

Development of an Optimal Charging Infrastructure Deployment Model Considering the Adoption of Electric Trucks for Long-Distance Transport

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Electrifying heavy-duty freight transport is essential for achieving carbon neutrality. However, battery electric trucks face significant hurdles, including limited driving range, long charging times, and the high cost of large-capacity batteries. To overcome these challenges, combining dynamic wireless power transfer (DWPT) systems with stationary quick chargers (QC) — installed at locations such as parking areas—has emerged as a promising solution. DWPT enables charging while driving, thereby drastically reducing the required battery capacity and the downtime associated with charging stops. However, DWPT entails high initial installation costs and suffers from low power transmission efficiency. Consequently, optimizing the combined deployment of DWPT and QC is crucial. Previous research on such combined deployment has largely been limited to static analyses at a single point in time. While some studies have examined phased expansion strategies accompanying the adoption of electric vehicles (EVs), these have focused exclusively on QCs.

Therefore, this study constructs a model that assumes the combined use of DWPT and QC, accounts for phased infrastructure deployment aligned with the adoption of electric trucks, and carries over deployment results from one period as constraints for the next. Furthermore, rather than requiring every vehicle to complete its entire journey, the study establishes a constraint based on a minimum guaranteed travel completion rate (service level) to identify the realistic minimum deployment cost that meets the specified standard. Additionally, correlation and sensitivity analyses regarding infrastructure placement and traffic conditions were conducted to examine the characteristics of the deployment for each infrastructure type.

Methodologically, traffic volume data between interchanges (ICs) in Japan and inter-prefectural freight flow data are used to determine origin-destination (OD) pairs and departure times, thereby generating an operational dataset. The optimization problem was formulated as a mixed-integer programming (MIP) problem to simulate traffic and charging dynamics. Simulation results based on various adoption scenarios revealed trends in phased deployment. Fig. 1 illustrates the changes in total infrastructure deployment costs. An analysis of the deployment process reveals an inverse relationship between the rate of vehicle adoption across stages and the increase in DWPT section length; specifically, the slower the vehicle adoption rate between stages, the greater the expansion in deployment costs. Given this trend and the exceptionally high unit cost of DWPT, it is evident that DWPT accounts for most of the total infrastructure investment. Interestingly, while the total length of DWPT continued to expand alongside the growth in truck numbers, the number of QCs eventually plateaued, suggesting the existence of an optimal upper limit for QC deployment.

Regression analysis conducted to elucidate the deployment mechanism revealed that the installed length of DWPT is influenced more significantly by travel speeds on road links than by traffic volume; specifically, DWPT tended to be prioritized on road sections with slower speeds to maximize energy supply duration. Conversely, although QCs were frequently installed near long DWPT sections, the impact of this correlation was limited.

Sensitivity analysis regarding charging output highlighted the distinct operational characteristics of each system. Increasing DWPT output resulted in a proportional reduction in the required installation length but had negligible impact on the number of QCs, demonstrating that DWPT and QC play roles that are independent yet complementary. In contrast, increasing QC output led to a monotonic decrease in DWPT installation length, confirming a clear substitution effect. Furthermore, the adoption of ultra-high-output QCs allowed total demand to be met with fewer units, leading to infrastructure consolidation and an overall reduction in the number of QCs installed.

In conclusion, this study has clarified the phased deployment dynamics and physical characteristics of a combined DWPT and QC system. However, an over-reliance on consolidation via high-output QCs risks triggering localized surges in power demand, potentially placing a strain on the regional power grid. To ensure realistic feasibility, future models must consider grid capacity constraints, distances to substations, and temporal fluctuations in equipment costs.

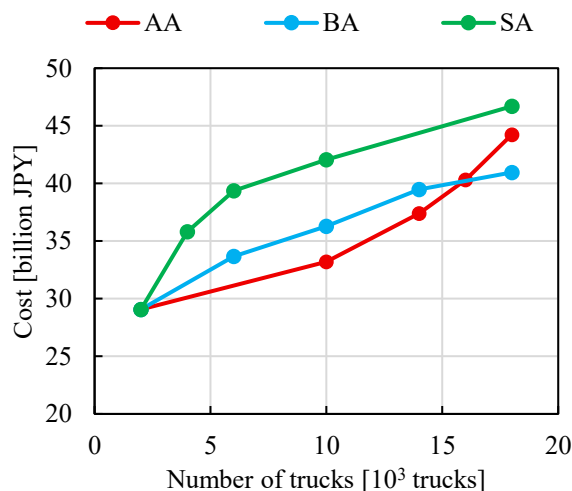


Fig. 1 Filling Infrastructure Installation Cost