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Quantitative Evaluation of Truck Caravanning

Final Report

by

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DISCLAIMER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 EXCUTIVE SUMMARY

Truck caravanning is closely related to the truck platooning concept but is defined as a convoy of trucks with the first driven by a human driver, while the following trucks operate as SAE Level 5 autonomous vehicles. The primary contribution of this project is to quantify the benefits of caravanning coordination. At this direction, we propose two caravan scheduling problems. The initial mathematical model considers a restrictive case of truck caravanning, where all trucks must form caravans to reach the destination. Additionally, a hybrid truck caravan scheduling problem is developed, where a truck is given the option to not participate in a caravan and follow the traditional shortest origin-destination path. The purpose of the hybrid model is to reap the maximum benefit from this scheduling, reducing the inevitable wasting time at caravan coupling points. Both programs are linear mixed integer and are solved exact with GAMS/CPLEX with optimality gap less than 1%. The cost benefit of truck caravanning models derives through the comparison with a traditional shortest path origin-destination model.

Multiple network instances are used to evaluate the proposed models and results indicate that cost savings could reach up to 50% when compared to the single truck scheduling, and that the optimal caravan size (if one takes under consideration traffic flow, safety, and the complexity of forming and operating higher capacity caravans) is equal to five. The results indicate also that the caravans that are formed, irrespective of the network, will utilize the full caravan capacity, set by the decision maker. Finally, the sensitivity analysis between important parameters provides a robust insight of concept's profitability.

2 INTRODUCTION

The freight transportation system in the United States is one of the foundation stones of economic prosperity and relies heavily on efficient transport by road. Truck remains the leading mode of freight transportation and it is estimated that their share among all other modes will growth further in the future (U.S. Department of Transportation, 2022) fueled by the significant shift to e-commerce along with the long-term economic growth. The latest version of the Freight Analysis Framework (Freight Analysis Framework, 2022) projects that, by 2045, truck traffic in the US will increase 30% by tonnage and 60% by value and account for 65% of total freight movements (both by tonnage and value). In 2020 trucks handled 72.5% of the nation's total domestic tonnage which accounted for 80.4% of the nation's freight bill (American Trucking Associations, 2021b). Simultaneously this growth must comply with the environmental regulations. Transportation, in the US, accounted for the largest portion (29%) of total greenhouse gas emissions in 2017 with light, medium, and heavy-duty trucks contributing 82% of this portion (United States Environmental Protection Agency, 2019).

The trucking industry must tackle not only the rapid increase in freight demand, but also the truck driver shortage and insufficient truck parking supply. In 2021, it is estimated that the difference between the optimal number of truck drivers based on freight demand and the current number of active drivers in the market is 81,000 (American Trucking Associations, 2021a). For many, the truck driver shortage issue may push the trucking industry to the "*edge of the cliff*" which will "*exacerbate the supply chains ability to meet demand*" (Witkowski, 2022; Woods, 2022).

The development of intelligent transportation systems that integrate information and communication-based technologies, provide sustainable solutions to these increasing truck transportation challenges (Chan-Edmiston *et al.*, 2020). The main goal of technology is the overall enhancement of the transportation system to meet the economic growth demand and comply with environmental needs. The United States Department of Transportation acknowledges that connected automated driving systems will transform how the nation's highways will operate in the future (Asare, Chang and Staples, 2020). Truck platooning constitutes one application of technology towards that goal and is considered by researchers and practitioners (Fleet Owner, 2017; Bishop, 2020; Volvo, 2021) as an approach that can reduce fuel consumption while simultaneously increase safety and driver retention (among other benefits like traffic flow stability). A platoon of trucks is defined as a convoy of truck traveling in the same direction within sufficient proximity to reduce aerodynamic drag. Through vehicle-to-vehicle (V2V) communication as well as vehicle-to-infrastructure (V2I) communication, the leading truck is responsible for platoon navigation (i.e., steering, brake acceleration, and deceleration). Truck caravanning is closely related to the truck platooning concept but is defined as a convoy of trucks with the first driven by a human driver, while the following trucks operate as SAE Level 5 autonomous vehicles. Based on the rapid advancement of autonomous vehicle technology, the development of truck caravanning (aka hybrid driverless platoons where typically only the lead truck has a driver) might be a reality soon where cost savings from driver compensation are easily verifiable and quantifiable. Both truck platooning and, the proposed ***Truck Caravanning Network Problem (TCNP)*** constitutes a first step towards automated freight transportation (Bhoopalam, Agatz and Zuidwijk, 2018) which may have significant monetary savings, deriving largely from reductions in truck driver compensation costs.

The research proposed herein is motivated by the research outcomes of Marzano et al., (2022) and Engholm et al., (2021). Both research, case studies in Italy and Sweden respectively, evaluated the impact of truck platooning on the multimodal freight transport market and analyzed the potential impact of driverless truck adoption. They concluded that "*it would be appropriate to consider truck platooning as a new freight transport mode"*. More importantly, Engholm et al., (2021) concluded that the annual logistic cost in the case of the only hub-to-hub driverless trucks decreased $1.2 billion. The last Global Data forecast shows, that the expected annual production of level 5 autonomous vehicles will account nearly 8,000 units at the end of 2025 (GlobalData, 2020). However, the realistic implementation of any kind of autonomous vehicle technology on the road is not only a matter of technological feasibility (Ghosal *et al.*, 2021) but also public acceptance (Talebian and Mishra, 2022), legislation (Scribner, 2019) and reliability under extreme weather conditions (Xiaoxiang, Zhimin and Feng, 2022). The scope of this research is the development of a mathematical model that allows for the quantitative evaluation of the *TCNP* concept and quantification of (any) monetary savings under the assumption that technology advancement and new/updated infrastructure (e.g., truck dedicated corridors) will allow implementation.

