Susilo[1], and Constantinos Antoniou[2]

[1]University of Natural Resources and Life Sciences, Vienna, Austria
[2]Technical University of Munich, Germany

Short summary

One of the key challenges in decarbonising long-haul road freight is the provision of suitable charging technology. These systems, including plug-in charging, battery swapping, and electric road systems (ERS), differ in both operational and economic characteristics, with relative value that changes across corridors and scenarios. This paper develops a corridor-level equilibrium framework to allocate on-road charging technologies for battery-electric heavy-duty freight vehicles. The model captures freight-specific operating conditions, corridor heterogeneity, and the strategic interaction between carriers, who minimize generalized freight costs through mode allocation, and facility providers, who determine infrastructure deployment and pricing to maximize profit. In particular, it incorporates queueing effects, the hours-of-service rule, and electric road systems (ERS) as a corridor-level layer that reduces stop-based charging demand.

Using a case study for Bavaria, Germany, and Austria, we find three main results. First, the baseline equilibrium is strongly plug-in oriented in aggregate, but swapping remains active on a limited set of short and dense corridors. Second, a higher value of time broadens the corridor range in which swapping remains competitive. Third, higher charging power mainly affects longer corridors, where it further strengthens plug-in charging. Overall, the results suggest that charging allocation is corridor-specific rather than universal, and that infrastructure decisions should be evaluated as part of an interacting corridor system rather than as isolated technology choices.

Keywords: freight electrification; charging infrastructure allocation; battery swapping; electric road systems; equilibrium modeling; heavy-duty vehicles

1 Introduction

Road freight is central to European supply chains, but it remains a major source of greenhouse gas emissions. While emissions have declined in many sectors, transport emissions have not fallen at the same pace, and freight decarbonisation has become a necessary part of EU climate policy (Eurostat, 2025, 2024). At the same time, stricter CO_2 standards for new heavy-duty vehicles are pushing the sector toward zero-emission technologies (European Commission, 2024). Battery-electric trucks are therefore moving from pilot use toward wider deployment, but long-haul application remains difficult in practice (Aryanpur & Rogan, 2024; Raoofi et al., 2025a; Gillström, 2024).

One of the major challenges in electrified long-haul freight systems is that implementation depends not only on vehicle technology, but also on the availability and performance of charging infrastructure. Compared to passenger electric vehicles, long-haul trucks require much more energy, have less flexibility in dwell time, and are more sensitive to battery mass because battery size affects range, payload, and in some cases legal weight limits (Çabukoglu et al., 2018; Gillström, 2024; Aryanpur & Rogan, 2024). Their operation is also shaped by tight delivery schedules, driver break and rest rules, and service reliability requirements. Charging time, therefore, has a direct opportunity cost, while insufficient coverage, detours, or queueing can quickly reduce the attractiveness of an otherwise feasible electric operation (Gillström, 2024; Alp et al., 2022; Raoofi et al., 2025b; Fadranski et al., 2025).

In the literature, on-road charging alternatives are commonly classified into two categories: stop-based (static) and corridor-based (dynamic) (BBC Future, 2024; *eRoadArlanda*, n.d.; Zhu et al., 2023; Li et al., 2024; X. Wang et al., 2023). Stop-based options require the truck to halt at a dedicated facility. In the plug-in charging station, the vehicle connects to a stationary charger and remains idle for a duration determined by charging power and energy demand. In battery swapping systems, the depleted battery pack is replaced with a fully charged one within minutes. In contrast, corridor-based charging systems supply energy while vehicles are in motion. One of the most prominent emerging technologies in this category is the electric road system (ERS). ERS consists of dedicated lanes equipped with power transfer technologies that enable vehicles to receive energy while driving, including overhead catenary lines, ground-level conductive rails, and inductive elements embedded in the road surface.

These charging systems differ in their operational mechanisms, service time, throughput capacity, battery-size requirements, grid implications, and infrastructure cost structures. ERS can reduce both stop-charging demand and onboard battery requirements; however, its effectiveness depends on corridor characteristics and public investment conditions (Bakker et al., 2024). Swapping can significantly reduce service time, but its attractiveness depends on station utilization, standardization, inventory requirements, and pricing structures (Zhu et al., 2023; Li et al., 2024; Gao & Li, 2024). Each charging system offers distinct advantages and limitations, making the strategic combination and allocation of charging infrastructure critical.

Furthermore, the electrification of long-haul freight involves coordination across multiple stakeholders, including carriers, infrastructure providers, and public authorities. Carriers aim to minimize operational time and costs while maintaining high service quality and coverage. In contrast, charging infrastructure providers face high fixed costs, uncertain utilization, and pricing decisions. Public actors may subsidize, regulate, or directly support the deployment of charging infrastructure (Ogunclu et al., 2025; Raoofi et al., 2025a; Y. Wang et al., 2023). In the early stages of long-haul freight electrification, the interests of key stakeholders are not naturally aligned. Carriers may delay adoption until sufficient coverage and reliable service are available, while infrastructure providers may hesitate to invest without committed demand (Raoofi et al., 2025a). As a result, the transition to electrified freight is not only a technological challenge but also a coordination and infrastructure allocation problem.

