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Hyperconnected Transportation Planning: Advancing a Multimodal Relay Ecosystem

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Abstract: *This paper introduces the concept of hyperconnected transportation, drawing inspiration from the Physical Internet, as a sustainable approach to addressing economic, environmental, and social challenges in regional overland transport. It is characterized by three types of connectivities (i.e., shipper-to-network, intra-network, and network-to-carrier connectivity), and incorporates five logistics strategies (i.e., demand aggregation, freight containerization, an interconnected hub network, multimodal transportation, and relay-based transportation). Our study investigated a scenario where a hyperconnected transportation planning platform (HTPP) interfaces with a network of relay hubs to manage bulky goods shipping demands from shippers over time. Unlike conventional systems, the HTPP collaborates with multimodal relay carriers that offer both rail and truck services, optimizing the movement of goods from origins, through hubs, to destinations. We developed a novel Rolling-Horizon Hyperconnected Transportation Planning Framework and a Multimodal Relay Service Network Design optimization model for the HTPP to tactically plan deliveries, with goals to minimize lateness, reduce costs, and decrease emissions. A case study in the Southeastern US automotive delivery sector was conducted to validate the effectiveness of our methodology, considering varying shippers' preferences for delivery velocity, timeliness, and sustainability. We also examined the potential benefits of integrating rail services and clean-powered truck technologies to further improve efficiency, lower costs, and strive towards a zero-emission logistics network. Overall, this research promotes the advancement of a multimodal relay ecosystem by establishing foundational concepts, offering a relevant business model, and proposing a scalable decision-making model to enhance the sustainability and efficiency of regional overland transportation.*

Keywords: *Hyperconnected Transportation; Transportation Planning Platform; Rolling-Horizon Framework; Multimodal Relay Service Network Design; Bulky Goods; Interconnected Hub Network; Multimodality; Electric and Hydrogen Trucks; Driver Daily Returning Home; Sustainability; Physical Internet*

Main Paper

1 Introduction

The current way of transporting physical objects is unsustainable economically, environmentally, and socially. This problem is particularly acute in regional overland transportation, which predominantly relies on a fragmented connection of rail and truck services. Rail systems, while cost-effective and environmentally friendly for bulk and long-distance hauls, suffer from inflexibility due to fixed routes and schedules. Trucks, on the other hand, provide essential flexibility and can access remote areas not served by rail, but they come with substantial operational costs, significant environmental impacts, and issues like a severe driver shortage and poor long-haul working conditions. Furthermore, emerging technologies such as electric and hydrogen trucks offer greener alternatives, though they face challenges with elevated costs and limited range.

To tackle these prevalent challenges, we introduce the concept of Hyperconnected Transportation, inspired by the digital internet's data transmission, as depicted in Figure 1. Like the digital internet, where data packets travel through interconnected routers, this concept envisions a similar approach for goods—starting with demand aggregation from multiple shippers, followed by freight containerization. The containerized goods then move through an interconnected hub network using multimodal transportation and relay truck drivers, culminating in last-mile deliveries. The notion of hyperconnectivity originates from Physical Internet to enable massively open asset sharing and flow consolidation, thereby improving efficiency and sustainability in transportation, distribution, and production. Achieving hyperconnectivity necessitates comprehensive integration across physical, data, digital, operational, transactional, legal, and personal dimensions. In this paper, we focus on defining hyperconnectivity in the context of transportation through three types of connectivities: Shipper-to-Network Connectivity, involving demand aggregation from various shippers and freight containerization for building loads; Intra-Network Connectivity, leveraging an interconnected hub network moving beyond traditional hub-and-spoke structures by allowing each hub for secure load transfers and storage; and Network-to-Carrier Connectivity, integrating multimodal transportation options and relay truck drivers from different carriers to move freight between hubs. Collectively, these connectivities forge a more efficient and sustainable framework for regional overland transportation, enhancing flexibility and robustness, and enabling relay truckers returning home daily.

