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Stochastic Service Network Design with Different Operational Patterns for Hyperconnected Relay Transportation

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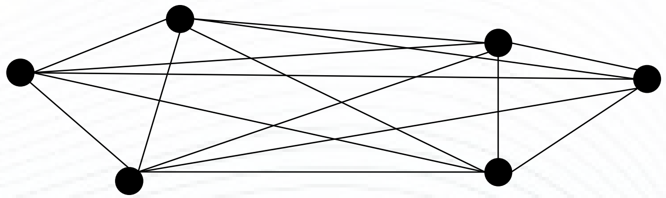
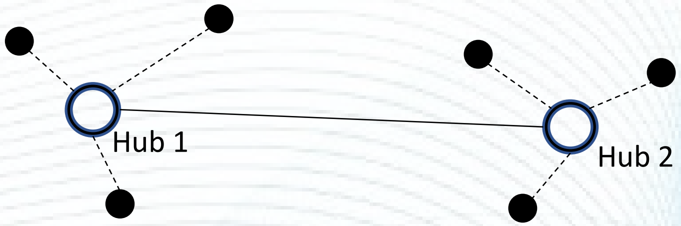
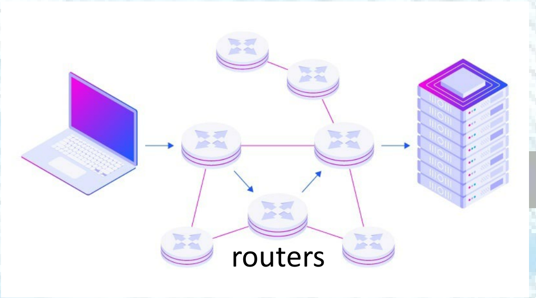
Towards hyperconnected relay transportation



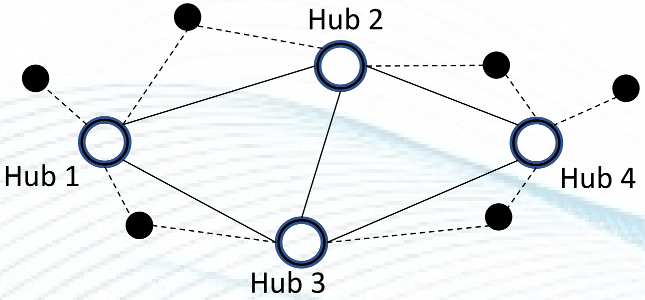
Point-to-point (end-to-end) transport



Hub-and-spoke transport



Network routing
(https://www.ipxo.com/blog/network-routing/)

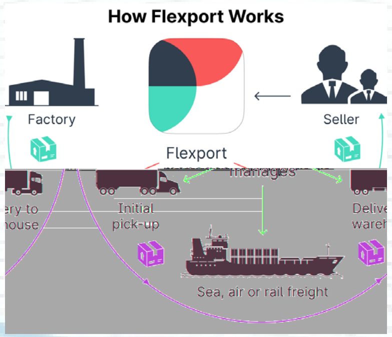


Hyperconnected relay transport

Inspired by Physical Internet [1], hyperconnected relay transport enables more consolidation opportunities, flexible delivery options, higher transportation efficiency and truckers' daily returning home, etc.

Logistics platform for implementing hyperconnected relay transport

- An increasing number of logistics platforms streamline market access, simplify load matching, enhance shipment visibility , and increase delivery efficiency.

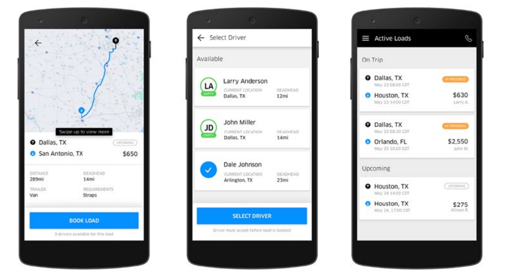


Flexport enables booking, tracking and delivering freight shipments from factory floor to customer door

(https://dizraptor.app/offerings/52/)

Amazon Relay makes short-term contracts with carriers and allows drivers to access loads at no cost and to get back home

https://relay.amazon.com



Uber Freight connects shippers to massive competitive carriers in the open market

https://www.freightwaves.com/news/technology/uber-freight-launches-fleet-mode-tool-that-caters-to-small-fleet-owners

- This paper explores the application of a logistics platform (called hyperconnected logistics platform) to facilitate the implementation of hyperconnected relay transport.