The *TCNP* presented in this research, is based on the idea that trucks depart from several origins, couple in platoons at predetermined locations, travel in convoys to predetermined decoupling stations, and from there traverse individually to their destinations. Note, that the models proposed herein will choose which (de)coupling locations will be utilized (i.e., it works in an indirect way as a location-allocation model). Two different mathematical models are proposed to investigate the dynamic nature of *TCNP*. The first one is the Simple Truck Caravanning Model (*STCM*)

The second model is the Hybrid Truck Caravanning Model (*HTCM*), which extends the basic model *STCM* by: i) allowing variable numbers of trucks to form a platoon with a preset upper bound, ii) offering trucks the options of never joining a platoon and driving directly from the origin to the destination through a shortest path, and iii) considering one- and two-drivers per platoon and thus, increasing truck platooning travel time while meeting Hours of Service (HOS) regulations.

The goal of this research is not to advocate or validate the technical feasibility of *TCNP* but rather propose a model that can estimate cost savings if such a concept is technically feasible and define the optimal number of trucks per platoon. Based on a report published in 2019 (Scribner, 2019), twenty US jurisdictions permit commercial automated vehicles to be formed in convoys (i.e., platoons). The model presented herein can provide decision makers with additional information on cost savings when setting upper bounds for truck platoon sizes (from now on referred to as hybrid platoon capacity or platoon capacity) in their states.

In this research, and unlike research published for truck platooning to date, cost savings considered are easily verifiable as they only consider driver compensation savings (i.e., a reduction of drivers needed for the platoons). In this research we do not consider fuel savings or emissions reduction at they depend on several factors (i.e., spacing, vehicle speed, vehicle position, and vehicle mass) and accounting for all these factors results in reduced reliability of any research findings as they are difficult to accurately quantify and model. As revealed by an extensive literature review by Zhang et al. (2020) fuel consumption savings remains a controversial issue and ranges from 3% to 21% (Bonnet and Fritz, 2000; Lammert *et al.*, 2014; California Department of Transportation, 2017; Lammert, Kelly and Yanowitz, 2018). Possible cost savings from fuel and/or emissions reduction could be incorporated into the proposed model if reliable data/linear models become available. Note, that we also do not consider cost savings from the reduction of vehicle insurance that might stem from the safer operations of a platoon and the automation deployed (Greenblatt and Shaheen, 2015).

The remainder of the research is structured as follows: Section 3 provides an overview of the related literature followed by section 4 in which the mathematical formulations of the *STCM* and *HTCM* are presented and defined in detail. Section 5 and 6 presents results from numerical experiments and section 7 concludes the research and proposes future research directions.

3 LITERATURE REVIEW

In this section, we will review research dedicated to truck platooning coordination. The fundamental classification of operational research studies for truck platooning coordination is based on the availability of trip announcements (Bhoopalam, Agatz and Zuidwijk, 2018) and is divided into three different categories: **(i) scheduled platoon planning**, where a centralized authority knows in advance the departure time of trucks, **(ii) real-time platooning**, where all the trip information is announced just before or during the trip, and **(iii) opportunistic (i.e., spontaneous or on-the-fly) planning** where trucks in the vicinity of a locality act opportunistically to reap the benefits from existing traveling convoys. Most research published to date has focused on the first two platooning categories. Next, we present a brief discussion of the published literature in each one of the three categories.

3.1 SCHEDULED PLATOON PLANNING

Larsson et al.(Larsson, Sennton and Larson, 2015), proved that scheduled truck platooning routing problem without deadlines at the destination points and with similar starting points in a planar network graph is NP-hard. An integer linear formulation was proposed that resulted in a maximum of 9% in fuel savings for the instance of a system of 200 trucks. This work was extended by Larson et al. (Larson, Munson and Sokolov, 2016) who proposed a mixed-integer problem that produced optimal solution for routing and platoon scheduling with up to 25 trucks. Fuel savings up to 8% were obtained when trucks were willing to wait at coupling points. Larson et al. (Larson *et al.*, 2013; Larson, Liang and Johansson, 2015) proposed a formulation where a local controller, based on a road network junction, determines whether fuel costs from speed adjustments of trucks to merge in a platoon was profitable when compared to the conventional individual truck routing. Results from simulation-based analysis showed fuel reductions close to 9% with problem instances of more than 7,000 trucks. Larsen et al.(Larsen, Rich and Rasmussen, 2019) studied a hub-based platooning schedule with fixed hub locations and truck routes. Results showed that total profits fluctuated between 4% and 5% for instances up to 500 trucks, when the ability of drivers to rest when they participate in platoons, fuel reduction, and waiting costs are the objectives. Adler et al. (Adler, Miculescu and Karaman, 2020) formulated the platooning schedule problem between two fixed hubs. The main purpose of their model was the evaluation of the energy-delay tradeoffs between idle time and energy savings in platooning policy. They concluded that efficient platoon sizes vary between five and seven trucks, but the consideration of only one origination point and one destination point limits the generalization of their results to real world applications.
Boysen et al. (Boysen, Briskorn and Schwerdfeger, 2018) considered an identical-path truck platooning problem to evaluate the impacts of a) platooning technology dissemination, b) maximum number of trucks in every platoon, and c) willingness of trucks to wait to merge in platoons. Results showed that 91% of total cost savings (i.e., energy and reduced wage savings) were derived from unmanned follower trucks and that platoons with more than six trucks are not cost beneficial due to high truck waiting times to form the platoon. This was the first published study to quantify cost savings from truck drivers' compensation and proved that it could be substantial enough to justify investment costs. Nourmohammadzadeh and Hartmann

(Nourmohammadzadeh and Hartmann, 2016), proposed a genetic algorithm based heuristics to solve the platoon scheduling problem. Results showed a 5% fuel reduction for instances of fifty trucks. An extension of this work was presented by the same authors (Nourmohammadzadeh and Hartmann, 2019) with the implementation of a meta-heuristic algorithm, inspired by an ant colony optimization (ACO). The proposed meta-heuristic could handle problem instances of up to 500 trucks with fuel savings around 7%. Meisen and Seidl (Meisen and Seidl, 2013) proposed an algorithm to detect beneficial platooning throughout a database of routes. They used random departure times from zip codes that showed an exponential increase of platoon formation as the number of routes increased, with a maximum of 5000 routes. A game theoretic framework based on the Nash equilibrium was proposed by Farokhi and Johansson (Farokhi and Johansson, 2013) to explore the trade-off between road traffic congestion and truck platooning incentives. They introduced an atomic congestion game with two types of agents. The first agent type consists of trucks and cars without platooning equipment, and the second of trucks motivated to participate in platooning to decrease fuel consumption. A joint strategy fictitious play to derive a pure strategy Nash equilibrium game was applied. A linear relationship between the velocity of commuting and the number of trucks which travel on the road at the same time was observed. Lue and Larson (Luo and Larson, 2020) proposed a repeated route-then-schedule heuristic method to deal with the complexity of truck platoon scheduling. The results indicated fuel reductions of 4.5% for problem instance with 150 trucks. Abdolmaleki et al. (Abdolmaleki *et al.*, 2019) formulated the itinerary truck platoon planning as a network flow problem with time discretization. Fuel consumption savings fluctuated between 2% and 8% depending on the number of trucks.