Existing research provides important foundations, but three gaps remain. First, many infrastructure planning models do not capture the operational features that matter most in long-haul freight, especially time loss, break rules, congestion, and the productivity penalty associated with charging (Alp et al., 2022; Raoofi et al., 2025b; Fadranski et al., 2025). Second, the literature remains centered on plug-in charging, with limited attention to battery swapping and ERS, and typically models these alternatives as substitutes rather than as complementary technologies that may coexist within a corridor system (Bakker et al., 2024; Zhu et al., 2023; Li et al., 2024; Gao & Li, 2024). Third, infrastructure is often planned either under centralized optimization or as exogenously fixed provision, thereby overlooking the market feedback between carrier choices, provider profitability, and service quality during early deployment (Y. Wang et al., 2023; Ogunclu et al., 2025; Raoofi et al., 2025a).

This paper aims to identify the allocation of on-road charging alternatives that are operationally feasible and economically efficient for battery-electric heavy-duty freight vehicles under heterogeneous corridor conditions and evolving techno-economic and policy scenarios. Specifically, three related questions are addressed: (1) where does battery swapping remain active alongside plug-in charging rather than disappearing from the allocation?; (2) how does this pattern vary across corridors with different distance and demand characteristics?; and (3) how strongly do changes in key drivers shift technology shares, corridor-level allocation patterns, and provider-side outcomes?

To address these questions, this paper develops a corridor-level equilibrium framework for battery-electric heavy-duty freight vehicles. Rather than detailed site-level placement, the framework considers corridor-level allocation, which is the relevant decision level for early markets where the main uncertainty is not charger location but which charging architecture is feasible and efficient. The model conditions on corridor demand and electrified market shares, and studies how allocation responds to variations in charging power, value of time, energy consumption, infrastructure cost, electricity price, and policy support.

The paper contributes a tractable framework that couples carrier-side operational choices with

provider-side capacity and pricing decisions, while accounting for queueing effects and break-rule integration within the freight system. It further underpins the comparative statics analysis presented later in the paper, aiming to identify the optimal charging technology options and to quantify the influence of key drivers on corridor-level allocation patterns.

2 Methodology

Model scope and equilibrium structure

We study the allocation of on-road charging alternatives for battery-electric heavy-duty freight vehicles on a set of directed OD corridors $r \in \mathcal{R}$. The model has two strategic actors. The carrier allocates the electrified corridor demand between plug-in charging and battery swapping. The infrastructure provider decides stop-based service capacity, swapping battery inventory, service fees, and the extent of electric road system (ERS) deployment on each corridor. ERS is modelled as a corridor layer that reduces the stop-based charging requirement. Following recent evidence that ERS is a line infrastructure requiring strong public commitment and policy support, we treat ERS capital deployment as publicly financed, while allowing operation, pricing, and operating support to be managed by a provider (Scherrer et al., 2026; Rogstadius et al., 2025). The overall model structure is summarised in Figure 1.

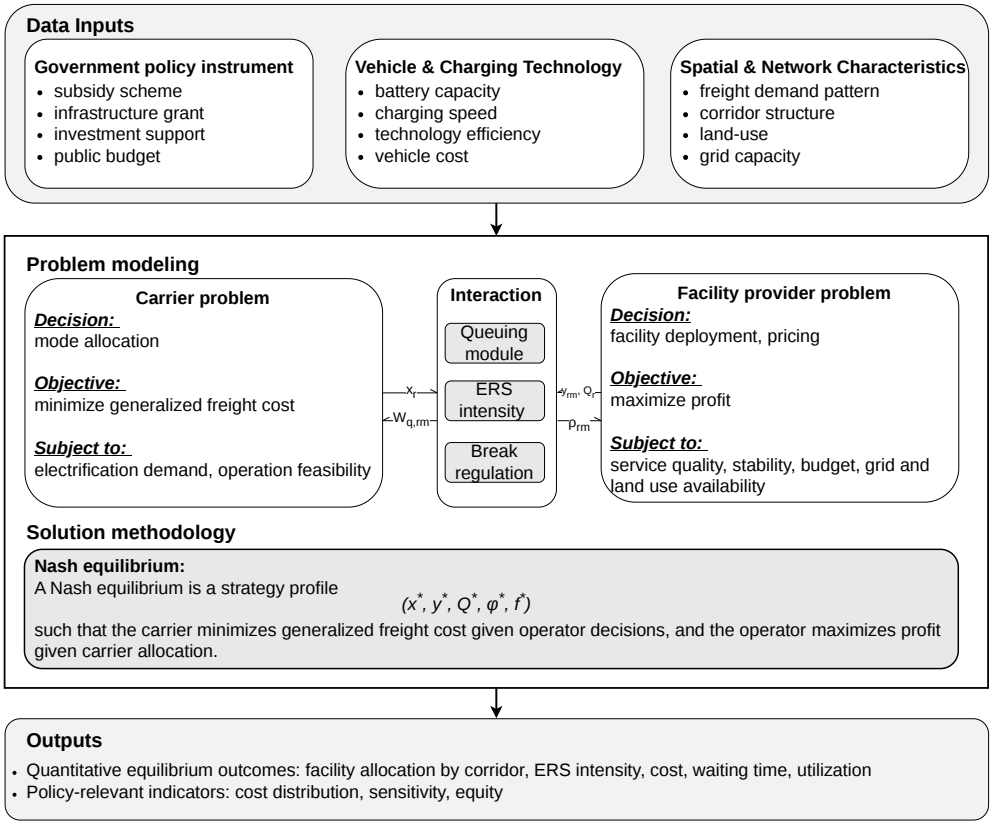


Figure 1: Model framework.