Towards truck-based hyperconnected service network

Vale propositions to three stakeholders of hyperconnected logistics platform

- *Shippers* To express transportation needs for the foreseeable future
- *Carriers* Too secure contracts, revenues, and shipments for their truckers
- *Drivers* To return home consistently and gain visibility of upcoming tasks

This paper proposes a methodology for optimizing the platform's tactical decisions of designing hyperconnected service network to persistently achieving its goals and value propositions.

Literature review – hyperconnected relay transport

Concept research	Assessment research	Solution design research
Physical Internet and Hyperconnectivity	Economic, environmental, and societal performances through simulation-based experiments	Key planning and operational decisions induced by the concept of the Physical Internet
• Montreuil, 2011 • Montreuil et al., 2018	• Hakimi et al., 2012 • Sarraj et al., 2014 • Hakimi et al., 2015	• Qiao et al., 2016 • Orenstein et al., 2022 • Li et al., 2022

In this paper, we consider how to plan logistics services and make contracts with carriers given demand uncertainty, within the novel business context of a hyperconnected logistics platform

- Hub operational patterns, schedule consistency, hauling capacities, as well as their impacts on the hyperconnected service network design

Literature review – service network design problem

- Service network design problem (SNDP) involves planning routing and scheduling of services and shipments through a network of terminals
  - Many researchers have approached the modeling of the SNDP by utilizing the time-space network formulation and incorporating customized rules for various settings (Scherr et al., 2019; Medina et al., 2019)
- Stochastic service network design problem (SSNDP)
  - Two common sources: demands (Bai et al., 2014; Wang et al., 2016) and traffic time (Lanza et al. 2021)
- In this paper, we focus on demand uncertainty in developing consistent approximate schedules, referred to as services, for contracted short-haul truckers.
  - Modelling as an "Inherently two-stage problem" (King and Wallace, 2012), which simplifies the multi-stage nature of the real problem
  - Listing refining approximate schedules as one of future works. Such idea of approximation-then-refining is inspired by Bolan et al., 2017.

Relay hub network, planning horizon, and commodities

- The logistics platform manages the logistics service over a provided relay hub network, $\mathcal{G}^P = (\mathcal{N}^P, \mathcal{A}^P)$, where
  - $\mathcal{N}^P$ represents hub nodes
  - $\mathcal{A}^P$ represents connected arcs between hub nodes

- A planning horizon is considered and discretized into $T + 1$ evenly distributed time instants, denoted as $\mathcal{T} = \{0,1, \ldots, T\}$

- The platform receives the transportation requests for multiple commodities. Each commodity $k \in \mathcal{K}$ has an origin hub o_k, a destination hub d_k, an entry time t_k^e, a due time t_k^d and volume v_k.
  - All commodities are expected to be delivered on time
  - The platform can either ship each commodity by itself or outsource it to third-party logistics carriers.

Time-space network and services

- The model formulation is based on a time-space network $\mathcal{G} =$

Three different operational patterns

		Freight loading and unloading		Hauler swapping
		Multiple commodity paths (FLU-MCP)	*Single commodity path (FLU-SCP)*	*(HS)*
Operational requirements		Drivers stay with trucks (tractors/haulers) Commodities can be split into multiple paths for delivery	Drivers stay with trucks (tractors/haulers) Commodities are delivered through a unique path	Haulers can separate from truckers (drivers/tractors) Commodities stay with haulers from origin to destination
Decision variables	*First stage*	$X_s \in \mathbb{Z}^+$: number of drivers contracted to service $s, \forall s \in \mathcal{S}$	$X_s \in \mathbb{Z}^+$: number of drivers contracted to service $s, \forall s \in \mathcal{S}$	$X_s \in \mathbb{Z}^+$: number of truckers (drivers/tractors) contracted to service $s, \forall s \in \mathcal{S}$
	Second stage	$Y_{su}(w) \in \mathbb{Z}^+$: number of trucks with size u rent for service s in scenario $w, \forall s \in \mathcal{S}, u \in \mathcal{U}, w \in \mathcal{W}$	$Y_{su}(w) \in \mathbb{Z}^+$: number of trucks with size u rent for service s in scenario $w, \forall s \in \mathcal{S}, u \in \mathcal{U}, w \in \mathcal{W}$	$Y_{ku}(w) \in \mathbb{Z}^+$: number of haulers with size u rent for commodity k in scenario $w, \forall k \in \mathcal{K}, u \in \mathcal{U}, w \in \mathcal{W}$
		$F_{ka}(w) \in \mathbb{Z}^+$: volume of commodity k traversing arc a in scenario $w, \forall k \in \mathcal{K}, a \in \mathcal{A}, w \in \mathcal{W}$	$F_{ka}(w) \in \mathbb{Z}^+$: volume of commodity k traversing arc a in scenario $w, \forall k \in \mathcal{K}, a \in \mathcal{A}, w \in \mathcal{W}$	$F_{ka}(w) \in \mathbb{Z}^+$: number of haulers holding commodity k traversing arc a in scenario $w, \forall k \in \mathcal{K}, a \in \mathcal{A}, w \in \mathcal{W}$