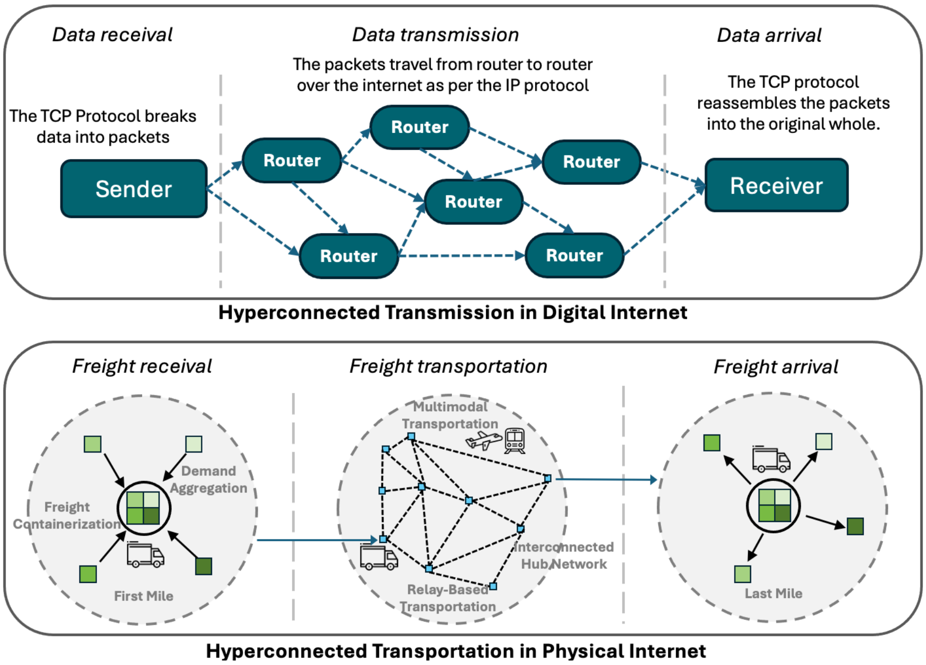

Figure 1: An Analogy from Hyperconnected Transmission in Digital Internet to Hyperconnected Transportation in Physical Internet

As an applicable scenario of Hyperconnected Transportation, this paper considers a Hyperconnected Transportation Planning Platform (HTPP), which interfaces with a network of relay hubs. Shippers transmit their logistic requests to the HTPP, which are then coordinated with multimodal relay carriers to optimize the distribution of goods via efficient hub transfers. To enhance the tactical decision making of the HTPP, we propose a novel Rolling-Horizon Hyperconnected Transportation Planning Framework (RHHTPF) coupled with a Multimodal Relay Service Network Design (MRSND) optimization model. RHHTPF enables HTPP to dynamically plan deliveries based on the status of shipping demands and in-transit services. MRSND aids HTPP in optimizing multimodal relay service selection during the delivery process, aimed at minimizing lateness, reducing costs, and cutting emissions. Specifically, our freight focus is on bulky goods, such as machinery, vehicles, and containers. Unlike parcel or packages, these items are often in heavy weights or uniquely shaped and require crating. They are typically transported together, arriving at destinations simultaneously.

We validate our concept and methodology through a case study in the automotive delivery sector within the Southeastern United States. We first assess the efficacy of our HTPP model in optimizing hyperconnected transportation planning using a single modality as diesel trucks. Specifically, we compare the model performances given various shipping preferences, including delivery velocity, timeliness, and sustainability. Furthermore, we explore the potential of integrating rail services and transitioning to electric and hydrogen-powered trucks as steps toward establishing a multimodal relay ecosystem. This ecosystem aims to achieve enhanced efficiency, cost savings, punctuality, and zero-emission targets.

The structure of the paper is outlined as follows: Section 1 introduces the study's background and focus. Section 2 reviews relevant literature and highlights the unique aspects of our research. Section 3 details our proposed rolling-horizon hyperconnected transportation planning framework and coupled optimization model. Section 4 discusses results from a case study in automotive delivery sector across the Southeastern USA. Finally, section 5 concludes the paper by summarizing key contributions and identifying promising avenues for future research.

2 Literature Review

The traditional logistics sector primarily relies on point-to-point and hub-and-spoke transport models, operating over the networks that are often fragmented and dedicated to specific companies or markets. This contrasts sharply with the highly interconnected nature of the Digital Internet. To address the inefficiencies and unsustainability that plague global logistics, a groundbreaking paradigm known as the Physical Internet has been proposed [1]. This innovative paradigm aims to globally interconnect logistics services, mirroring the connectivity of digital networks. The Physical Internet is structured by thirteen interlaced characteristics designed to address thirteen critical symptoms in existing logistics systems, potentially meeting the Logistics Sustainability Grand Challenge [1, 3]. Additionally, a seven-layer Open Logistics Interconnection model has been introduced to seamlessly integrate logistics services within the Physical Internet, ensuring its adaptability across diverse economic, technological, and regional landscapes. [2]

Within the framework of the Physical Internet, the transportation sector is envisaged to transition towards a distributed, multi-segment intermodal transport system through a meshed hub network [1]. This evolution embraces the notion of hyperconnectivity, akin to data transmission in the Digital Internet. This paper elaborates on the concept of hyperconnectivity in transportation by embodying essential strategies such as demand aggregation, freight containerization, an interconnected hub network, and the utilization of multimodal transportation services, along with relay truck drivers. Such strategies have been proven effective in numerous practical scenarios. [4, 5] Our review seeks to reframe these strategies within a unified framework, aiming to spearhead the next generation of transportation solutions.