Sun et al. (Sun *et al.*, 2021) provide a robust insight of energy saving potential of truck platooning, utilizing real truck demand data for 363,570 trucks over a simplified U.S. highway freight network. They formulated the itinerary planning problem to minimize the total energy consumption. The results of the approximation algorithm indicate gas consumption savings between 5% and 8% depending mainly on platoon size and scheduling flexibility.

3.2 REAL-TIME PLATOONING

Hoef et al. (Hoef, Johansson and Dimarogonas, 2015) proposed a pairwise catch-up platooning formulation (i.e., acceleration of following truck to merge into platoon). The leading truck of each platoon was selected by a clustering method based on pairwise fuel-optimal speed profiles. After the leaders have been selected, all pairs were composed into an overall coordination. Alternatively, to catch-up (i.e., acceleration of following trucks), the leading trucks can decelerate to allow merging with following trucks. In either case, the existence of extra cost is inevitable, as there exists increase of fuel consumption during acceleration and penalties for late arrival during deceleration. Fuel reductions between 6% and 8% were estimated. To avoid the use of a central authority decision maker, Saeednia et. al. (Saeednia and Menendez, 2017) proposed a consensus-based algorithm for real-time platooning. In every iteration of the algorithm, trucks try to reach a consensus on the common characteristic of speed, which allows all the members to participate in beneficial platoons. Trucks with intervehicle distance up to 3 kilometers require approximately 14 minutes to merge in a platoon. However, a real-life implementation of any platooning formation may differ from theoretical models. The dynamic nature of road traffic with a platoon structure has been described by Li (Li, 2017a, 2017b). In the former, a stochastic dynamic model for truck platooning was proposed. They used a Markov regime-switching method to deal with the dynamic nature of platoon-to-platoon transition and a space-state model to detect the dynamic motions of individual trucks in platoons. The latter took into consideration platoon size, within-platoon headway, between-platoon headway, and platoon speed. Under this coordination scheme, the optimal platoon size was 1.08 and 1.58 trucks for lower and higher velocity models respectively. This appears to contradict most of the literature on optimal platoon size (i.e., from 2 to 10 trucks). However, studies about aerodynamic evaluation of truck platooning (already mentioned in the introduction) dissented about the fuel reduction, it was a common observation that the first truck in a convoy has almost no or the least benefit. Benefit for one and only truck cannot render platooning concept profitable. In short, the benefit for a one and only truck does not make platooning profitable. The uncertainty of travel time was taken into consideration by Hoef et al. (van de Hoef, Johansson and Dimarogonas, 2017) in a stochastic dynamic problem formulated to maximize the probability of two different trucks being in the vicinity to merge in a platoon. . Notably, the merging probability using optimal control under reliable type segments was 52%.

3.3 OPPORTUNISTIC PLANNING

Liang et al.(Liang, Martensson and Johansson, 2014) compared results of opportunistic platooning coordination and real-time coordination where vehicles departure can be adjusted. The fuel savings from the latter were almost three times greater as compared to the opportunistic case and platooning rate increased substantially when trucks were willing to adjust their departure time. Liang et. al. (Liang, Mårtensson and Johansson, 2016) extended their research (*29*) by formulating the optimal fuel-speed problem for two trucks. Fuel savings from this opportunistic planning were less than 5% and depended on the vehicles' weight. Under opportunistic planning, platooning is fuel-beneficial if the distance to the destination of the following truck is 16.5 times longer than the inter-vehicle distance the following truck must cover to catch the leading truck (Liang, Martensson and Johansson, 2013).
The potential of opportunistic platooning scheduling was studied by Noruzoliaee et al. (Noruzoliaee, Zou and Zhou, 2021) through a system-level equilibrium model. This constitutes one of the very few large-scale network researches about truck platooning. A multiclass network equilibrium model intergrades the relationship between, platoon formation time, fuel saving, and increase in effective road capacity. Despite the substantial, almost 8% of fuel savings, platooning could lead to an increase of road capacity up to 60% on rural interstate road networks.

3.4 LITERATURE REVIEW SUMMARY

Table 1 summarizes the examined literature regarding truck platooning. The examined literature demonstrates that, despite the plethora of studies about truck platooning and vehicle scheduling, most of them concentrate on the fuel savings potential of the concept. However, truck platooning and truck caravanning share many similarities, truck caravanning is introduced to quantify the benefit of labor savings by using fewer truck drivers. To the author's best knowledge, no published research exists that deals with the truck caravanning problem, as was defined above by the authors, and is discussed in more detail in the problem setup in the next section.

Table 1: Overview of examined literature.

