

Network Deployment of Battery Swapping and Charging Stations within Hyperconnected Logistic Hub Networks

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Abstract: The rapid proliferation of electric vehicles emphasizes the importance for logistics companies to strategically integrate electric vehicles into their freight transportation systems to optimize the environmental impact and efficiency of freight operations. Battery swapping stations (BSS) have been gaining attention and interest for the swift replacement of depleted battery with a charged battery, handling the obstacles regarding to the traditional charging methods. The discharged batteries will be charged at Battery charging stations (BCS), either at the service location or through central collections. Lateral transshipments between stations involve the redistribution of batteries and offering a solution to optimize resource utilization and enhance the overall efficiency of the charging network. To consider the integration of battery swapping and charging stations with hyperconnected hub networks, this paper jointly determines station localization and sizing, freight consolidation and routing, and battery inventory and transshipment. We formulate the problem with a mixed integer programming model to optimize the total system cost, including site fixed cost, freight transportation cost, battery leasing, charging and transshipment cost over multiple time intervals. Two charging strategies are discussed with the deployment of battery swapping and charging stations, including 'Swap-Locally, Charge-Locally' and 'Swap-Locally, Charge-Centrally' strategies. Through comprehensive mathematical modeling and analysis, we investigate the effects of 'Swap-Locally, Charge-Centrally' strategy with centrally managed battery inventory on less facility depreciation cost, higher battery utilization rate and stable safety stock of charged batteries, thereby enhancing efficiency and resilience against potential risks.

Keywords: Electric Trucks; Hyperconnected Transportation; Battery Swapping Stations; Battery Charging Stations; Hyperconnected Networks; Logistic Hubs; Resource Lateral Transshipments.

Conference Domain Fitness: Physical Internet; Clean Energy; Network Deployment; Hyperconnected Logistic Hub Networks; Net Zero Freight System; Battery Swapping and Charging Stations; Resource Allocation.

Physical Internet (PI) Roadmap Fitness: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan: ☒ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☐ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☐ Governance.

Targeted Delivery Mode-s: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation

1 Introduction

The Electric Vehicles Initiative, formed by 15 countries such as Canada, China, Germany, and the United Kingdom, aims to achieve a 30% market share for Electric Vehicles by the year 2030. The United States declared their goal of achieving 50% of all new passenger cars and light trucks sold in 2030 to be zero-emission vehicles [1]. Despite global initiatives and efforts, significant barriers to adoption persist, particularly in relation to charging infrastructure. Driven by advancements in battery and charging technology and the growing demand for zero emission transportation solutions, the heavy-duty Electric Trucks industry is growing rapidly. Long-haul freight distribution with Electric Trucks is planned by companies like Tesla, Daimler AG, and Volvo for mass production within this decade [2,3].

Since heavy-duty trucks account for near half of global road freight emissions, it is important for logistics companies to integrate Electric Trucks into their freight transportation systems to optimize the environmental impact and efficiency of freight operations. Since significant energy is required for long-haul freight transportation with heavy-duty trucks, Megawatt Battery Charging Stations (BCSs) are introduced recently for their high charging capabilities and improving communication, especially for logistics hubs where fleets of electric vehicle are large. However, limitations for those stations including high infrastructure cost and potential grid strain make it infeasible and economically demanding to deploy charging stations in some logistic hubs within the networks.

Battery Swapping Stations (BSSs) offer a solution by swiftly replacing depleted batteries with charged batteries, and effectively overcoming obstacles regarding to the traditional charging methods [4,5]. The swapped discharged batteries can be charged at Battery Charging Stations (BCS), either at the service location or through central collections [6]. Compared with other charging strategies like overnight charging or charging on-the-move, battery swapping not only eliminates additional downtime and potential grid constraints at logistic hubs, but also offers scalability for large fleets or high-demand operations due to its modular nature and potential for incremental expansion. Therefore, we propose the deployment of both Megawatt Battery Charging Stations and Battery Swapping Stations in the logistic hub networks to leverage the advantages of both charging infrastructures.