Extensive research has delved into various decision-making aspects supporting hyperconnected transportation. Studies have explored hub network design [6, 7], hub capacity allocation [8], and the planning and operations of transportation systems [9, 10, 11, 12]. Additionally, similar studies have been conducted focusing on synchro-modal transportation [13, 14], which further emphasizes the importance of synchronized decision-making across different transportation modes to optimize efficiency and responsiveness in logistics networks. Moreover, simulation assessments [15, 16, 17] have been performed to compare the performances of hyperconnected transportation over traditional models like end-to-end and hub-and-spoke systems, thus highlighting the potential improvements in efficiency and sustainability that hyperconnected transportation offers.

Our paper focuses on a practical scenario wherein a hyperconnected transportation platform manages demands from various shippers, accesses an interconnected hub network, and contracts with multiple carriers providing multimodal transportation services, including relay truck drivers. Unlike prior studies that compare hyperconnected and traditional transportation models, our research emphasizes planning and operational strategies within a hyperconnected framework. This includes transitioning from diesel-powered trucks to more sustainable multimodal options like rail, electric, or hydrogen trucks. Our goals align with diverse delivery speeds, cost-efficiency, timeliness, improved working conditions for drivers (enabling daily home returns) and advancing towards a zero-emission target.

3 Methodology

In this section, we discuss the methodology of the Hyperconnected Transportation Planning Platform (HTPP) to plan and manage deliveries within the realm of hyperconnected transportation.

The HTPP interfaces with a strategically placed network of relay hubs near critical logistics points like factories, railheads, ports, and major highway intersections. This setup enhances connectivity and reduces detours. Some inter-hub arcs are exclusively for trucks, while others accommodate both trucks and rail. The design of the hub network ensures that the arc durations with truck mode, including traveling, processing, and mandatory resting periods, do not exceed half of the maximum daily on-duty time for truckers. This strategic design allows truck drivers to complete their daily arcs and then return home within the same day, ensuring compliance with government regulations.

Shipping demands from shippers are processed by the HTPP over time. Each demand originates from an entry hub and must be delivered to an destination hub by a specified deadline. While delivery delays beyond these deadlines are permitted within predefined limits, they incur a penalty calculated in dollars based on the volume of the shipment and the number of hours late.

The HTPP utilizes multimodal relay services between hubs, provided by contracted carriers. Rail services operate with arc-based schedules and transportation costs are charged per railcar mile, with a uniform railcar size assumed. Truck services are provided with path-based schedules and costs are assessed per truck mile for standard-sized trucks. The trucks are powered by diesel, electric, or hydrogen engines, each with specific cost rates per mile and CO_2 emissions per ton-mile of freight. HTPP categorizes all truck drivers as short-haul relay drivers, ensuring they can return home daily.