Two-Stage Programming Formulation for FLU-MCP

- **Objective function**

$$\min \underbrace{\sum_{s\in\mathcal{S}} c_s^f X_s}_{\text{Total driver contract fees}} + E_{w\in\mathcal{W}}[\underbrace{\sum_{s\in\mathcal{S},u\in\mathcal{U}} c_{su}^v Y_{su}(w)}_{\text{Total truck rental cost in scenario w}} + \underbrace{\sum_{k\in\mathcal{K}} c_k^o Z_k(w)}_{\text{Total commodity outsourcing cost in scenario w}}]$$

- **Constraints**
  - *To guarantee contracted drivers not exceeding service capacity:*

$$X_s \le q_s, \qquad \forall s \in \mathcal{S}$$

  - *To rent trucks for drivers in each scenario:*

$$\sum_{u\in\mathcal{U}} Y_{su}(w) \le X_s, \qquad \forall s \in \mathcal{S}, w \in \mathcal{W}$$

  - *To satisfy truck volume capacity in each scenario:*

$$\sum_{s\in\mathcal{S}_a,u\in\mathcal{U}} uY_{su}(w) \ge \sum_{k\in\mathcal{K}} F_{ka}(w), \qquad \forall a \in \mathcal{A}^M, w \in \mathcal{W}$$

  - *To ensure freight flow balance and delivery timelines in each scenario:*

$$\sum_{a\in\delta^-(n)} F_{ka}(w) - \sum_{a\in\delta^+(n)} F_{ka}(w) = \begin{cases} v_k(w)(Z_k(w)-1), & if\ n = (o_k, t_k^e) \\ v_k(w)(1-Z_k(w)), & if\ n = (o_k, t_k^e), \\ 0, & o.w. \end{cases} \qquad \forall k \in \mathcal{K}, a \in \mathcal{A}$$

  - *To define variable domains:*

$$X_s, Y_{su}(w) \in \mathbb{Z}^+, F_{ka}(w) \in \mathbb{R}^+, \qquad \forall s \in \mathcal{S}, u \in \mathcal{U}, k \in \mathcal{K}, a \in \mathcal{A}$$

Two-Stage Programming Formulation for FLU-SCP

- **Objective function**

$$\min \underbrace{\sum_{s\in\mathcal{S}} c_s^f X_s}_{\text{Total driver contract fees}} + E_{w\in\mathcal{W}}[\underbrace{\sum_{s\in\mathcal{S},u\in\mathcal{U}} c_{su}^v Y_{su}(w)}_{\text{Total truck rental cost in scenario w}} + \underbrace{\sum_{k\in\mathcal{K}} c_k^o Z_k(w)}_{\text{Total commodity outsourcing cost in scenario w}}]$$

- **Constraints**
  - *To guarantee contracted drivers not exceeding service capacity:*

$$X_s \le q_s, \quad \forall s\in\mathcal{S}$$

  - *To rent trucks for drivers in each scenario:*

$$\sum_{u\in\mathcal{U}} Y_{su}(w) \le X_s, \quad \forall s\in\mathcal{S}, w\in\mathcal{W}$$

  - *To satisfy truck volume capacity in each scenario:*

$$\sum_{s\in\mathcal{S}_a,u\in\mathcal{U}} uY_{su}(w) \ge \sum_{k\in\mathcal{K}} v_k(w)F_{ka}(w), \quad \forall a\in\mathcal{A}^M, w\in\mathcal{W}$$

  - *To ensure freight flow balance and delivery timelines in each scenario:*

$$\sum_{a\in\delta^-(n)} F_{ka}(w) - \sum_{a\in\delta^+(n)} F_{ka}(w) = \begin{cases} Z_k(w)-1, & if\ n=(o_k,t_k^e) \\ 1-Z_k(w), & if\ n=(o_k,t_k^e), \\ 0, & o.w. \end{cases} \quad \forall k\in\mathcal{K}, a\in\mathcal{A}$$