Let $s_r \in [0, 1]$ denote the electrified share on corridor r. The carrier chooses

$$x_{rP}, x_{rS} \geq 0, \qquad x_{rP} + x_{rS} = s_r, \qquad \forall r \in \mathcal{R},$$

where x_{rP} and x_{rS} are the shares of corridor demand served by plug-in charging and battery swapping, respectively.

The provider chooses corridor-level plug-in capacity y_{rP}, swapping capacity y_{rS}, battery inventory Q_r, service fees f, and ERS intensity $\phi_r \in [0, 1]$, where ϕ_r is interpreted as the share of corridor

length equipped with ERS. A Nash equilibrium is a strategy profile

$$(x^*, y^*, Q^*, \phi^*, f^*)$$

such that the carrier minimizes generalized freight cost given provider decisions, and the provider maximizes profit given carrier allocation.

Demand, service, and queueing

Let L_r be corridor length, q_r the total truck demand on corridor r, and e_P, e_S the energy consumption per km under plug-in charging and battery swapping. The ERS layer reduces the energy that must be served by stop-based infrastructure. Residual stop-based daily energy demand is therefore

$$E_{rP}^{\text{stop}}(x, \phi) = q_r x_{rP}(1 - \phi_r) e_P L_r, \tag{1}$$

$$E_{rS}^{\text{stop}}(x, \phi) = q_r x_{rS}(1 - \phi_r) e_S L_r. \tag{2}$$

Let $\bar{E}_P^{\text{sess}}$ denote the average energy delivered per plug-in session, and let C_S denote the swap battery capacity. The implied number of daily service events is

$$n_{rP}(x, \phi) = \frac{E_{rP}^{\text{stop}}(x, \phi)}{\bar{E}_P^{\text{sess}}}, \qquad n_{rS}(x, \phi) = \frac{E_{rS}^{\text{stop}}(x, \phi)}{C_S}. \tag{3}$$

For plug-in charging, session duration is

$$\tau_P^{\text{sess}} = \tau_P^{\text{fix}} + \frac{\bar{E}_P^{\text{sess}}}{P_P^{\text{eff}}}, \tag{4}$$

where τ_P^{fix} is connection and handling time and P_P^{eff} is effective charging power. For battery swapping, physical exchange time is treated as fixed:

$$\tau_S^{\text{sess}} = \tau_S^{\text{op}}. \tag{5}$$

Let H denote daily operating hours. Daily arrival rates are

$$\lambda_{rP}(x, \phi) = \frac{n_{rP}(x, \phi)}{H}, \qquad \lambda_{rS}(x, \phi) = \frac{n_{rS}(x, \phi)}{H}. \tag{6}$$

For plug-in charging, the service rate implied by installed capacity is

$$\mu_{rP}(y) = \frac{y_{rP}}{\tau_P^{\text{sess}}}, \tag{7}$$

and expected waiting time is represented by the standard $M/M/1$ formula

$$W_{rP}^q(x, y, \phi) = \frac{\lambda_{rP}(x, \phi)}{\mu_{rP}(y)\left[\mu_{rP}(y) - \lambda_{rP}(x, \phi)\right]}, \qquad \mu_{rP}(y) > \lambda_{rP}(x, \phi). \tag{8}$$

For swapping, service performance depends both on front-end handling capacity and on the availability of fully charged replacement packs. Let

$$t_c = \frac{C_S}{P_S^{\text{chg}}} \tag{9}$$

denote the battery recharge cycle time, where P_S^{chg} is charging power per pack. With Q_r packs deployed on corridor r, the battery replenishment rate is

$$\mu_r^{\text{bat}}(Q) = \frac{Q_r}{t_c}. \tag{10}$$

The effective swap service rate is then

$$\mu_{rS}(y, Q) = \min\left\{\frac{y_{rS}}{\tau_S^{\text{sess}}},\ \frac{Q_r}{t_c}\right\}. \tag{11}$$

Expected waiting time at swapping facilities is

$$W_{rS}^q(x, y, Q, \phi) = \frac{\lambda_{rS}(x, \phi)}{\mu_{rS}(y, Q)\left[\mu_{rS}(y, Q) - \lambda_{rS}(x, \phi)\right]}, \qquad \mu_{rS}(y, Q) > \lambda_{rS}(x, \phi). \tag{12}$$

Integration of the hours-of-service rule

For long-haul freight, stop time should not be valued mechanically as productive time loss, because part of that time may satisfy the driver break requirement under operation regulation. For instance, under Regulation (EC) No 561/2006, a driver must take a break of at least 45 minutes after at most 4.5 hours of driving (European Parliament and Council of the European Union, 2006). We therefore integrate the mandatory break rule directly into generalized cost.

Let average speed be v. Corridor driving time is

$$T_r^{\mathrm{drv}} = \frac{L_r}{v}. \tag{13}$$

The total break credit available on corridor r is

$$R_r = 0.75 \left\lfloor \frac{T_r^{\mathrm{drv}}}{4.5} \right\rfloor, \tag{14}$$

measured in hours.