The Physical Internet initiative, introduced in [24], aims to enhance global logistics efficiency and sustainability. Due to high cost of charging infrastructures and limited availability of public stations, open-access hubs in the hyperconnected logistic networks offer an opportunity for deploying charging infrastructures to provide shared charging services and enhance the utilization of charging stations. With the settings of hyperconnected transportation system where long-haul shipments are transported via multiple short-haul route segments and logistic hubs in a relay manner, the high connectivity of network infrastructure facilitates efficient battery charging and swapping operations, in line with the transport distance constraints and charging needs of electric heavy-duty trucks. Furthermore, this hyperconnected network configuration has been extensively studied, demonstrating its potential to increase consolidation opportunities, improve delivery efficiency, and enhance the working conditions of truck drivers.

Heavy-duty truck battery swapping has also been launched as a solution provided by companies recently in the real world. As illustrated in Figure 1, CATL released a heavy-duty truck chassis battery swap solution - QIJI Energy, offering a fast and low-cost refueling solution for electric heavy-duty trucks, including includes battery blocks, battery swap station, and cloud platform

[31]. In this paper, we propose an innovative network deployment strategy for battery swapping and charging stations within hyperconnected logistic hub networks. This approach also involves centrally managing the battery inventory levels at these stations, considering the inbound and outbound trucks of the hubs. Lateral transshipments between stations refer to the redistribution of batteries to optimize resource utilization and enhance the overall efficiency of the charging network [2]. By assuming shared capacity of transportation for both freight and battery flow, we jointly consider the station localization and sizing with freight consolidation and routing, and battery inventory and transshipment within the framework. We formulate the problem with a mixed integer programming model to optimize the total system cost, including site fixed cost, freight transportation cost, battery leasing, charging and transshipment cost over multiple time intervals. Two charging strategies are discussed with the battery swapping and charging stations, including ‘Swap-Locally, Charge-Locally’ (SLCL) and ‘Swap-Locally, Charge-Centrally’ (SLCC) strategies. Our findings suggest that centrally managed battery inventory results in less facility depreciation cost, higher battery utilization rate and smoother safety stock of charged batteries, thereby enhancing efficiency and resilience against potential risks.

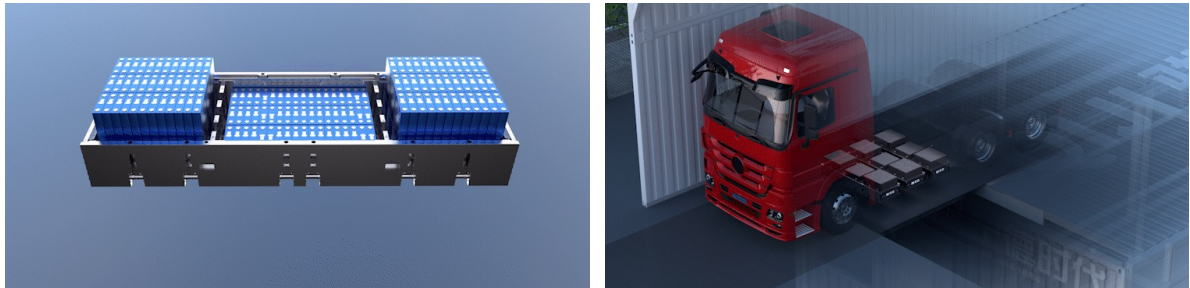


Figure 1: QIJI Energy heavy-duty truck battery swapping solution: battery blocks (left) and battery swap stations (right; source: CATL [31])

2 Literature Review

During the past few years, a significant surge in scholarly papers has been dedicated to exploring various aspects of electric trucks. For example, [8] explores perceived social, technological, and economic barriers to heavy-duty truck electrification, focusing on commercial and public fleets operating heavy-duty trucks in California. [9, 10] investigate the viability of long-haul electric truck adoption as a competitive alternative to diesel trucks, also from the perspective of truck fleet managers. [11] assesses the public charging, energy, and power requirements for electric trucks in long-haul operations in Europe in 2030. Numerous studies focus on the transition of vehicle fleets from diesel to electric vehicles. [12] present a general research framework to analyze electric vehicles adoption decisions based on a collaborative effort between a taxicab company and an infrastructure service provider. [13] consider the case in which a firm that owns and operates a fleet of diesel trucks and decides to invest in the charging infrastructure required to support this transition, either because the public charging infrastructure is currently inadequate or for strategic reasons.