3.1 Rolling-Horizon Hyperconnected Transportation Planning Framework

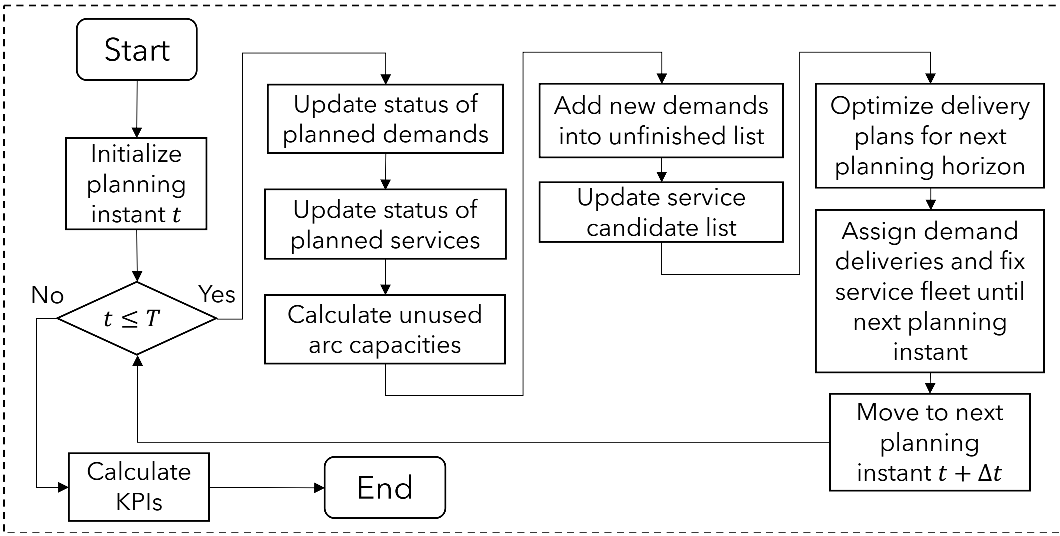

Figure 2: The decision flow chart of RHHTPF

We proposed a Rolling-Horizon Hyperconnected Transportation Planning Framework (RHHTPF) as the cornerstone of tactical decision support for the HTPP. Figure 2 depicts the decision flowchart of the RHHTPF. The HTPP operates over a testing horizon of length T, divided into uniformly distributed time instants. At the start of each planning instant, the delivery status of planned demands and the transit status of planned services are updated. Concurrently, the unused capacities across all inter-hub arcs are recalculated. Subsequently, new demands are received by the HTPP and added to the list of unfinished demands. Based on the current time, we refresh the candidate service list for the upcoming planning horizon, which is offered by multimodal carriers between hubs. At this point, the Multimodal Relay Service Network Design (MRSND) optimization model is employed to optimize delivery plans for the next planning horizon, utilizing the latest demand, service, and unused arc volume information. However, only the delivery plans up to the next planning instant are finalized, and the required service fleet is updated accordingly. The process then advances to the next planning instant, repeating this cycle in a rolling manner until the testing horizon concludes.

3.2 Multimodal Relay Service Network Design

To present the MRSND optimization model, we first define the sets, parameters, and decision variables pertinent to the model formulation.

<u>Sets:</u>

- Set of time instants: $\mathcal{T}$
- Set of shipping demands: $\mathcal{K}$
- Set of hubs: $\mathcal{H}$
- Set of time-expanded nodes (short for nodes): $\mathcal{N} \subseteq \mathcal{H} \times \mathcal{T}$
- Set of time-expanded arcs (short for arcs): $\mathcal{A} \subseteq \mathcal{N} \times \mathcal{N}$, where $\mathcal{A} = \mathcal{A}^m \cup \mathcal{A}^\hbar$ with moving arc set $\mathcal{A}^m$ and holding arc set $\mathcal{A}^\hbar$
- Set of holding arcs at hub h: $\mathcal{A}_h^\hbar, \forall h \in \mathcal{H}$
- Set of modes (including rail and truck-related modes): $\mathcal{M} = \{rail\} \cup \mathcal{M}^{truck}$
- Set of truck-related modes (including diesel, electrical and hybrid trucks): $\mathcal{M}^{truck}$
- Set of moving arcs with mode m: $\mathcal{A}_m^m \subseteq \mathcal{A}^m$, $\forall m \in \mathcal{M}$
- Set of multimodal services: $\mathcal{S}$
- Set of moving arcs of service s: $\mathcal{A}_s^m$, $\forall s \in \mathcal{S}$
- Set of services with mode m: $\mathcal{S}_m \subseteq \mathcal{S}$, $\forall m \in \mathcal{M}$

<u>Decisions</u>

- $X_{kma}^m \in \{0,1\}$: whether shipping demand k is moved over arc a via mode m, $\forall k \in \mathcal{K}, m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- $X_{ka}^\hbar \in \{0,1\}$,: whether shipping demand k is held over arc a, $\forall k \in \mathcal{K}, a \in \mathcal{A}^\hbar$
- $Y_s \in \mathbb{N}^{\geq 0}$: fleet size of relay service s, $\forall s \in \mathcal{S}$
- $L_k \in \mathbb{R}^{\geq 0}$: delivery lateness of shipping demand k, $\forall k \in \mathcal{K}$

<u>Parameters</u>

- h_k^e, h_k^d: entry and destination hubs of demand $k, \forall k \in \mathcal{K}$
- t_k^e, t_k^d, t_k^ℓ: entry, due and latest due time instants of demand $k, \forall k \in \mathcal{K}$
- h_a^+, h_a^-: starting and ending hubs of arc $a, \forall a \in \mathcal{A}$
- t_a^+, t_a^-: starting and ending time instants of arc $a, \forall a \in \mathcal{A}$
- u_{ma}: unused volume capacity of mode m over arc a, $\forall m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- p_k^t: timeliness penalty per unit of lateness of shipping demand k, $\forall k \in \mathcal{K}$
- c_{kma}^m: transportation cost of shipping demand k traversing arc a via mode m, $\forall k \in \mathcal{K}, m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- e_{kma}^m: greenhouse gas emission of shipping demand k traversing arc a via mode m, $\forall k \in \mathcal{K}$, $m \in \mathcal{M}, a \in \mathcal{A}_m^m$
- u_s^{max}: volume capacity of service s, $\forall s \in \mathcal{S}$
- c_s^s: transportation cost of service s per unit of fleet size, $\forall s \in \mathcal{S}$
- e_s^s: greenhouse gas emission of service s per unit of fleet size, $\forall s \in \mathcal{S}$
- p^e: sustainability penalty per greenhouse gas emission

Give the above notions, we then formulate a mixed-integer programming model for the MRSND problem.