For a stop of type $m \in \{P, S\}$, total stop duration is

$$D_{rm} = W_{rm}^q + \tau_m^{\mathrm{sess}}. \tag{15}$$

Let $\tilde{R}_r$ denote the remaining regulatory break credit at the time of the stop. The amount of stop time that can be credited to mandatory break compliance is

$$\beta_{rm} = \min\left\{D_{rm},\ \tilde{R}_r,\ 0.75\right\}. \tag{16}$$

The residual time that enters the carrier's generalized cost is then

$$\Delta T_{rm}^{\mathrm{cost}} = D_{rm} - \beta_{rm}. \tag{17}$$

Carrier Problem

Let VOT_r denote the value of time, p_r^e the electricity price paid at stop-based facilities, f_r^P the plug-in service fee, and f_r^S the fixed swapping fee per session. The generalized cost per electrified trip is

$$g_{rP}(x, y, \phi) = c_{rP}^{\mathrm{veh}} + p_r^e(1 - \phi_r)e_P L_r + f_r^P + VOT_r\, \Delta T_{rP}^{\mathrm{cost}}, \tag{18}$$

$$g_{rS}(x, y, Q, \phi) = c_{rS}^{\mathrm{veh}} + p_r^e(1 - \phi_r)e_S L_r + f_r^S + VOT_r\, \Delta T_{rS}^{\mathrm{cost}}. \tag{19}$$

The carrier solves

$$\min_x \sum_{r\in\mathcal{R}} q_r \left(x_{rP} g_{rP}(x, y, \phi) + x_{rS} g_{rS}(x, y, Q, \phi)\right) \tag{20}$$

subject to

$$x_{rP} + x_{rS} = s_r, \qquad x_{rP}, x_{rS} \geq 0, \qquad \forall r \in \mathcal{R}. \tag{21}$$

Provider Problem

The facility provider chooses stop-based capacity, swapping inventory, ERS deployment, and service fees to maximize profit. Let $C_r^P(y_{rP})$ and $C_r^S(y_{rS}, Q_r)$ denote the cost of plug-in and swapping provision. Let $c_r^{\mathrm{ERS,op}}$ be the operating cost per km of ERS deployed on corridor r, ω_r^{ERS} any operating policy support per km, B^{ERS} the public budget for ERS capital deployment, and $c_r^{\mathrm{ERS,cap}}$ the public investment cost per km. Finally, let $\overline{G}_r$ denote the corridor-level grid capacity available for stop-based charging, $\overline{A}_r$ denote the available land area for charging facilities, and a_{rP} and a_{rS} are the land-use coefficients of plug-in and swapping, respectively. The provider problem is

$$\max_{y,Q,\phi,f}\ \Pi = \sum_{r\in\mathcal{R}} \left[f_r^P n_{rP}(x, \phi) + f_r^S n_{rS}(x, \phi) - C_r^P(y_{rP}) - C_r^S(y_{rS}, Q_r) + \left(\omega_r^{\mathrm{ERS}} - c_r^{\mathrm{ERS,op}}\right)\phi_r L_r\right] \tag{22}$$

subject to

$$\mu_{rP}(y) > \lambda_{rP}(x,\phi), \qquad \mu_{rS}(y,Q) > \lambda_{rS}(x,\phi), \qquad \forall r \in \mathcal{R}, \tag{23}$$

$$W^q_{rP}(x,y,\phi) \le \bar{W}_P, \qquad W^q_{rS}(x,y,Q,\phi) \le \bar{W}_S, \qquad \forall r \in \mathcal{R}, \tag{24}$$

$$E^{\text{stop}}_r(x,\phi) \le \overline{G}_r, \qquad \forall r \in \mathcal{R}, \tag{25}$$

$$a_{rP} y_{rP} + a_{rS} y_{rS} \le \overline{A}_r, \qquad \forall r \in \mathcal{R}, \tag{26}$$

$$\sum_{r \in \mathcal{R}} c^{\text{ERS,cap}}_r \phi_r L_r \le B^{\text{ERS}}, \tag{27}$$

$$0 \le \phi_r \le 1, \qquad y_{rP}, y_{rS}, Q_r \ge 0, \qquad \forall r \in \mathcal{R}. \tag{28}$$

3 Results and discussion

Study area and baseline data

The empirical application focuses on Bavaria, Germany, and Austria. The study area is represented by 131 NUTS3 zones, and the analysis is carried out on the OD corridors between these zones. Corridor distances are computed as road-network shortest-path distances using the OpenRouteService heavy-goods-vehicle routing profile (OpenRouteService, 2026), with each NUTS3 zone represented by an internal point snapped to the nearest high-level road node (motorway, trunk, or primary road), combined with OD demand to characterize corridor heterogeneity in both length and flow intensity. Figure 2 characterises the study area.

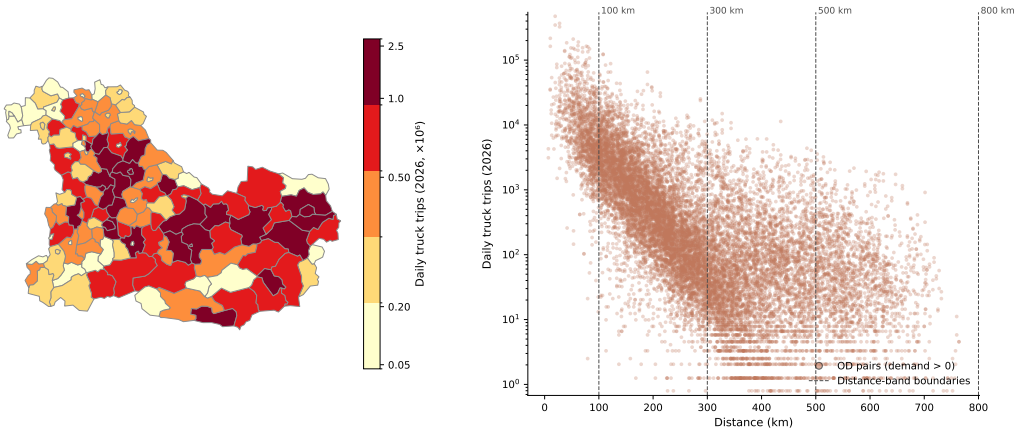


Figure 2: Study-area characterisation. Left: NUTS3-level aggregate daily truck demand (outbound plus inbound, 2026 baseline scenario). Right: distance–demand scatter of all inter-zonal OD pairs; dashed lines mark the distance bands used in the analysis (100, 300, 500, 800 km).