The design, planning and operation of an electric vehicle charging network has received attention in the research literature. Different kinds of charging infrastructure are discussed in the design of electric vehicle charging networks [14,16]. For example, [14] designs an electric vehicle charging network where battery swap and supercharging are jointly coordinated. Deployment of charging infrastructure for electric vehicles has been discussed in [15], considering investment and operation costs, and the building of storage systems. Additionally, many papers work on the planning and operation for electric fleets, including planning for

electric commercial vehicle fleets within the retail mid-haul logistics networks [17], electric vehicle routing with public charging stations[18], and joint scheduling of electric truck routing and charging [19, 20].

Battery swapping has garnered significant attention in discussions recently surrounding the accelerated electrification of heavy-duty trucks. [21] have identified that battery swapping is the most cost-effective energy supply mode for electric heavy trucks when the station utilization rate is high, and will be further expanded with the battery technology improvement and traffic density increase in the future. A battery swapping station system that exclusively serves an electric truck fleet has been studied in [22], where a battery charging management strategy to enhance cost efficiency is proposed considering battery degradation effects. The allocation of battery swapping stations has been frequently addressed as a location-inventory problem in various studies [23, 24], with [24] proposing the adoption of “swap-locally, charge-centrally” network, citing that faster charging accessible at centralized charging stations can significantly reduce the system-wide battery stock level.

Shared charging is proposed as a solution to enhance utilization and mitigate the high cost of charging infrastructures and limited availability of public stations, particularly within the logistics industry. Union battery swapping stations for multiple logistics companies has been established by some investors [23]. Hyperconnected city logistics leverages massively open multi-party multi-modal asset sharing and flow consolidation through seamless interconnectivity within and between urban environments for increased economic, environmental, societal efficiency and sustainability [25, 26, 27]. It is materialized through a multi-tier urban logistics web [28], whose nodes are hyperconnected logistic hubs facilitating freight consolidation and resource sharing among them [29, 30]. These open-access hubs offer an opportunity for deploying charging infrastructures to provide shared charging services to multiple stakeholders participating in the hyperconnected logistic hub networks.

3 Problem Description and Formulation

Sets		Parameters	
R	set of routes	C_h^{BSS}	depreciation cost of BSS at hub location h
K	set of commodities	C_h^{BCS}	depreciation cost of BCS at hub location h
R_k	set of available routes for commodity k	C_h^{CAP}	unit capacity cost at hub location h
L	set of connected lanes	G_h^{cap}	capacity of charging capability at hub location h
T	set of time units in the planning horizon	D_l	transportation cost on lane l
H	set of hubs, including a dummy location for truck flow balance	α/β	capacity of shipments/ battery transshipments per truck.
$In(h)$	inbound lanes of hub $h \in H$, $\{(i, h) (i, h) \in L\}$	B_h	battery charging cost at hub location h
$Out(h)$	outbound lanes of hub $h \in H$, $\{(h, i) (h, i) \in L\}$	$V_{k,t}$	volume demand of commodity k on day t
		A	depreciation cost of battery
Decision variables			
$x_{r,t}$	binary, whether a route $r \in R$ is selected on day t	$y_{h,t}^c$	number of fully charged batteries left at hub h and day t
f_h^{BSS}	binary, whether a hub h is selected as a BSS	$y_{h,t}^d$	number of depleted batteries at left hub h and day t
f_h^{BCS}	binary, whether a hub h is selected as a BCS	$m_{l,t}^c$	number of fully charged batteries transshipped on lane l on day t
$g_{h,t}$	integer, the number of batteries charged at hub h and day t	$m_{l,t}^d$	number of depleted batteries transshipped on lane l on day t
$n_{l,t}$	integer, the number of trucks dispatched on lane l and day t	z_h	the capacity required in hub h
$v_{l,t}$	total shipment volume on lane l and day t		