$$\min \sum_{k\in\mathcal{K}} p_k^t L_k + \left(\sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{M}} \sum_{a\in\mathcal{A}_m^m} c_{kma}^m X_{kma}^m + \sum_{s\in\mathcal{S}} c_s^s Y_s \right) + p^e \Big(\sum_{k\in\mathcal{K}} \sum_{m\in\mathcal{M}} \sum_{a\in\mathcal{A}_m^m} e_{kma}^m X_{kma}^m + \sum_{s\in\mathcal{S}} e_s^s Y_s \Big)$$

$s.t.$

$$\sum_{m\in\mathcal{M}} \sum_{a\in\sigma^+(n)\cap\mathcal{A}_m^m} X_{kma}^m + \sum_{a\in\sigma^+(n)\cap\mathcal{A}^\hbar} X_{ka}^\hbar - \sum_{m\in\mathcal{M}} \sum_{a\in\sigma^-(n)\cap\mathcal{A}_m^m} X_{kma}^m - \sum_{a\in\sigma^-(n)\cap\mathcal{A}^\hbar} X_{ka}^\hbar = \begin{cases} 1, & if\ n = (h_k^e, t_k^e) \\ -1, & if\ n = \left(h_k^d, t_k^\ell\right) \\ 0, & o.w. \end{cases}, \forall k \in \mathcal{K}, n \in \mathcal{N} \quad (1)$$

$$\sum_{k\in\mathcal{K}} v_k X_{kma}^m \leq \sum_{s\in\mathcal{S}_m : a\in\mathcal{A}_s^m} u_s^{max} Y_s + u_{ma}, \forall m \in \mathcal{M}, a \in \mathcal{A}_m^m \quad (2)$$

$$L_k \geq t_k^{\ell} - t_k^{d} - \sum_{a \in \mathcal{A}^{\hbar}_{h_a^+} : t_k^d \leq t_a^+ < t_k^{\ell}} (t_a^- - t_a^+) X^{\hbar}_{ka}, \forall k \in \mathcal{K} \quad (3)$$

The objective function consists of timeliness penalties of late deliveries, total transportation cost, and sustainability penalties of overall greenhouse gas emission. There are three constraints: Constraint 1 is the flow balance constraints of shipping demands. It also requires the delivery times of all shipping demands not exceeding the latest due times; Constraint 2 ensures the arc volume induced by all shipping demands not exceeding the arc capacity provided by all services in both current and previous planning; Constraint 3 calculates the delivery lateness of shipping demands.

3.3 Results and Discussion

In this section, we perform a case study with setup described in subsection 3.3.1 and then discuss the results in subsection 3.3.2.

3.3.1 Case study Setup

We consider a Hyperconnected Transportation Planning Platform (HTPP) having access to a hyperconnected hub network across the Southeastern United States, encompassing the seven states (i.e., Tennessee, North Carolina, South Carolina, Georgia, Alabama, Mississippi, and Florida). This network consists of 24 hub nodes shown in Figure 3, strategically positioned near key infrastructure such as highway intersections, rail terminals, and port locations to optimize connectivity and minimize detours. Of these hub nodes, 8 are multimodal, accommodating both rail and truck services, while the remaining 16 are exclusively for truck use. A fundamental design criterion for this network is ensuring that the travel time between any two adjacent hubs does not exceed 5.5 hours, which is half the daily driving limit set by traffic regulations. This design criterion allows drivers to visit any adjacent hub from their domicile hubs and return home within the same day.