Author	Platooning Planning	Objective	Formulation	Solution Algorithm	Results	Remarks
Larsson et al. 2015	**S**	min fuel consumption	ILP	Branch and Bound	9% fuel reduction for 200 trucks (same starting point for all trucks)	Heuristic and local search improvement heuristic algorith for large scale instances
Larson et al . 2016	**S**	min fuel consumption and delays	MIP	Branch and Bound	8% fuel reduction for 25 trucks when they are willing to wait to merge in platoons	Auxiliary parameters and constraints introduction for large scale instances
Larson et al. 2013	**S**	min fuel consumption	Distributed method	Local Search Controllers	Less than 2% fuel reduction for 300 trucks and 9% fuel savings for less than 9,000 trucks	Large scale simulation
Larsen et al. 2018	**S**	max profits of driving in platoon	MIP	Simulation and Heuristic	4-5% fuel reduction for 100-500 trucks	Local search heuristic implementation (delays are taken into consideration as cost)
Adler et al. 2020	**S**	min energy consumption and delays	Queueing Theory	Pareto-Optimal boundary	Efficient platoon size between 5 to 7 trucks	Policies: i)open loop (time-table) and ii)feedback. Pareto-optimal policies and the optimal energy-delay curves are explored for each case.
Boysen et al. 2018	**S**	min platooning cost	LP-MIP	Heuristic	Saving only from reduced number of drivers from 80% to 95% depending on drivers salary and diesel price	The costs are fuel costs, driver wages and early or late delivery costs
Nourmohammadzadeh and Hartmann 2016	**S**	min fuel cost	MIP	Genetic Algorithm	5% fuel reduction for 50 trucks by GA	For instances more than 20 trucks only the GA implemented
Nourmohammadzadeh and Hartmann 2019	**S**	min fuel cost	MIP	Genetic Algorithm	3.26% fuel savings by exact solution (optimality gap is not mentioned as the termination condition is 30 min) and 7.26% by metaheuristic solution for 500 trucks	Metaheuristic solution method inspired by ant colony optimazation
Meisen and Seidl 2008	**S**	max profits of driving in platoon	Mining frequent sequences	Truck Platoon Sequential Pattern	Profit up to 4.5€ per truck	Platoons are increased exponentailly with increase in number of trucks
Farokhi and Johansson 2013	**S**	car traffic and truck platooning incentives interaction	Non-cooperative Nash Equilibrium	Simulation	Linear relationship between the velocity of commuting and the number of trucks which are travel on the road at the same time	Trade-off between road traffic congestion and platooning incentives
Lue and Larson 2020	**S**	max fuel savings	MILP	Branch and Bound	4.5% fuel reduction for 150 trucks	Route-then-shedule heuristic method and valid inequalities implementation
Abdolmaleki et al. 2019	**S**	max fuel savings	MINLP	Outer Approximation cuts and local Search	Less than 9% fuel reduction for 10,000 trucks by heuristic	Dynamic-programming heuristic implemented for large scale networks
Xiaotong Sun and Yafeng Yin 2019	**S**	max utility of the platoon (optimal platoon speed and vehicle sequence)	MINLP	Exact	Average energy reduction of 8.48% per truck (platoon size seven trucks and 30 min schedule flexibility)	The introduction of labor-cost savings could make platooning very promising
Hoef et al. 2015	**R**	max fuel savings	MIP	Leader Selection Clustering based on speed	6%-8% fuel reduction for 7,000 trucks	Monte Carlos simulations
Saeednia et al. 2017	**R**	min fuel consumption and delays	MIP	Exact	Superiority of consensus-based algorith under changing traffic conditions	Comparison between optimazation-based and consensus-based algorithms
Li 2017	**R**	speed and travel time	State space model	Kalman and Hamilton filters	At the lower velocity model trucks tend to travel alone and not to form platoons (average platoon size 1.08 at optimum)	More statistical dustribution models to evaluate crucial platoon characteristics
Hoef et al. 2017	**R**	max probability of successful platoons	Integer Dynamic Programming	Backwards recursion	Merging prabability 52% using optimal control under reliable type segments	Model's evaluation through simulation
Liang et al. 2014	**O**	max fuel savings	Simulation	Map-matching and path-inference	0.60% fuel reduction with departure coordination and 0.22% fuel reduction with catch up coordination (20km coordination horizon)	Flexibility of departure time shows promising fuel saving
Liang et al. 2016	**O**	max fuel savings	MINLP	Interior Point (fmincon in Matlab)	1.7%-3.8% fuel reduction depending on truck weight	Model's evaluation through simulation
Liang et al. 2013	**O**	max fuel savings	Simulation	Scenario based analysis	Up to 7% fuel reduction with catch up coordination strategy	Platooning incentive factor is introduced to evaluate catch-up attempts
Noruzoliaee et al. 2021	**O**	interlocking relationship between, platoon formation time, fuel saving, and increase in effective road capacity	NLP	Dial’s bush-based algorithm.	Platooning could reach fuel saving up to 7.9%	Fuel-saving is increased by increasing platoon size and is decreased by decreasing inter-truck distance

S - Scheduled , **R** - Real-Time , **O** - Opportunistic

4 PROBLEM DESCRIPTION AND MATHEMATICAL MODELS

The main problem studied in this project is the typical transshipment problem where the intermediate nodes serve as the (de)coupling locations for the caravans. An example of a simple truck caravanning network (*STCN*) is shown in Figure 1. In the models proposed herein trucks start from several predefined origins (*O*) at different times to cover demand at various destinations (*D*). In the *STCN* there are some restrictions. More specifically, all trucks must participate in a caravan (i.e., passes through node sets K_1 and K_2) to reach their destinations. Another characteristic of *STCN* is that the caravan capacity of trucks for every caravan must be fulfilled. For instance, in a network with caravan capacity of five trucks all the formed caravans must constitutes of exactly five trucks. Consequently, in this case, the caravan capacity number must be multiple with the number of total demand (i.e., the number of trucks).