  - *To define variable domains:*

$$X_s, Y_{su}(w)\in\mathbb{Z}^+, F_{ka}(w)\in\mathbb{R}^+, \quad \forall s\in\mathcal{S}, u\in\mathcal{U}, k\in\mathcal{K}, a\in\mathcal{A}$$

Two-Stage Programming Formulation for HS

- **Objective function**

$$\min \sum_{s\in\mathcal{S}} c_s^f X_s + E_{w\in\mathcal{W}}\Big[\sum_{s\in\mathcal{S},u\in\mathcal{U}} c_{su}^v Y_{su}(w) + \sum_{k\in\mathcal{K}} c_k^o Z_k(w)\Big]$$

Total trucker contract fees | Total hauler rental cost in scenario w | Total commodity outsourcing cost in scenario w

- **Constraints**
  - *To guarantee contracted truckers not exceeding service capacity:*

$$X_s \le q_s, \qquad \forall s\in\mathcal{S}$$

  - *To rent haulers for holding commodities in each scenario:*

$$\sum_{u\in\mathcal{U}} uY_{ku}(w) \ge v_k(1 - Z_k(w)), \qquad \forall s\in\mathcal{S}, w\in\mathcal{W}$$

  - *To have enough truckers for carrying haulers in each scenario:*

$$\sum_{s\in\mathcal{S}_a} X_s \ge \sum_{k\in\mathcal{K}} F_{ka}(w), \qquad \forall a\in\mathcal{A}^M, w\in\mathcal{W}$$

  - *To ensure hauler flow balance and delivery timelines in each scenario:*

$$\sum_{a\in\delta^-(n)} F_{ka}(w) - \sum_{a\in\delta^+(n)} F_{ka}(w) = \begin{cases} -\sum_{u\in\mathcal{U}} Y_{ku}(w), & if\ n = (o_k, t_k^e) \\ \sum_{u\in\mathcal{U}} Y_{ku}(w), & if\ n = (o_k, t_k^e), \\ 0, & o.w. \end{cases} \qquad \forall k\in\mathcal{K}, a\in\mathcal{A}$$

  - *To define variable domains:*

$$X_s, Y_{su}(w) \in \mathbb{Z}^+, F_{ka}(w) \in \mathbb{R}^+, \qquad \forall s\in\mathcal{S}, u\in\mathcal{U}, k\in\mathcal{K}, a\in\mathcal{A}$$

Model variants with different consistency requirements

- Assume the planning horizon $\mathcal{T}$ includes C cycles and each cycle has L^c time instants, where c-th cycle $\mathcal{T}_c = \{c * L^C, \dots, c * L^C + (L^C - 1)\}$. The platform may want to have consistent services across cycles.

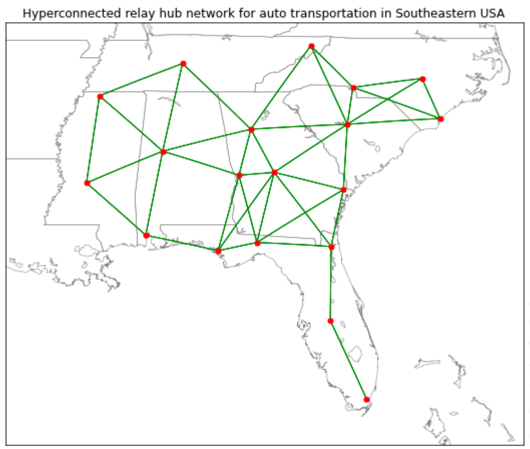
- Strong version of consistency constraint:

  $X_s = X_{s'}$, if service s and service s' have the identical route path and cycle time but just in different cycles