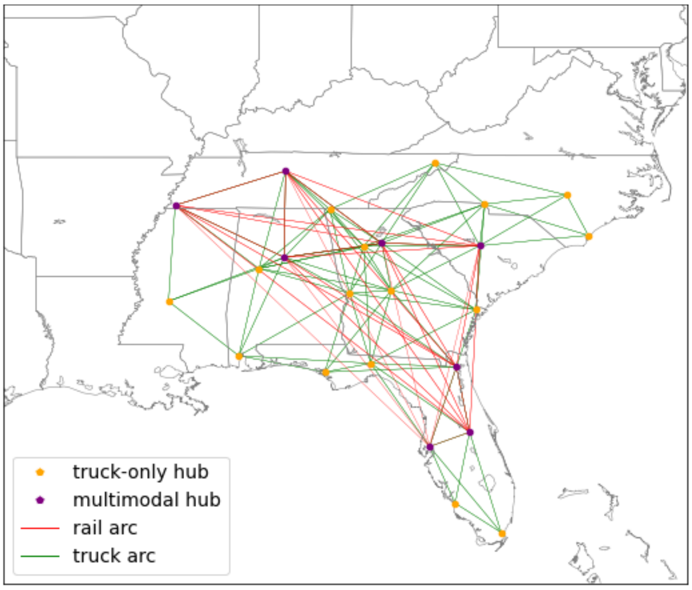

Figure 3: Hyperconnected Hub Network in the Southeastern United States

To model shipping demands for the HTPP, we use data from the Freight Analysis Framework (FAF). Developed jointly by the Bureau of Transportation Statistics (BTS) and the Federal Highway Administration (FHWA), the FAF combines data from various sources to provide a detailed view of freight movements across states and major metropolitan areas via all transport modes. Our specific focus is on the transportation of automotive goods by truck in 2021, which encompasses imports, exports, and domestic movements. The demand generation process is structured into three main steps: Firstly, we convert the weight of freight flows reported by the FAF from tons to an equivalent number of vehicles, using an average weight of 2.165 tons per vehicle. Secondly, we refine the freight flows, originally organized by FAF regions, by estimating the origins and destinations of flows using regional centroids. These flows are then aggregated to designated entry and destination hubs based on their directions and geographical locations. From this analysis, we identified 242 inter-hub pairs with an average daily demand of 23,144 vehicles, as depicted in Figure 4. Lastly, we assume that the HTPP captures a consistent market share of the total daily inter-hub freight demands. Given this market share, we then randomly generate daily demand samples, which become known to the HTPP at the start of each day. By setting this share at 5%, the HTPP manages the shipping demands of approximately 1,157 vehicles daily and 32,396 vehicles in total for a testing horizon of 28 days.

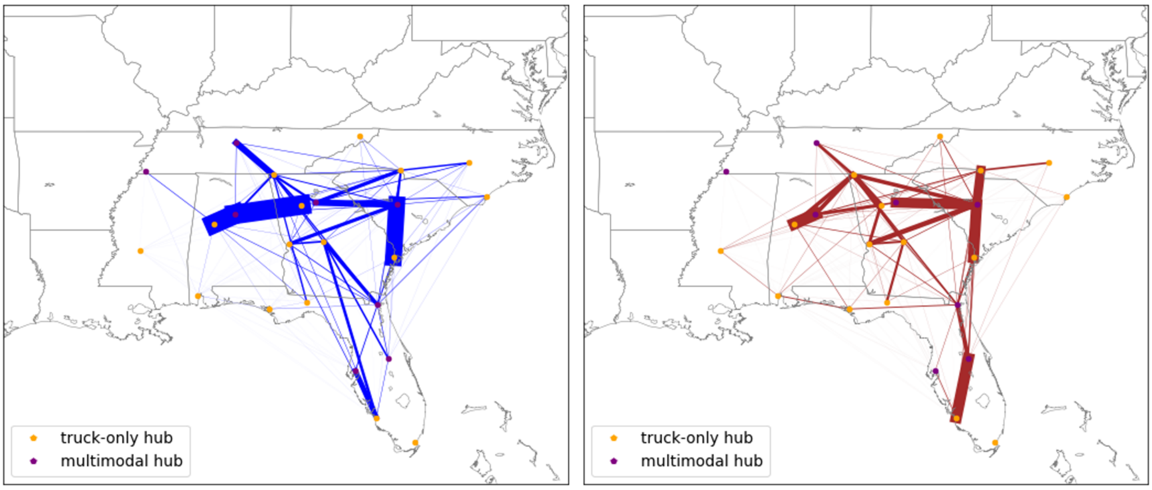

Figure 4: FAF-Data-Based Inter-Hub Shipping Demands Towards the East (Left) vs. West (Right)

To facilitate freight movement across the network, we utilize both rail and truck transportation options to link the hubs. Figure 3 illustrates these connections with 49 rail arcs and 168 truck arcs between the hubs. Rail services operate according to arc-based schedules provided by CSX Corporation. For truck transportation, we arrange for services between two hubs, ensuring that drivers can return to their home hub daily. This involves each driver starting from their domicile hub, traveling to an adjacent hub, and then returning. Potential departures are scheduled for 12 AM, 8 AM, and 4 PM. The maximum allowable waiting time at non-domicile hubs is 2 hours to minimize delays. Additionally, we include a buffer of 1.5 hours per arc to cover both transshipment activities at hubs and any potential traffic congestion. This precaution also ensures that the duration of all truck services does not exceed the 14-hour daily on-duty limit mandated by traffic regulations. Further details of both rail and truck transportation services are outlined in Table 1.

Table 1: Key Parameters in Rail and Truck Transportation Services

Service Mode	Rail Services	Truck Services		
Average Speed (MPH)	50	60		
Fleet Type	Tri-level auto-rack railcars (Capacity: 15 vehicles)	8-car hauler trucks (Capacity: 8 vehicles)		
Fuel Type	Diesel	Diesel	Electricity	Hydrogen
Cost Rate (Per Fleet Unit Per Mile)	\$0.67	\$2.00	\$2.25	\$2.42
CO_2 Emission Rate (Per Ton Mile)	0.021	0.12	0.07	0.06

3.3.2 Experimental results

In this subsection, we share the results of our experiments. All the experiments are based on a testing horizon of 28 days and the optimality gap of the MRSND model is set as 5%.