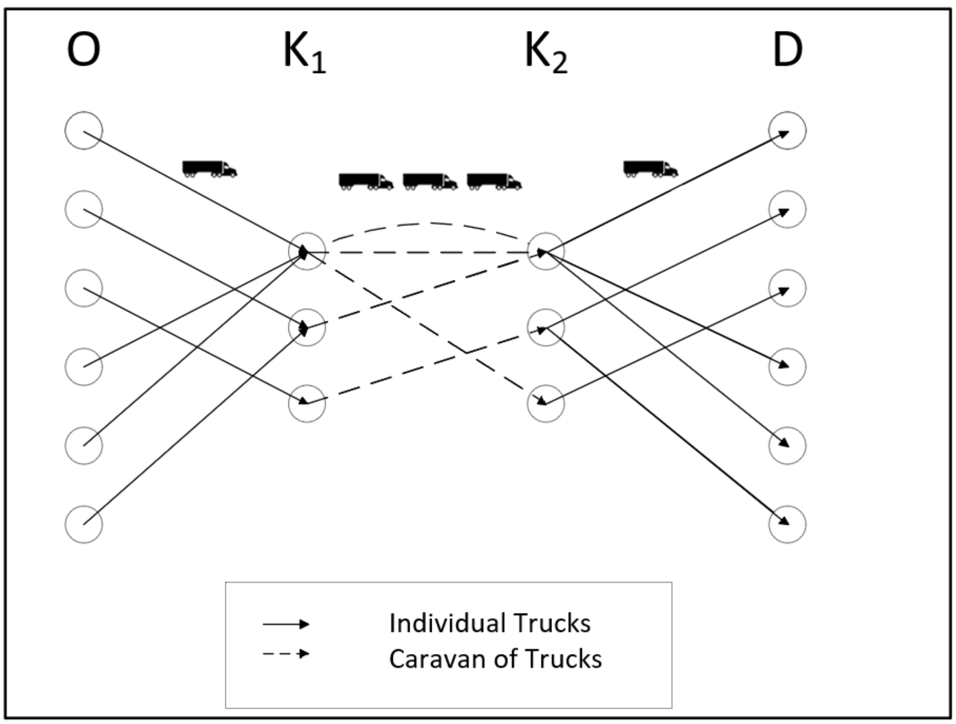

Figure 1: Simple Truck Caravanning Network (*STCN*)

The second proposed model is developed to eliminate the aforementioned restrictions. Drivers have the option of either traveling directly from the origin to their final destinations or using the coupling and decoupling points (i.e., node sets K_1 and K_2), to join and leave a caravan before traveling to the final destination. Additionally, the caravan capacity is still a parameter, but it is used as an upper bound. For instance, in a network with caravan capacity five trucks, all the formed caravans could have capacity from one to maximum five trucks. This network from now on referred to as Hybrid Truck Caravanning Network (*HTCN*) and an example of it, is shown in Figure **2**.

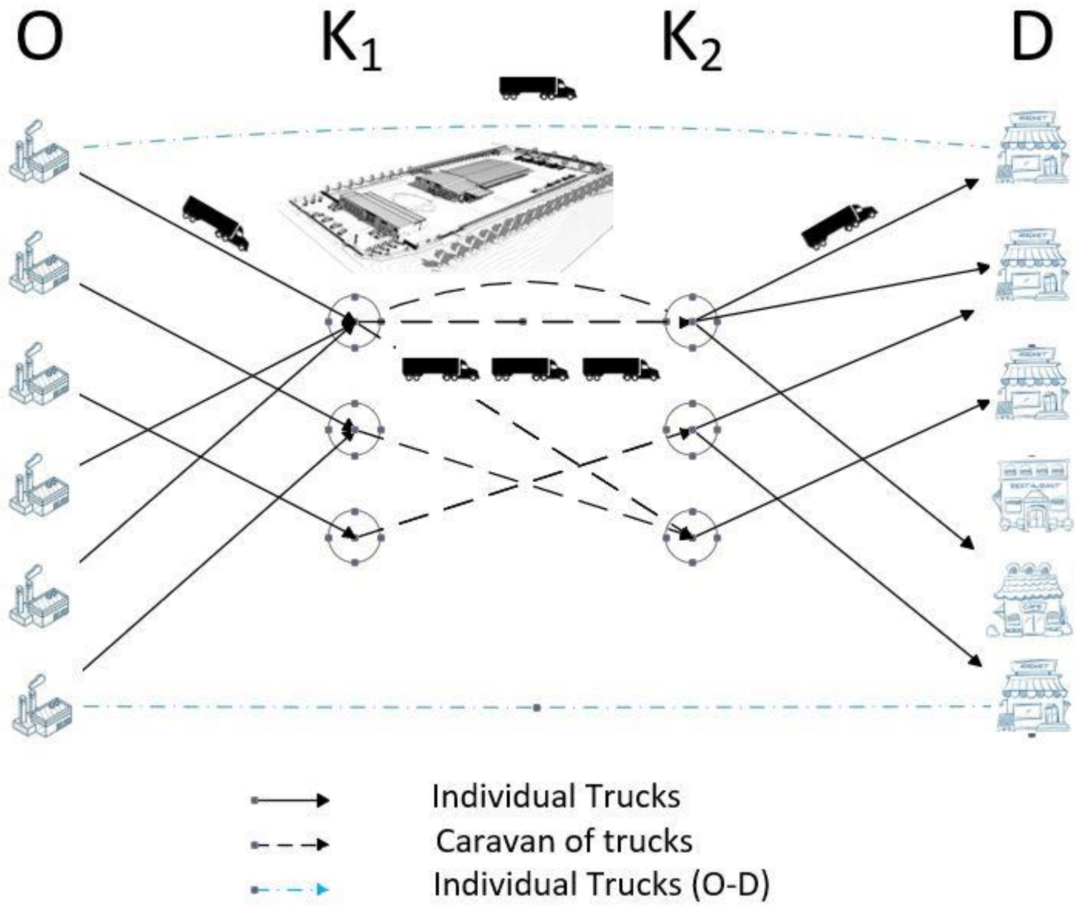

Figure 2: Hybrid Truck Caravanning Network (*HTCN*)

The proposed mathematical models (presented next) will decide which intermediate nodes should be used. In our formulation we do not consider costs associated with opening the facility as these would be a one-time expense and should not be considered when calculating long term benefits form the proposed concept.

Drivers at the decoupling nodes are available to drive the individual trucks to their destination. The objective of the proposed models is to minimize labor and costs for the entire network. Labor savings are derived from using fewer drivers while costs can increase due to late delivery times caused by delays at the coupling nodes and longer paths to accommodate the formation of caravans. Evidently, the proposed coordination could lead to sub-optimal solutions for individual trucks. The caravanning coordinator will be responsible for compensating those trucks through the derived savings. Driver compensation from/to the coupling/decoupling nodes (either bobtail or deadheading which depends heavily on the continent) is also considered and set equal to the regular truck driver compensation rate.

In this project we do not consider the cases of reverse logistics where a load is available at nodes K_1 or where a truck driver delivers a load at node K_2 destined to be returned to the origin, since both will reduce total cost of the proposed concept. Travel times between every node in the network are known and deterministic and the maximum internode travel time is limited to time allowed by the hours of service (HOS) regulation of the US (Federal Motor Carrier Safety and Administration (FMCSA), 2020). Each truck departs from its origin at a predetermined release time, can join any available caravan at any coupling node, and can satisfy the demand at any destination point. Consequently, supply and demand are expressed in the whole truck fraction. Each demand point has a delivery deadline. Next, we present the nomenclature used throughout the report, followed by the mathematical models.