Table 1: Descriptions of sets, parameters, and decision variables

In this section, we present the problem we aim to address and outline our proposed a mixed integer programming model to tackle it. We consider a hyperconnected network composed of a finite set H of hubs and L of connected lanes. For each hub $h \in H$, $In(h)$ and $Out(h)$ denote the inbound and outbound lanes, respectively. A commodity entails freight deliveries share the same origin and destination pair. Each commodity has a defined set of available freight transportation routes, and one route among them needs to be assigned for each commodity in a finite set K . To achieve a NetZero freight system, we propose the deployment of network infrastructure, including battery swapping and charging stations, within hyperconnected logistic hub networks. We assume that upon electric trucks' arrival at a hub, battery swapping services are provided. Depleted batteries are swiftly exchanged with fully charged ones, so that trucks' dwell time in hubs could be minimized.

Battery inventories are managed centrally within the proposed charging network considering the inbound and outbound freight flow with battery swapping requests. In this paper, we compare two charging strategies, named as 'Swap-Locally, Charge-Locally' and 'Swap-Locally, Charge-Centrally' strategy. In the 'Swap-Locally, Charge-Locally' scenario, swapped batteries are charged locally within the same hub with the swapping station. Meanwhile, in the 'Swap-Locally, Charge-Centrally' strategy, depleted batteries can be transported to a central charging station via lateral transshipments between hubs. In addition, we assume shared capacity of shipment trucks for freight transportation and battery transshipments, taking into account their respective size and weight.

We propose a mixed integer programming model to deploy stations and batteries in the hyperconnected networks considering infrastructure and battery depreciation costs, battery charging cost, capacity cost and transportation cost. With detailed notation, including the sets, parameters and decision variables listed in Table 1, the proposed model for the network deployment problem is formulated as follows:

$$\text{Min} \sum_{h \in H} (C_h^{BSS} f_h^{BSS} + C_h^{BCS} f_h^{BCS} + C_h^{CAP} z_h) + \sum_{l \in L} \sum_{t \in T} D_l n_{l,t} + \sum_{h \in H} A(y_{h,0}^c + y_{h,0}^d) + \sum_{h \in H} \sum_{t \in T} B_h g_{h,t} \quad (1)$$

subject to:

$$\sum_{r \in R_k} x_{r,t} = 1 \quad \forall k \in K, \forall t \in T \quad (2)$$

$$v_{l,t} = \sum_{k \in K} \sum_{\{r \in R_k | l \in r\}} V_{k,t} x_{r,t} \quad \forall l \in L, \forall t \in T \quad (3)$$

$$\frac{v_{l,t}}{\alpha} + \frac{m_{l,t}^c + m_{l,t}^d}{\beta} \leq n_{l,t} \quad \forall l \in L, \forall t \in T \quad (4)$$

$$y_{h,t}^d = y_{h,t-1}^d + \sum_{l \in In(h)} n_{l,t-1} + \sum_{l \in In(h)} m_{l,t-1}^d - \sum_{l \in Out(h)} m_{l,t-1}^d - g_{h,t-1} \quad \forall h \in H, \forall t \in T \setminus \{0\} \quad (5)$$

$$y_{h,t}^c = y_{h,t-1}^c - \sum_{l \in Out(h)} n_{l,t-1} + \sum_{l \in In(h)} m_{l,t-1}^c - \sum_{l \in Out(h)} m_{l,t-1}^c + g_{h,t-1} \quad \forall h \in H, \forall t \in T \setminus \{0\} \quad (6)$$

$$\sum_{l \in In(h)} n_{l,t} = \sum_{l \in Out(h)} n_{l,t} \quad \forall h \in H, \forall t \in T \quad (7)$$

$$y_{h,t}^c + y_{h,t}^d \leq z_h \quad \forall h \in H, \forall t \in T \quad (8)$$

$$g_{h,t} \leq G_h^{cap} f_h^{BCS} \quad \forall h \in H, \forall t \in T \quad (9)$$