In this study, we consider the 2026 freight corridor demand across Bavaria, Germany, and Austria. This demand is interpolated from the synthetic road freight transport dataset (Momeni et al., 2021), which provides spatially disaggregated road freight flows for 2010, 2019, and 2030.

The baseline scenario combines 2026 corridor demand with a set of techno-economic and policy parameters introduced previously. Numerical experiments then vary selected parameters around this baseline to examine how corridor-level charging allocation responds under different operational and policy conditions.

For the base scenario, the main parameter values used in the numerical analysis are summarized as follows:

$$e = 1.8 \text{ kWh/km}, \quad p^e = 0.30 \text{ EUR/kWh}, \quad VOT = 41 \text{ EUR/h}, \quad v = 80 \text{ km/h},$$

$$P^{\text{eff}}_P = 150 \text{ kW}, \quad \tau^{\text{fix}}_P = 0.083 \text{ h}, \quad \bar{W}_P = 0.75 \text{ h}, \quad \bar{W}_S = 0.50 \text{ h},$$

$$C_S = 300 \text{ kWh}, \quad P^{\text{chg}}_S = 150 \text{ kW}, \quad \tau^{\text{op}}_S = 0.033 \text{ h}, \quad \phi_r \in [0, 0.6].$$

Current-pattern allocation across heterogeneous routes

Under the current condition with 150 kW plug-in charging and $VOT = 41$ EUR/h (Vallender et al., 2023; Binsuwadan et al., 2022; de Jong et al., 2014), the equilibrium is strongly plug-in oriented in aggregate: the flow-weighted plug-in share is 93.9%, while swapping accounts for 6.1%. On the ERS side, the equilibrium deploys electrified road segments on 18.3% of all corridors, but these corridors carry about 85% of the total freight flow. Where deployed, the average share of corridor length equipped with ERS is 28%, with the maximum reaching 48%. ERS is concentrated on shorter and denser corridors: 63.5% of corridors below 100 km receive ERS, compared with less than 1% above 500 km. Despite this aggregate dominance, the allocation is not uniform (Figure 3). Across the 17,161 directed OD routes, only 336, or about 2.0%, show non-trivial use of both alternatives when each share exceeds 5%. The system is therefore dominated by plug-in charging overall, but with a limited set of mixed outcomes rather than a uniform single-solution pattern.

This variation is closely linked to route characteristics. Swapping is concentrated mainly on short, high-demand trips, whereas medium- and long-distance flows are assigned almost entirely to plug-in charging. The flow-weighted swapping share is 8.5% for routes below 100 km, 2.8% for 100–300 km, 2.4% for 300–500 km, and only 1.1% for 500–800 km. On the facility-provider side, the median swap fixed fee is 30 EUR per session under the current-reference setting, which further limits swapping to the part of the market where shorter service time is valuable enough to offset the extra fee.

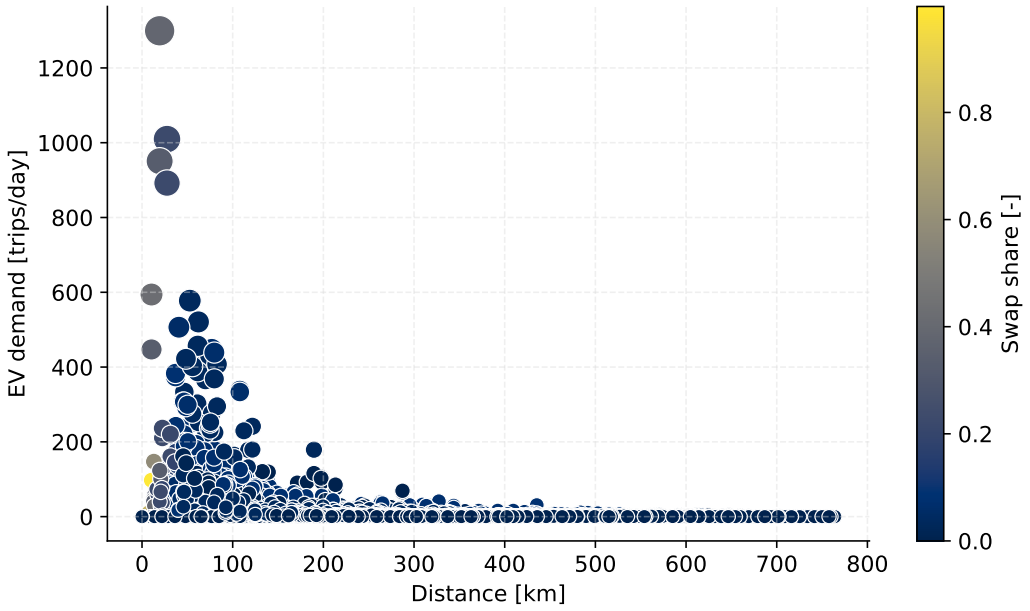


Figure 3: Route-level equilibrium allocation under base scenario. Each point represents one directed OD corridor; the x-axis shows corridor distance and the y-axis shows total electrified truck demand on that corridor (trips/day). Color indicates the equilibrium swapping share; $x_{plug-in} = 1 - x_{swapping}$.