4.1 NOMENCLATURE

4.1.1 Sets

I:	Set of all nodes
O:	Set of origins
D:	Set of destinations
K_1:	Set of coupling nodes
K_2:	Set of decoupling nodes
P:	Set of caravans from K_1 to K_2
C:	Set of trucks

Note that $O \cap K_1 = \emptyset$, $O \cap K_2 = \emptyset, O \cap D = \emptyset, K_1 \cap K_2 = \emptyset, K_1 \cap \mathrm{D} = \emptyset, K_2 \cap \mathrm{D} = \emptyset$,
$O \cup K_1 \cup K_2 \cup D = I$

4.1.2 Input parameters

$t_{ij} \in R$:	travel time (in hours) between nodes $i, j \in I$
$dm_m \in N$:	demand at destination $m \in D$, $\sum_m dm_{m \in D} = C$
$cs \in \{2, 4, 5, 8, 10\}$:	fixed number of trucks needed to form a caravan
$O_{ic} \in \{0, 1\}$:	1 if truck $c \in C$ is located at origin $i \in O$
$ad_{mc} \in R$:	arrival deadline at destination $m \in D$ for truck $c \in C$
$rt_c \in N$:	release time of truck $c \in C$
$R_{jk}^p \in \{0, 1\}$:	1 if caravan $p \in P$ is available between nodes $j \in K_1$ and $k \in K_2, \sum_{j,k} R_{jk}^p = 1, \ \forall p \in P$
$DC_1 \in \{25\}$:	regular truck driver compensation ($/hour)
$DC_2 \in \{50, 75\}$:	caravan truck driver compensation ($/hour)
$DAP = \$500$:	delayed arrival penalty ($/day)

For the numerical experiments in the research, we assumed that the total supply is equal with the total demand (i.e., $\sum_{m \in D} \mathrm{dm_m} = \sum_{i \in \mathrm{O}, \mathrm{c} \in \mathrm{C}} \mathrm{O_{ic}} = C$). Supply and demand are allocated with a uniform distribution along all origin (i.e., node set *O*) and destination (i.e., node set *D*) points respectively. The departure time of every truck from the origin ($\mathrm{rt_c}$) is chosen by a uniform distribution U [2, 9]. This reflects that all trucks are released between 2am and 9am. The regular truck driver compensation is defined as 25$/hour. The caravan truck driver will be compensated by the double and the triple of the regular truck driver salary. The rationale behind of those two cases selection, as the selection of travel time and arrival deadline, is explicitly described in the next section. If any truck, reaches its destination after the deadline, it will be penalized by 500$/day or 20.8$/hour.

4.2 SIMPLE TRUCK CARAVANNING MODEL (*STCM*)

The simple truck caravanning problem can be formulated as follows (equations 1 through 15):

4.2.1 *STCM* Decision variables

$x_{ij}^{c} \in \{0,1\}$	1 if truck $c \in C$ traverses from origin node $i \in O$ to coupling node $j \in K_1$ and zero otherwise
$y_{jk}^{cp} \in \{0,1\}$	1 if truck $c \in C$ is assigned to caravan $p \in P$ from coupling node $j \in K_1$ to decoupling node $k \in K_2$ and zero otherwise
$z_{km}^{c} \in \{0,1\}$	1 if truck $c \in C$ traverses from decoupling node $k \in K_2$ to destinationnode $m \in D$ and zero otherwise
$f_{jk}^{p} \in \{0,1\}$	1 if caravan $p \in P$ is formed from node $j \in K_1$ to $k \in K_2$ and zero otherwise
dt_p	departure time of caravan p ∈ P from coupling node K_1
at_c	arrival time of truck $c \in C$ at its destination
tt_c	total travel time of truck $c \in C$
dh_c	hours of delayed arrival at destination for truck $c \in C$

4.2.2 *STCM* Objective Function

$$\boldsymbol{STCN}: min \sum_{\substack{i\in O, j\in K_1, k\in K_2,\\ m\in D. c\in C}} 2DC_1(x_{ij}^{c}\, t_{ij} + z_{km}^{c} t_{km}) + \sum_{\substack{j\in K_1, k\in K_2,\\ p\in P}} (DC_1 + DC_2) f_{jk}^{p}\, t_{jk} + \sum_{c\in C} dh_c DAP \qquad \textbf{\textit{Equation 1}}$$

Subject to:

Supply/Demand constraints

$$\sum_{j\in K_1} x_{ij}^{c} \le O_{ic} \;, \forall i \in O, c \in C \qquad \textbf{\textit{Equation 2}}$$

$$\sum_{k\in K_2, c\in C} z_{km}^{c} = dm_m \,, \forall\, m \in D \qquad \textbf{\textit{Equation 3}}$$

Conservation of flow constraints

$$\sum_{i\in O, c\in C} x_{ij}^{c} = \sum_{k\in K_2, p\in P, c\in C} y_{jk}^{cp} \;, \forall\, j \in K_1 \qquad \textbf{\textit{Equation 4}}$$

$$\sum_{j\in K_1, p\in P, c\in C} y_{jk}^{cp} = \sum_{m\in D, c\in C} z_{km}^{c}, \forall\, k \in K_2$$ ***Equation 5***

$$\sum_{k\in K_2 m\in D,} z_{km}^{c} = 1, \forall\, c \in C$$ ***Equation 6***

Caravan size constraint

$$\sum_{c\in C} y_{jk}^{cp} = f_{jk}^{p} cs, \forall\, j \in K_1, k \in K_2, p \in P$$ ***Equation 7***

A truck can be assigned to only one caravan

$$\sum_{j\in K_1, k\in K_2, p\in P} y_{jk}^{cp} = 1, \forall\, c \in C$$ ***Equation 8***