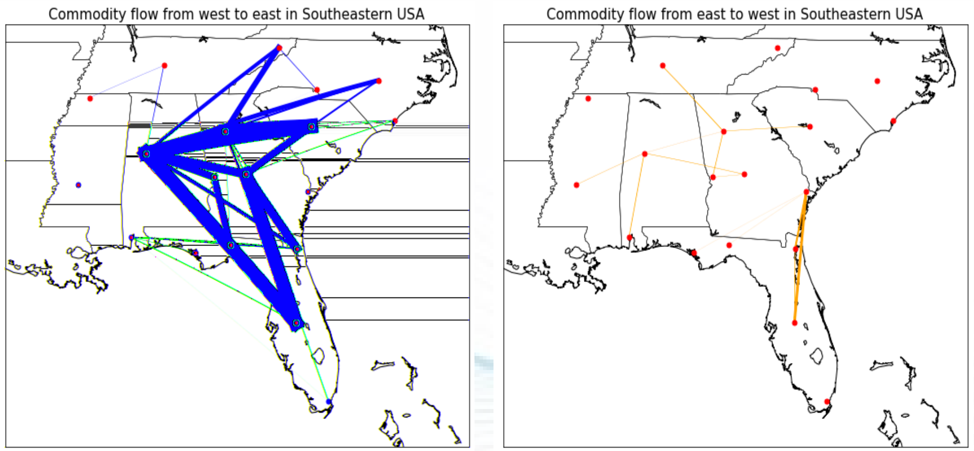
- Soft version of consistency constraint:

  Add penalty of schedule inconsistency, measured by sum of service contract numbers across cycles, into objective function

Experiment setups



Hyperconnected relay hub network



Commodity flows from west to east (left) vs. from east to west (right)

Hourly driver contract fee ($)	29	Hourly size-8 hauler rental fee ($)	10
Hourly tractor rental fee ($)	18	Hourly size-4 hauler rental fee ($)	5
Outsourcing cost per vehicle per mile ($)	0.93	Average mile per hour	50
Contracted trucker capacity per service	10	Consistency cost discount factor	0.8

Key experimental parameters

Experiment setups

- Planning horizon: one week
  - Time discretization unit: six hours
- Services: all potential short-haul services adhering to USA federal hour-of-service regulations
  - Maximal driving time duration as 11 hours
  - Maximal on-duty time duration as 14 hours
- Experimental designs:
  - Deterministic design in stochastic demands vs. stochastic design in stochastic demands
  - Stochastic model with three different operational patterns FLU – MCP, FLU – SCP, and HS respectively
  - Stochastic model with different consistency requirements and hauling capacities

Experimental results: deterministic design vs. stochastic design

KPIs \ Model	Deterministic design	Stochastic design
Total contracted hours of drivers (hrs)	9,408	12,444
Average rental hours of tractors (hrs)	8,023	9,285
Average rental hours of haulers (hrs)	8,023	9,285
Average outsourcing rate of commodities	10.3%	0%
Total expected transportation cost ($)	556,494	422,985

- The Value of Stochastic Solution (VSS) = 556,464 – 422,985 = 133,509 in dollars, which means stochastic design can save about 24% of the total expected transportation cost

Experimental results: three different operational patterns

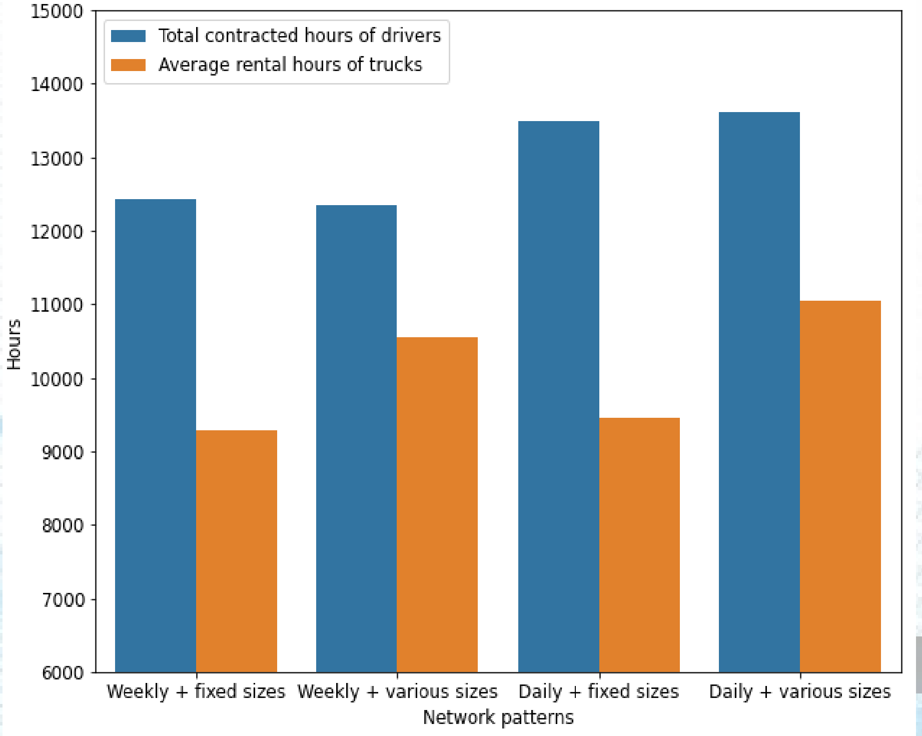
KPIs \ Operational patterns	FLU-MCP	FLU-SCP	HS
Total contracted hours of drivers (hrs)	12,444	12,864	12,528
Average rental hours of tractors (hrs)	9,285	9,312	12,528
Average rental hours of haulers (hrs)	9,285	9,312	955.2
Average outsourcing rate of commodities	0%	0%	1.3%
Total expected transportation cost ($)	422,985	431,880	492,742