$$y_{h,t}^d + \sum_{l \in In(h)} n_{l,t} + \sum_{l \in In(h)} m_{l,t}^d - \sum_{l \in Out(h)} m_{l,t}^d \geq 0 \quad \forall h \in H, \forall t \in T \quad (10)$$

$$y_{h,t}^c - \sum_{l \in Out(h)} n_{l,t} + \sum_{l \in In(h)} m_{l,t}^c - \sum_{l \in Out(h)} m_{l,t}^c \geq 0 \quad \forall h \in H, \forall t \in T \quad (11)$$

$$\sum_{l \in In(h)} (m_{l,t}^c + m_{l,t}^d) + \sum_{l \in Out(h)} (m_{l,t}^c + m_{l,t}^d) \leq M(f_h^{BCS} + f_h^{BSS}) \quad \forall h \in H, \forall t \in T \quad (12)$$

$$\sum_{l \in \text{In}(h)} v_{l,t} + \sum_{l \in \text{Out}(h)} v_{l,t} \leq M f_h^{BSS} \quad \forall h \in H, \forall t \in T \quad (13)$$

The objective function (1) minimizes the total cost including depreciation and capacity cost of battery swapping and charging stations, battery depreciation and charging cost, and transportation cost. Constraints set (2) and (3) ensure that for each commodity with an origin and destination, a route is assigned and freight volume for each arc is calculated via hyperconnected transportation. Constraints set (4) makes sure that the number of trucks is calculated based on the volume of freight and the battery transshipments. Constraints set (5) and (6) indicates the flow of depleted and charged batteries respectively. To make it clear, the sum of $y_{h,t}^d$ and $y_{h,t}^c$ is a constant, which indicates the total number of batteries required in the system. Constraints set (7) ensures that the number of trucks arrive at a hub equal to the number of trucks depart. Constraints set (8) controls the battery inventory capacity while Constraints set (9) makes sure batteries are charged at a hub only if it is selected as a charging station and the number of batteries charged should smaller than its charging capacity. Constraints set (10) and (11) make sure the number of battery available is larger than required at each hub and time unit. Lastly, constraints set (12) and (13) ensure that battery transship only between battery stations and battery swapping is required once a truck arrives at a hub.

4 Case Study

In this section, we utilize a case study to illustrate the effectiveness of our proposed model with a real-world instance. We consider an open-access hub network consisting of hubs and regional centers, given the daily demand of each origin destination pair generated based on estimated US freight flows from Freight Analysis Framework (FAF) database from Bureau of Transportation Statistics [7]. A designed hyperconnected logistic hub networks for freight transportation of southeast United States are assumed to be given to our proposed model. In the experiments, we assume 5% of the flow utilizes the network. Also, we utilize designed hyperconnected logistic hub networks for freight transportation in 7 states of southeast United States, consisting of 111 hubs and 2996 edges, as shown in Figure 3. The planning horizon is set to be one year, divided into 13 durations, each lasting 28 days. The depreciation cost of battery swapping stations and battery charging stations is set to be \$100,000 and \$300,000 respectively, while the depreciation cost of a battery is set to be \$7800 during the planning horizon. We currently ignore the capacity cost and the battery charging cost is set to be \$50 per battery. We assume that at most 27 batteries can be carried on a truck and the transportation cost is \$50 per hour of driving. The cost structure for hubs may be tailored to reflect their unique characteristics in future research.

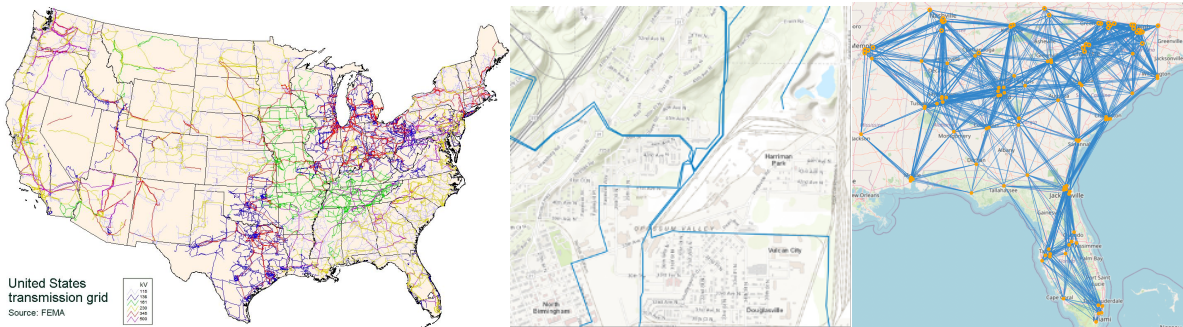


Figure 2: United States transmission grid (left; source FEMA), electric power lines (middle; [32]) and proposed hyperconnected transportation networks