We begin by evaluating scenarios where only diesel trucks were used, considering different shippers' preferences for delivery velocity (either short or long distances), timeliness, and sustainability across 12 scenarios, as shown in Table 2. Table 3 summarizes statistics of four key performance indicators (KPIs) across these scenarios. On average, each truck driver works for 6.85 hours, which allows them to return home daily while minimizing trips without cargo. Our findings also show that, on average, trucks travel without cargo 9.27% of the time, emit 0.26 kg of CO2, and incur a cost of $2.37 per mile per demand unit. We use these numbers as baseline references for further experiments. Additionally, the small variation in these values (less than 6%) suggests that our results are consistent in this diesel-truck-only setup. Figure 5 displays the average late percentage and delay time per demand unit across different scenarios. We observe that tighter delivery schedules slightly increased delays. Nevertheless, all scenarios had an average lateness less than 0.7% and less than 3 minutes per demand unit, demonstrating the reliability of our proposed method in managing deliveries on time.

Table 2: Scenario designs for diesel-truck-only hyperconnected transportation

Scenario ID	1	2	3	4	5	6	7	8	9	10	11	12
Delivery velocity for short haul demands	1-Day Delivery w/ 1-Day Penalty Period				1-Day Delivery w/ 1-Day Penalty Period				2-Day Delivery w/ 1-Day Penalty Period			
Delivery velocity for long haul demands	1-Day Delivery w/ 1-Day Penalty Period				2-Day Delivery w/ 1-Day Penalty Period				3-Day Delivery w/ 1-Day Penalty Period			
Lateness penalty ($ per demand unit per late hour)	10		40		10		40		10		40	
Emission penalty ($ per demand unit per CO_2 tons)	20	80	20	80	20	80	20	80	20	80	20	80

Table 3: KPI Statistics for Diesel-Truck-Only Hyperconnected Transportation

KPI	**Mean**	**SD**	**SD/Mean**
Average Travel Hours per Truck Driver (hrs)	6.85	0.02	0.3%
Average Empty Travel Percentage per Truck Driver (%)	9.27	0.51	5.5%
Average CO2 Emission per Demand Unit per Mile (kg)	0.26	0.00	0.0%
Average Overall Cost per Demand Unit per Mile ($)	2.37	0.01	0.4%

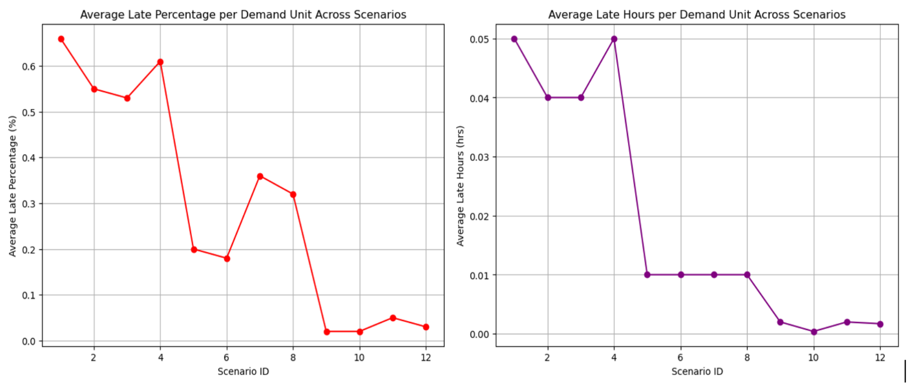

Figure 5: Average Late Percentage (Left) and Late Hours (Right) per Demand Unit across Scenarios

Starting with a diesel-truck-only setting, we then add rail transportation to our study. We compare the diesel-only with the rail and diesel truck combination across key performance indicators (KPIs) such as timeliness, efficiency, sustainability, and cost (summarized in Table 4). We can observe that under the same delivery velocity requirements, switching from diesel-only to a combined rail and diesel truck transportation, lateness percentages rise from 0.36% and 0.05% to 7.11% and 1.73%, respectively. Meanwhile, CO2 emissions decrease from 0.26 kg per mile to 0.19 kg per mile, and overall costs drop from $2.36 and $2.37 to $1.87 and $1.90 per demand unit per mile for long haul and short haul demands, respectively. This shift reflects the advantages of rail in reducing costs and emissions, although the fixed schedules and limited locations of rail transport can lead to increased delays and detours.

Lastly, to achieve a zero-emission logistics ecosystem, we further explore replacing diesel trucks with cleaner truck technologies, such as electric-vehicle (EV) and hydrogen trucks, given the combination with rail transportation. According to Table 5, using rail combined with EV or hydrogen trucks result in an increase in lateness percentages from 7.11% to 10.75% and 14.02% respectively, while CO2 emissions decrease from 0.19 kg to 0.11 kg and 0.09 kg per demand unit per mile. Costs per mile also rise from \$1.87 to \$2.02 and \$2.05 per demand unit. This shift is due to the lower emissions of electric and hydrogen trucks compared to diesel trucks, though they incur higher costs per mile. Our proposed methods allow for some delays in consolidating shipments to reduce CO2 emissions, albeit at a slightly increased cost.