Swapping expands from 4.3% to 21.6% on time-sensitive freight

The clearest comparative-static pattern arises when time becomes more valuable. Increasing VOT from 35 to 80 EUR/h reduces the flow-weighted plug-in share from 95.7% to 78.4% and raises the swapping share from 4.3% to 21.6%. More importantly, the change is not limited to aggregate shares. The number of routes with mixed allocation rises from 237 to 2,176, from 1.4% to 12.7% of all routes. The stronger result is where this shift appears. It is concentrated in the part of the network where the stop-time advantage of swapping is meaningful, while plug-in charging remains feasible enough to stay in the market. This is precisely where queueing and service-time differences matter most.

The distance breakdown clarifies this mechanism (Figure 4). For routes below 100 km, the flow-weighted swapping share rises from 5.5% at low VOT to 34.3% at high VOT. In the 100–300 km

range, the weighted share increase is smaller, from 2.7% to 4.7%, but the number of mixed routes rises sharply, from 45 to 782. This indicates that more time-sensitive and higher-value operations do not simply increase swapping on average. They also widen the part of the network in which swapping remains part of the economically viable charging mix.

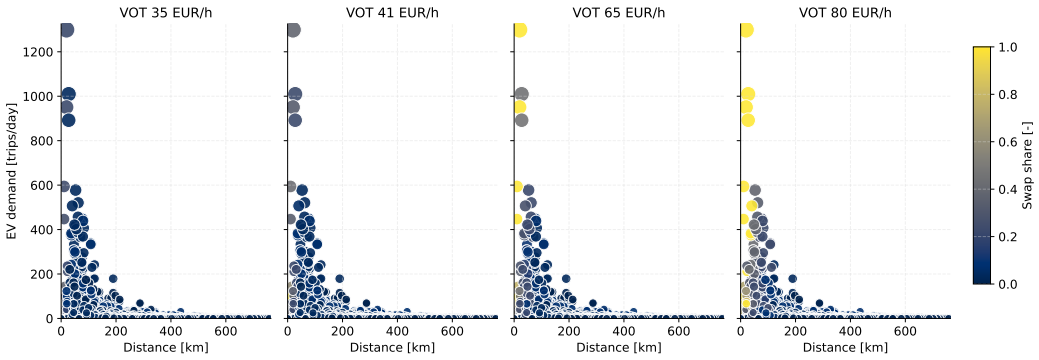


Figure 4: Distance–demand panels under alternative values of time. Color indicates the equilibrium swapping share; $x_{plug-in} = 1 - x_{swapping}$.

Technology progress in charging power mainly changes longer routes

A less intuitive result is that faster plug-in charging is not as important in aggregate as one might expect. Increasing plug-in charging power from 150 to 1000 kW raises the flow-weighted plug-in share only from 93.9% to 96.0%. Read at the network average, this suggests a limited role for megawatt-class charging. The more important effect appears once the results are broken down by route length (Figure 5).

The main response is concentrated on longer routes. In the 300–500 km band, the flow-weighted plug-in share rises from 97.6% to 99.5%. In the 500–800 km band, it rises from 98.9% to almost 100%. Over the same range, the number of mixed routes falls from 80 to 7 in the 300–500 km band and from 15 to 0 in the 500–800 km band. By contrast, the response is much smaller for short trips. Below 100 km, the swapping share declines from 8.5% to 5.6%, which is visible but not transformative.

This asymmetry matters for interpretation. Better charging performance does not broadly reorganize the whole system. Instead, it mainly removes the remaining economic space for swapping on routes where plug-in charging is already close to dominant but still carries a residual service-time disadvantage. Once that disadvantage is reduced, longer routes move toward near-complete plug-in allocation.

Taken together, the results suggest a clear pattern. Under current-reference conditions, plug-in charging is the dominant option overall, but not uniformly across the network. More time-sensitive and higher-value freight broadens the part of the network in which swapping remains competitive, while better charging performance mainly removes that role from longer routes and further strengthens plug-in charging there. The preferred allocation of on-road charging alternatives is therefore not fixed at system level. It depends on route heterogeneity and on a small set of operational drivers that change the relative value of service time, queue exposure, and charging performance.