In addition, we utilize the transmission grid of the United States to provide us the charging availability and capacity for the potential station locations in the selected area. Given the electric power lines [32], we find out the maximum power voltage γ_h of station candidates, as shown in Figure 2. We then assume the capacity of the potential station location $G_h = \frac{6000\gamma_h^2}{115^2}$.

Given our proposed model, some routes are selected from the top shortest paths for each OD commodity, and the average freight flow on each leg is illustrated in Figure 3(a). Also, some of the hub locations are selected to be battery swapping stations, as indicated by the orange circles, and some of the hubs are selected to be battery charging stations, as indicated by the green circles. Across the stations selected, we also plot the average charged and depleted battery flow in the network, as shown in Figure 3(b) and (c), while the width of the lines indicates the number of batteries transported on each leg. We can clearly see that a few locations are selected as charging stations, and the hyperconnected freight transportation networks are utilized for battery transshipments between charging stations and the swapping stations.

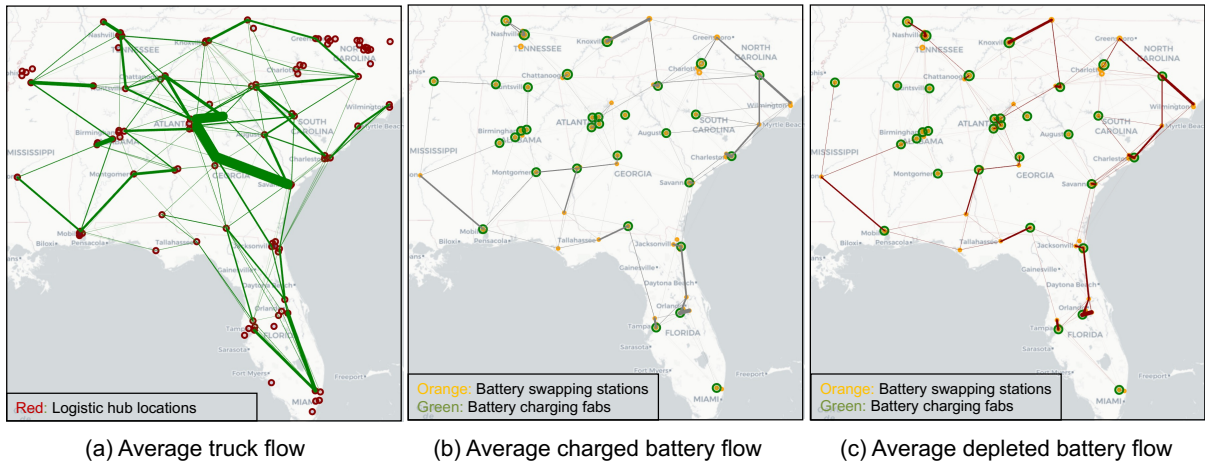


Figure 3: Illustration of locations of logistic hubs, battery swapping stations and charging fabs, along with freight and battery flow between them