Caravan departure time estimation constraint

$$dt_p \geq rt_c + \sum_{i\in O, j\in K_1, k\in K_2} x_{ij}^{c}\, t_{ij} R_{jk}^{p} - M(1 - \sum_{j\in K_1, k\in K_2} y_{jk}^{cp}), \forall\, c \in C, p \in \mathrm{P}$$ ***Equation 9***

Arrival time of trucks at destination estimation

$$at_c \geq dt_p + \sum_{j\in K_1, k\in K_2} t_{jk} y_{jk}^{cp} + \sum_{k\in K_2, m\in D} z_{km}^{c} t_{km} - M\left(1 - \sum_{j\in K_1, k\in K_2} y_{jk}^{cp}\right), \forall\, c \in C, p \in P$$ ***Equation 10***

Truck travel time estimation (from origin to destination)

$$tt_c = at_c - rt_c, \forall\, c \in C$$ ***Equation 11***

Hours of late arrival estimation

$$dh_c = at_c - \sum_{k\in K_2, m\in D} z_{km}^{c}\, ad_{mc}, \forall\, \mathrm{c} \in \mathrm{C}$$ ***Equation 12***

Waiting time at coupling points estimation

$$\mathrm{wt_c} = \mathrm{tt_c} - (\sum_{i\in O\, j\in K_1} x_{ij}^{c}\, t_{ij} + \sum_{j\in K_1, k\in K_2, p\in P} y_{jk}^{cp} t_{jk} + \sum_{k\in K_2, m\in D} z_{km}^{c} t_{km}), \forall\, c \in C$$ ***Equation 13***

Caravan formation constraints

$$f_{jk}^{p} \leq R_{jk}^{p}, \forall\, j \in K_1, k \in K_2, p \in P$$

Equation 14

$$y_{jk}^{cp} \leq R_{jk}^{p}, \forall\, j \in K_1, k \in K_2, c \in C, p \in P$$

Equation 15

To better understand the mathematical model for the *STCM* we underline the importance of the binary decision variable f_{jk}^{p} along with parameter R_{jk}^{p} . The latter is equal to 1 if a caravan exists between a coupling and a decoupling node. We chose to include this parameter to reduce the models' complexity. The alternative would be the introduction of a decision variable to assign caravans between the coupling and decoupling nodes which would significantly increase the columns of the constraint matrix. For instance, if the total demand is 100 trucks and the caravan size is 5 then a maximum of 20 caravans can be formed between each K_1 and K_2 node pair (i.e., $\sum_{p\in P} R_{jk}^{p} = 20, \forall\, j \in K_1, k \in K_2$). Consequently, at this case the total member of available caravans will be $\sum_{j\in K_1, k\in K_2, p\in P} R_{jk}^{p} = 20 * |K_1| * |K_2|$. The decision variable f_{jk}^{p} decides which of these available caravans will be used. Note, that future research could introduce a decision variable that assigns caravans between the (de)coupling nodes; a formulation that would support the development of a column generation-based heuristic (or Bender's decomposition for the dual) to solve the resulting model.

The first two components of the objective function (Equation 1) calculate the total driver cost (bobtail/deadheading driver compensation is included by doubling the one-way driver cost) while the third component calculates the cost from delayed arrivals at the destinations. Constraints sets 2 through 6 are the supply and demand constraints, and conservation of flow constraints at the (de)coupling nodes respectively. Constraints set 7, sets the number of trucks that join a caravan (if that caravan is formed) equal to a predetermined number. Constraints set 8 assigns each truck to only one caravan. Constraints set 9 estimates the departure time of a caravan, while constraints set 10 the arrival time of a truck at the destination. Constraints set 11 estimates the travel time of a truck while constraints set 12 estimates the hours of late arrival. Constraints set 13, calculates the individual truck waiting (idle) time at the coupling points. Constraints sets 14 and 15 set the values of variables *y* and *f* equal to zero for the (de)coupling nodes where a caravan is not defined.

4.3 HYBRID TRUCK CARAVANNING MODEL (*HTCM*)

The hybrid truck caravanning problem can be formulated as follows (equations 16 through 30):

4.3.1 *HTCM* Decision variables

The *HTCM* retains all the aforementioned decision variables of *STCM*. For the needs of the hybrid caravanning formulation a new variable is introduced herein:

$r_{im}^{c} \in \{0,1\}$ 1 if truck $c \in C$ traverses from node $i \in O$ to node $m \in D$ and zero otherwise

4.3.2 *HTCM* Decision variables

$$\boldsymbol{HTCM}: min \sum_{i\in O, j\in K_1, k\in K_2, m\in D, c\in C} 2DC_r\left(x_{ij}^c t_{ij} + z_{km}^c t_{km}\right) + \sum_{i\in O, m\in D, c\in C} 2DC_r r_{im}^c t_{im} + \sum_{j\in K_1, k\in K_2, p\in P} (DC_r + DC_c) t_{jk} y_{jk}^{cp} + \sum_{c\in C} dh_c DAP$$ ***Equation 16***

Subject to:

Supply/Demand Constraints

$$\sum_{i\in O, j\in K_1} x_{ij}^c\, O_{ic} + \sum_{i\in O, m\in D} r_{im}^c\, O_{ic} \leq 1, \forall\, c \in C$$ **Equation 17**

$$\sum_{k\in K_2, c\in C} z_{km}^c + \sum_{i\in O, m\in D} r_{im}^c\, O_{ic} = dm_m, \forall\, m \in D$$ **Equation 18**

Conservation of flow Constraints

$$\sum_{i\in O, c\in C} x_{ij}^c\, O_{ic} = \sum_{k\in K_2, p\in P, c\in C} y_{jk}^{cp}, \forall\, j \in K_1$$ **Equation 19**

$$\sum_{j\in K_1, p\in P, c\in C} y_{jk}^{cp} = \sum_{m\in D, c\in C} z_{km}^c, \forall\, k \in K_2$$ **Equation 20**

$$\sum_{k\in K_2 m\in D,} z_{km}^c = 1, \forall\, c \in C$$ **Equation 21**

Hybrid Caravan size Constraints

$$\sum_{c\in C} y_{jk}^{cp} \leq cs, \forall\, j \in K_1, k \in K_2, p \in P$$ **Equation 22**