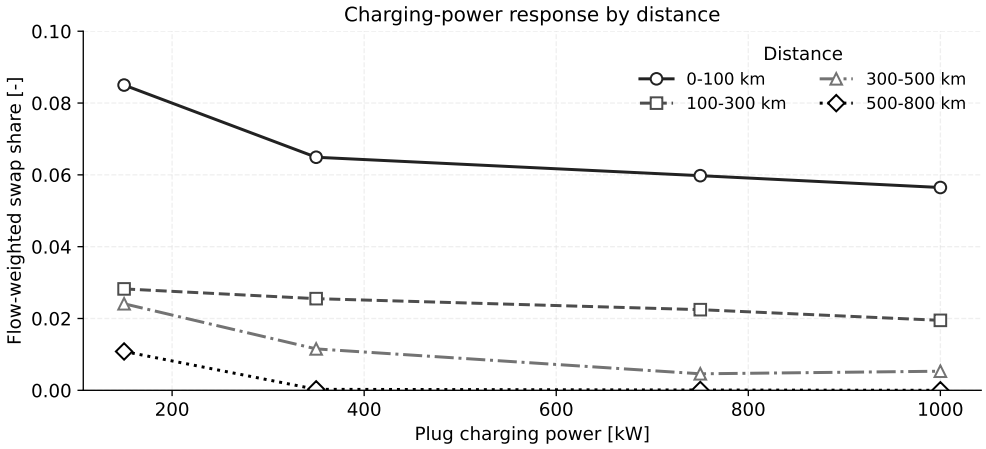


Figure 5: Technology allocation by distance band under alternative plug-in charging-power assumptions.

4 Conclusions

This paper evaluates the allocation of charging alternatives for battery-electric heavy-duty freight vehicles under corridor heterogeneity and scenario conditions that reflect plausible near-term changes in freight activity, electricity prices, and policy support. By developing a corridor-level equilibrium model with interacting carrier and provider decisions, it captures the operational and economic mechanisms that are specific to freight electrification. The case study of Bavaria, Germany, and Austria shows that the baseline equilibrium is clearly plug-in dominated in aggregate, but the allocation is not uniform across corridors. Swapping remains active mainly in a narrower set of short and high-demand corridors, indicating that corridor characteristics still matter even when one technology dominates at system level.

The comparative-statics results confirm that the value of time is the strongest driver of technology reallocation, expanding the swapping share from 4.3% to 21.6% and broadening its corridor range. By contrast, higher charging power has a modest aggregate effect but reshapes allocation on longer corridors where it eliminates the remaining service-time case for swapping.

Overall, the results suggest that the preferred allocation of on-road charging alternatives should not be treated as fixed or uniform. It depends systematically on corridor characteristics and on a small set of operationally meaningful drivers, especially time cost and charging performance. For early freight electrification, the key question is therefore not which single technology should dominate everywhere, but how different charging architectures should be matched to different corridor conditions and policy settings.

Future work

Future work will extend the current scenario analysis in three directions. First, we will expand the set of scenarios to represent alternative near-term and longer-term freight development paths, varying costs, technology parameters, and demand. Second, we will test a wider range of policy actions, including different forms of public support, technology-specific incentives, and ERS-related intervention rules. Third, this study will be linked to the planned policy-design stage, in which government acts more explicitly as a strategic actor rather than only through scenario input. The findings will provide a broader basis for understanding how infrastructure providers, freight operators, and public actors can jointly shape feasible road-freight electrification pathways.

Acknowledgements

This research was funded by the Austrian Science Fund (FWF) 10.55776/PIN6781124 and the Deutsche Forschungsgemeinschaft (DFG) 551933463.

References

Alp, O., Tan, T., & Udenio, M. (2022, June). Transitioning to sustainable freight transportation by integrating fleet replacement and charging infrastructure decisions. *Omega*, *109*, 102595. Retrieved 2026-02-05, from https://www.sciencedirect.com/science/article/pii/S0305048322000044 doi: 10.1016/j.omega.2022.102595

Aryanpur, V., & Rogan, F. (2024). Decarbonising road freight transport: the role of zero-emission trucks and intangible costs. *Scientific Reports*, *14*, 2113. doi: 10.1038/s41598-024-52767-5

Bakker, S., van den Borne, S., Alkemade, F., Smits, R., & van Wijk, A. (2024, March). A network design perspective on the adoption potential of electric road systems in early development. *Energy Policy*, *321*(March), 113741. Retrieved 2026-02-03, from https://linkinghub.elsevier.com/retrieve/pii/S0301421524000016 doi: 10.1016/j.enpol.2024.113741

BBC Future. (2024, January). *Wireless charging: The roads where electric vehicles never need to plug in.* Retrieved 2026-02-06, from https://www.bbc.com/future/article/20240130-wireless-charging-the-roads-where-electric-vehicles-never-need-to-plug-in

Binsuwadan, J., De Jong, G., Batley, R., & Wheat, P. (2022). The value of travel time savings in freight transport: a meta-analysis. *Transportation*, *49*, 1183–1209. doi: 10.1007/s11116-021-10207-2

de Jong, G., Kouwenhoven, M., Bates, J., Koster, P., Verhoef, E., Tavasszy, L., & Warffemius, P. (2014). New SP-values of time and reliability for freight transport in the netherlands. *Transportation Research Part E: Logistics and Transportation Review*, *64*, 71–87. doi: 10.1016/j.tre.2014.01.008

eRoadArlanda. (n.d.). Retrieved 2026-02-06, from https://www.interregeurope.eu/good-practices/eroadarlanda

European Commission. (2024). *Questions and answers on CO2 emission standards for heavy-duty vehicles.* Press corner Q&A. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_2527 (Accessed 2026-02-03)

European Parliament and Council of the European Union. (2006). *Regulation (ec) no 561/2006 of the european parliament and of the council of 15 march 2006 on the harmonisation of certain social legislation relating to road transport.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006R0561 (Official Journal of the European Union, L 102, 11.4.2006, p. 1–14; consolidated version consulted via EUR-Lex)