Table 4: Assessing the Impact of Rail Mode

	Mode	**Diesel Trucks**		**Rail + Diesel Trucks**	
	Delivery velocity for short haul demands	1-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period	1-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period
	Delivery velocity for long haul demands	2-Day Delivery w/ 1-Day Penalty Period	3-Day Delivery w/ 1-Day Penalty Period	2-Day Delivery w/ 1-Day Penalty Period	3-Day Delivery w/ 1-Day Penalty Period
Timeliness	Avg late percentage per demand unit (%)	0.36	0.05	7.11	1.73
	Avg Late hours per demand unit	0.01	.002	0.37	0.26
	Avg lateness penalty per demand unit (\$)	0.42	0.08	14.6	10.44
Efficiency	Avg rail transportation hours per short haul demand unit	-	-	1.08	1.07
	Avg truck transportation hours per short haul demand unit	3.71	3.73	2.99	2.98
	Avg rail transportation hours per long haul demand unit	-	-	5.48	5.39
	Avg truck transportation hours per long haul demand unit	9.05	9.54	5.36	6.02
	Avg travel hours per truck driver	6.85	6.87	6.27	6.26
	Avg empty travel percentage per truck driver (%)	9.19	9.49	9.85	10.32
Sustainability	Average CO_2 emission per demand unit per mile (kg)	0.26	0.26	0.19	0.19
	Average emission penalty per demand unit per mile (\$)	0.010	0.010	0.008	0.008
Cost	Average transportation cost per demand unit per mile (\$)	2.34	2.35	1.81	1.86
	Average overall cost per demand unit per mile (\$)	2.36	2.37	1.87	1.90

4 Conclusion

The contributions of this paper are multifaceted. First, it conceptualizes hyperconnectivity in transportation through three types of connectivities and five logistics strategies. Second, it explores a novel business model where a HTPP coordinates with multimodal relay transportation services to meet over-time shipping requirements and multi-dimensional targets. Third, it develops a tactical decision support prototype for the HTPP, with the core as a combination of the RHHTPF and the MRSND optimization model. Lastly, it performs a detailed case study to validate the proposed decision support prototype, as well as demonstrate the potentials of enhancing efficiency and sustainability of regional deliveries through hyperconnected transportation planning, thus advancing a multimodal relay ecosystem. In conclusion, our research calls for a paradigm shift towards hyperconnected transportation for regional overland deliveries. By fostering a sustainable multi-modal relay ecosystem, this transition has the potential to improve delivery timeliness, cost savings, and environmental friendliness, as well as create a more favorable environment for drivers.

Future research directions offer several promising paths. Firstly, developing more efficient algorithms for accelerating the MRSND optimization model, such as a dynamic discretization discovery algorithm, is essential for shifting to larger test cases or higher market shares. Additionally, the current model underestimates CO2 emissions by only considering emissions from freight trucks but omitting those from empty travels. Thus, addressing the underestimation of CO_2 emissions by including those from empty truck travels will refine environmental impact assessments. Additionally, correcting the simplified linear CO2 emissions formula to better match the nonlinear real-life emissions and evaluating the resulting errors is vital. Lastly, testing the robustness of the combined RHHTPF and MRSND model in scenarios with traffic uncertainty, specifically for rail schedules, will help confirm its effectiveness in real-world conditions.

Table 5: Assessing the Impact of Electrification and Hydrogen Transition

	Mode	**Rail + Diesel Trucks**	**Rail + EV Trucks**	**Rail + Hydrogen Trucks**
Timeliness	Average late percentage per demand unit (%)	7.11	10.75	14.02
	Average Late hours per demand unit	0.37	0.60	0.81
	Average lateness penalty per demand unit ($)	14.6	23.9	32.23
Efficiency	Average rail transportation hours per short haul demand unit	1.08	1.22	1.73
	Average truck transportation hours per short haul demand unit	2.99	2.91	2.67
	Average rail transportation hours per long haul demand unit	5.48	6.47	6.77
	Average truck transportation hours per long haul demand unit	5.36	5.06	4.83
	Average travel time per truck driver	6.27	6.22	5.88
	Average empty travel percentage per truck driver (%)	9.85	11.32	11.98
Sustainability	Average CO_2 emission per demand unit per mile (kg)	0.19	0.11	0.09
	Average emission penalty per demand unit per mile ($)	0.008	0.005	0.004
Cost	Average transportation cost per demand unit per mile ($)	1.81	1.94	1.95
	Average overall cost per demand unit per mile ($)	1.87	2.02	2.05

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