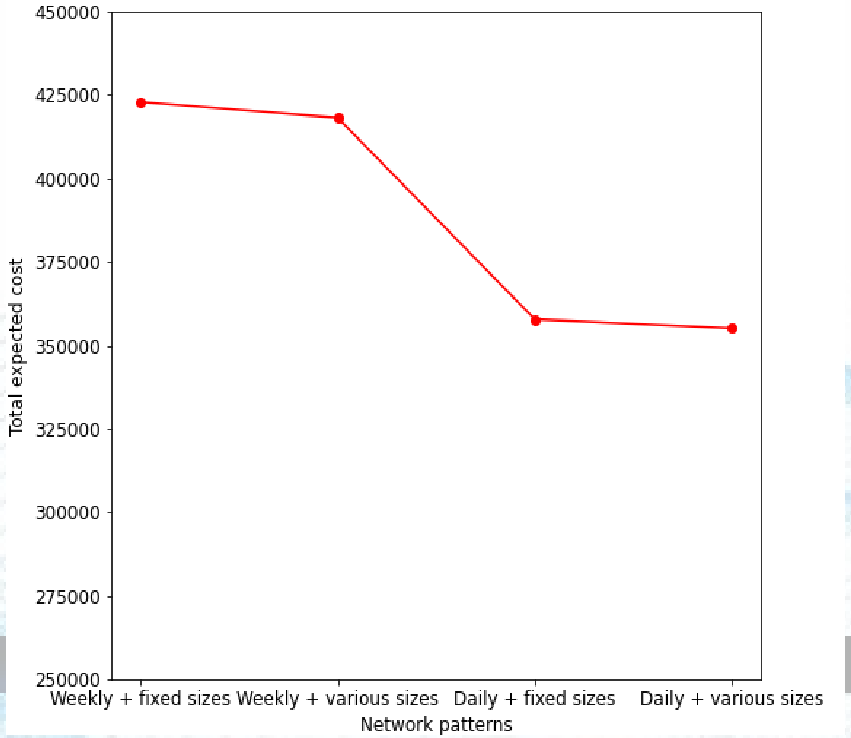
- FLU-MCP achieves better consolidation through crossdocking than FLU-SCP
- HS offers enhanced freight protection and saves operational efforts by maintaining the goods inside the haulers at a higher total expected transportation cost

Experimental results: consistency requirements and hauling capacities

Consistent patterns	Weekly		Daily	
KPIs \ Hauling capacity	Fixed	Various	Fixed	Various
Total contracted hours of drivers (hrs)	12,444	12,348	13,500	13,620
Average rental hours of tractors (hrs)	9,286	10,562	9,456	11,045
Average rental hours of haulers (hrs)	9,286	10,562	9,456	110,45
Average outsourcing rate of commodities	0%	0%	0%	0%
Total expected transportation cost ($)	422,985	418,253	357,840	355,152

Experimental results: consistent requirements and hauling capacities





- Compared with consistent requirements, various hauling capacities have more impact on contracted hours of drivers and rental hours of tractor-hauler pairs, yet less on savings of total expected transportation cost

Contributions

- Applying hyperconnected relay transportation as a sustainable solution to truck driver shortage issues through a logistics platform as a novel business context

- Providing a two-stage stochastic model for hyperconnected service network design of the platform.

- Exploring the impacts of demand uncertainty, operational patterns, consistent schedules, and various hauling capacities on the service network design through an automotive delivery test case in Southeastern USA

Future works

- To develop more advanced computation methods such as bender decomposition or sample average approximation for larger scale instances
- To perform sensitivity analysis upon experimental parameters such as delivery time window and maximal driving time window
- To model more route patterns for both short-haul and long-haul, contracted services tailored to trucker preferences, and on-market carrier capacity
- To refine the approximate service schedules accounting for traffic time stochasticity

References

Q&A

Thank you!