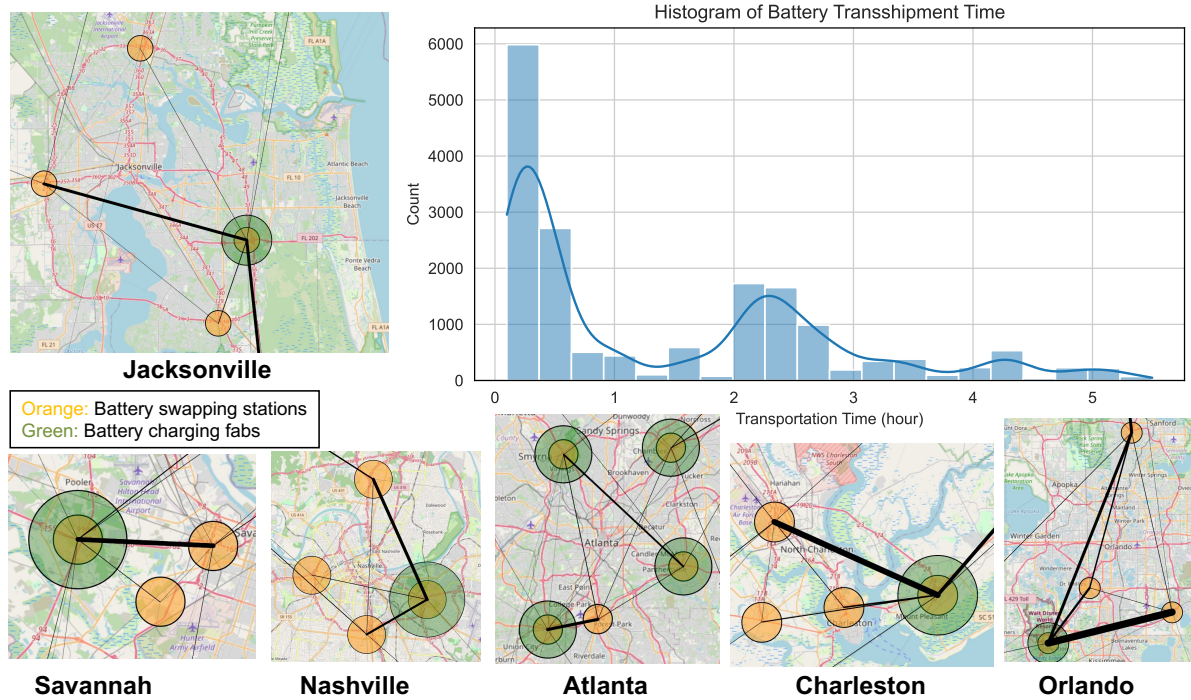


Figure 4: Battery swapping stations, charging fabs and transshipments within large cities; distribution of battery transshipment times

We also plot the locations of battery swapping stations and charging fabs within large cities in Southeast of the United States, along with battery transshipments among them, as shown in Figure 4. Based on the freight demand and the capacity of the charging facilities in each city, one or multiple charging hubs are strategically located. Batteries are transshipped between central charging hubs and swapping stations to enhance the utilization of charging resources. As shown in the histogram of battery transshipment times in Figure 4, many batteries are transshipped within cities in less than one hour. However, the transshipment durations of some batteries exceed two hours. This delay is due to the current limitations of charging capacity in certain areas based on our assumption, which could be mitigated with the development of electricity grids and charging technologies.

Additionally, we present a comparison of two charging strategies: ‘Swap-Locally, Charge-Locally’ (SLCL) and ‘Swap-Locally, Charge-Centrally’ (SLCC). In the SLCC scenario, battery charging fabs are deployed in all hubs except the locations has no charging availability based on current transmission grids. Some key performance indicators can be found in the Table 2. With the SLCL strategy, additional 37 charging stations are required, resulting in higher infrastructure depreciation costs. Conversely, the SLCC approach necessitates a slightly larger transportation costs due to battery transshipments. Overall, the SLCC approach saves about 4% of the total cost. Also, employing the SLCC strategy results in a reduction of charging fabs in the network without causing increase in the total number of batteries needed, which would further decrease if we took high charging efficiency of central charging stations into consideration.