Eurostat. (2024). *Key figures on european transport: 2024 edition.* Statistical report. Retrieved from https://ec.europa.eu/eurostat/documents/3217494/17316586/KS-05-24-051-EN-N.pdf (Accessed 2026-02-03)

Eurostat. (2025). *Greenhouse gas emission accounts.* Statistics Explained. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_accounts (Accessed 2026-02-05)

Fadranski, D., Tietz, T., & Göhlich, D. (2025). Methodology for optimizing charging infrastructure distribution for long-haul freight traffic based on multi-agent simulation and evolutionary bi-objective optimization. *Procedia Computer Science*, *257*, 951–958. doi: 10.1016/j.procs.2025.03.122

Gao, W., & Li, Z. (2024, January). Charging autonomous electric vehicle fleet for mobility-on-demand services: Plug in or swap out? *Transportation Research Part C: Emerging Technologies*, *158*(C), 104457. Retrieved 2026-02-03, from https://linkinghub.elsevier.com/retrieve/pii/S0968090X23004473 doi: 10.1016/j.trc.2023.104457

Gillström, H. (2024, January). Barriers and enablers: How logistics companies could tackle the transition to electrified road freight transport. *Cleaner Logistics and Supply Chain*, *13*, 100172. Retrieved 2026-02-03, from https://linkinghub.elsevier.com/retrieve/pii/S2772390924000167 doi: 10.1016/j.clscn.2024.100172

Li, Y., Zhu, F., Li, L., & Ouyang, M. (2024). Electrifying heavy-duty truck through battery swapping. *Joule*, *8*(6), 1556–1561. Retrieved from https://www.sciencedirect.com/science/article/pii/S2542435124001922 doi: https://doi.org/10.1016/j.joule.2024.04.008

Momeni, M., Osterhage, F., Thier, A., & Vortisch, P. (2021). A synthetic road freight transport flow dataset for germany and its neighbouring regions. *Data in Brief*, *39*, 107786. doi: 10.1016/j.dib.2021.107786

Ogunclu, V., Aksu, H., Tas, I., et al. (2025). Prioritizing electric vehicle charging infrastructure goals from a multi-stakeholder perspective: An application of ahp and fuzzy ahp. In *Intelligent and fuzzy techniques for emerging conditions in transportation systems* (Vol. 1530, pp. 45–52). Springer. doi: 10.1007/978-3-031-83888-8_6

OpenRouteService. (2026). *Openrouteservice.* Retrieved from https://openrouteservice.org/ (Accessed March 30, 2026)

Raoofi, Z., Huge Brodin, M., & Pernestål, A. (2025a, January). Electric truck adoption and charging development: Policy insights from a dynamic model. *Transportation Research Part D: Transport and Environment*, *139*, 104515. Retrieved 2026-02-03, from https://linkinghub.elsevier.com/retrieve/pii/S1361920925001259 doi: 10.1016/j.trd.2025.104515

Raoofi, Z., Huge Brodin, M., & Pernestål, A. (2025b, January). System-level impact of electrification on road freight transport efficiency. *Communications in Transportation Research*, 100211. Retrieved 2026-02-03, from https://linkinghub.elsevier.com/retrieve/pii/S2045232225000076 doi: 10.1016/j.commtr.2025.100211

Rogstadius, J., Alfredsson, H., Sällberg, H., & Faxén, K.-F. (2025). Correcting market failure for no-regret electric road investments under uncertainty. *Nature Communications*, *16*, 7398. doi: 10.1038/s41467-025-62679-w

Scherrer, A., Lockwood, M., Burghard, U., & Rogge, K. S. (2026). Institutional barriers to dynamic truck charging: why electric road systems struggle in europe. *Transportation Research Part D: Transport and Environment*, *153*, 105154. doi: 10.1016/j.trd.2025.105154

Vallender, Z., Knight, J., Dekker, T., de Jong, G., & Clarke, G. (2023, June). *Freight value of time and value of reliability: Final report* (Final Report). National Highways. Retrieved from https://assets.publishing.service.gov.uk/media/68f21191f5d433238a14c70f/freight-value-time-value-reliability.pdf

Wang, X., Jiang, J., Zhou, Y., & Wang, X. (2023, September). Integrated infrastructure planning of charging and electricity generation. *Transportation Research Part D: Transport and Environment*, *122*, 103807. Retrieved 2025-11-18, from https://www.sciencedirect.com/science/article/pii/S1361920923002043 doi: 10.1016/j.trd.2023.103807

Wang, Y., Fan, S., Sun, X., & Liu, X. (2023, June). Investigating the deployment of initial public charging infrastructure: Planning-based VS market-based approaches. *Transportation Research Part D: Transport and Environment*, *119*, 103755. Retrieved 2025-11-25, from https://www.sciencedirect.com/science/article/pii/S1361920923001529 doi: 10.1016/j.trd.2023.103755

Zhu, F., Li, L., Li, Y., Li, K., Lu, L., Han, X., ... Ouyang, M. (2023, January). Does the battery swapping energy supply mode have better economic potential for electric heavy-duty trucks? *eTransportation*, *15*, 100215. Retrieved 2025-10-07, from https://www.sciencedirect.com/science/article/pii/S2590116822000601

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2018, March). Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case-study. *Transportation Research Part C: Emerging Technologies*, *88*, 107–123. Retrieved 2025-09-20, from https://www.sciencedirect.com/science/article/pii/S0968090X18300470 doi: 10.1016/j.trc.2018.01.013