	Swap-Locally, Charge-Locally	Swap-Locally, Charge-Centrally
Number of swapping stations	73	72
Number of charging fabs	69	32
Number of batteries	32732	32132
Total cost	3.66E+08	3.51E+08
Infrastructure depreciation cost	2.80E+07	1.68E+07
Battery depreciation cost	2.55E+08	2.51E+08
Battery charging cost	1.87E+07	1.91E+07
Transportation cost	6.44E+07	6.49E+07

Table 2: Key performance indicator of the two proposed strategies

We also plot the number of transporting trucks and battery transshipments over the entire planning horizon to observe their temporal dynamics. Firstly, the blue line indicates the number of trucks, including those for battery transshipments, as depicted in Figure 5. Figure 5(b) illustrates a slightly increase in the required number of trucks in the SLCC scenario. Also, the orange and green lines depict the charged and depleted battery transshipments, about 5000 batteries are transshipped monthly between hubs with no charging capability (Figure 5 (a)) and above 10000 batterie are transshipped monthly to be charged centrally (Figure 5 (b)).

5 Conclusion and future research

Overall, we conclude that there are several benefits of implementing battery swapping in hub logistic networks. Firstly, the downtime of trucks at hubs would be minimized, and we can reduce the number of charging stations utilizing the hyperconnected freight transportation system. Benefits of ‘Swap-Locally, Charge-Centrally’ (SLCC) strategy are also discussed in

this paper. For example, we can centrally manage battery inventory in the system, allowing shared batteries with transshipments. Also, collaborative transportation helps us integrate freight transportation and battery transshipments so that resource utilization can be increased, and the overall efficiency can be enhanced. Moreover, the utilization of electrical resources can be optimized while overcoming limitations within the power grid, considering the potential for faster charging accessible at centralized charging stations.

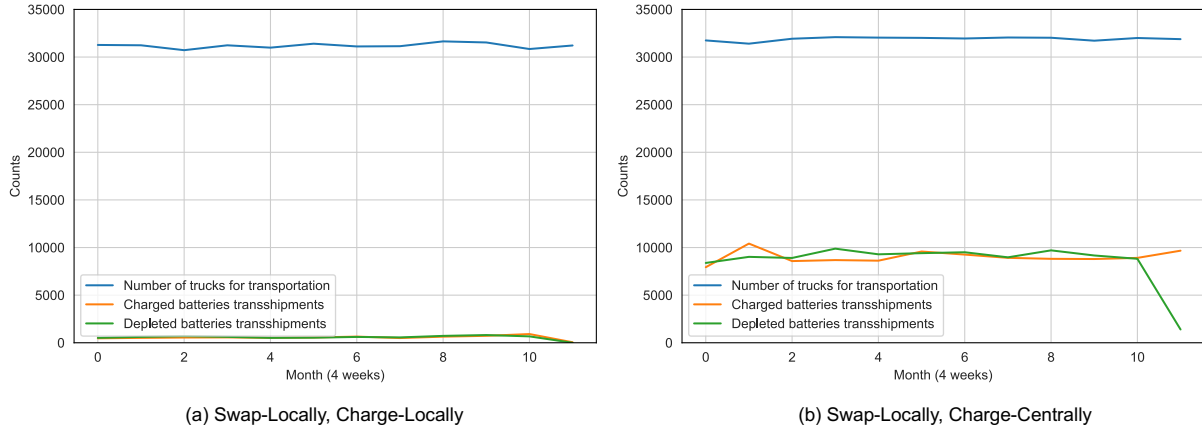


Figure 5: Comparison of the number of transporting trucks and battery transshipments

Regarding future research, exploring a mixed policy that includes both trucks on-site charging and battery swapping is worthwhile, and detailed comparison between our proposed and other alternatives is necessary, such as transportation using combustion engines or hydrogen fuel cells. Also, exploring the integration of battery inventory policies, like (r, Q) policy, at each swapping stations could offer valuable insights into realistic battery utilization. Additionally, the impact of different charging infrastructure types, including mega-charging, fast-charging and slow-charging in the network presents an avenue for further exploration. Moreover, strategic-tactical models that combining long-term planning with short-term leasing opportunities could be investigated to enhance the agility and responsiveness of the system. Furthermore, exploring the scalability of the proposed framework to accommodate larger-scale transportation networks could provide valuable insights into its applicability in broader contexts. Finally, shared charging options with existed public charging locations, and the potential environmental and sustainability implications of the proposed strategies could contribute to the development of more environmentally friendly and socially responsible freight transportation solutions.

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