A truck belongs to only one caravan or follows the OD path

$$\sum_{j\in K_1,k\in K_2,p\in P} y_{jk}^{cp} + \sum_{i\in O,m\in D} r_{im}^{c}\, O_{ic} \le 1, \forall\, c \in C$$ **Equation 23**

Caravan departure time estimation

$$dt_p \ge \mathrm{rt_c} + \sum_{i\in O,j\in K_1,k\in K_2,c\in C} x_{ij}^{c}\, t_{ij} y_{jk}^{cp} - M\left(1 - \sum_{j\in K_1,k\in K_2} y_{jk}^{cp}\right), \forall\, c \in C, p \in \mathrm{P}$$ **Equation 24**

Arrival time of trucks at destination estimation

$$at_c \ge \mathrm{dt_p} + \sum_{j\in K_1,k\in K_2} y_{jk}^{cp} t_{jk} + \sum_{k\in K_2,m\in D} z_{km}^{c} t_{km} - M\left(1 - \sum_{j\in K_1,k\in K_2} y_{jk}^{cp}\right), \forall\, c \in C, p \in P$$ **Equation 25**

$$at_c \ge \sum_{i\in O,m\in D} r_{im}^{c}\, t_{im} + rt_c \;, \forall\, c \in C$$ **Equation 26**

Total travel time estimation

$$tt_c = at_c - rt_c, \forall\, c \in C$$ **Equation 27**

Hours of late arrival estimation

$$dh_c \ge at_c - \sum_{i\in O,k\in K_2,m\in D} (z_{km}^{c} + r_{im}^{c})\, ad_{mc}, \forall\, c \in C$$ ***Equation 28***

Caravan formation constraints (One unique platoon can be formed between each coupling-decoupling node pair)

$$\sum_{j\in K_1,k\in K_2} y_{jk}^{cp} \le \sum_{j\in K_1,k\prime\neq k\in K_2} y_{jk\prime}^{cp}\ \forall\, c \in C, p \in P$$ ***Equation 29***

$$\sum_{j\in K_1,k\in K_2} y_{jk}^{cp} \le \sum_{j\prime\neq j\in K_1,k\in K_2} y_{j\prime k}^{cp}\ \forall\ c\in C,p\in P$$ ***Equation 30***

The objective function of the *YTCP* consists of four components. The first three are associated with the total driver cost, where bobtail/deadhead is included by doubling the one-way driver cost. The last component estimates the cost of violation of the delivery deadline at the destination. In the two-driver platoon case the objective function changes slightly where the third component, becomes equal to: $\sum_{j\in K_1,k\in K_2,c\in C,p\in P} 2(SDC_r + DC_c)t_{jk}y_{jk}^{cp}$. Drivers are compensated even when they are not on duty (e.g., resting time) as they are still on the truck and bobtail/deadhead is included as the cost of platoon drivers to return to the initial coupling point where their itinerary started. Note, that is the worst-case scenario in terms of truck driver compensation costs as the cost for a driver when not on duty can be less than when driving the platoon (in case of two platoon drivers).

Constraints sets 17 through 21 are the supply and demand constraints, and conservation of flow constraints at the (de)coupling nodes, respectively. The proposed model allows trucks to travel directly from an origin to a destination without joining a platoon. Consequently, there are no negative savings between the comparison of *YTCP* and the simple origin to destination model (described next in section). The introduction of the decision variable r_{im}^{c} allows as a feasible solution the case where all trucks will choose the direct route from the origin to the destination, bypassing the (de)coupling nodes. Constraints set 22 sets the upper bound for the number of trucks that join a platoon (if that platoon is formed). This bound is assumed known and predetermined by the decision maker. In the numerical examples section, we use various bounds to evaluate its effects to the cost savings and platoon utilization. Constraints set 23 allocates each truck to only one platoon or to the shortest origin-destination path. Constraints set 24 estimates the departure time of a platoon, while constraints sets 25 and 26 the arrival time of a truck at the destination. Constraints set 27 estimates the travel time of a truck while constraints set 28 estimates the hours of late arrival. Constraints sets 29 and 30 do not allow the same platoon to be formed between two different coupling-decoupling node pairs.

4.4 THE BASE NETWORK MODEL (*BNM*)

To calculate cost savings by the proposed concept (*STCM* and *HTCM*), we introduce a third model (from now on referred to as the base network or *BN* problem) where trucks traverse only directly from the origins to the destinations following the shortest (in time) possible route. Next, we present additional nomenclature and the *BN* model formulation (from own referred to as the Basic Network Model of *BNM*):

4.4.1 BNM Decision variables

$x_{im}^{c} \in \{0,1\}$ 1 if truck $c\in C$ traverses from node $i\in O$ to node $\mathrm{m}\in D$ and zero otherwise

at_c	arrival time of truck $c \in C$ at its destination
tt_c	total travel time of truck $c \in C$
dh_c	hours of delayed arrival at destination for truck $c \in C$

4.4.2 BNM Objective Function

$$\boldsymbol{BNM}: min \sum_{c \in C} 2tt_c DC_1 + \sum_{c \in C} dh_c DAP \qquad \textit{Equation 31}$$

Subject to:

Supply/Demand Constraints

$$\sum_{m \in D} x_{im}^c \leq O_{ic}, \forall\, i \in O, c \in C \qquad \textit{Equation 32}$$

$$\sum_{i \in O, c \in C} x_{im}^c = dm_m, \forall\, m \in D \qquad \textit{Equation 33}$$

Estimation of truck arrival time at destination

$$at_c \geq rt_c + \sum_{i \in O, m \in D} x_{im}^c t_{im}, \forall\; \mathrm{c} \in \mathrm{C} \qquad \textit{Equation 34}$$

Truck travel time estimation (from origin to destination)

$$tt_c = at_c - rt_c, \forall\, c \in C \qquad \textit{Equation 35}$$

Estimation of truck late arrivals (in hours)

$$dh_c \geq at_c - \sum_{i \in O, m \in D} x_{im}^c ad_{mc}, \forall\; \mathrm{c} \in \mathrm{C} \qquad \textit{Equation 36}$$

The objective function of the *BNM* (Equation 31) contains two components: the driver cost (bobtail driver compensation is included by doubling the one-way driver cost) and the cost from late arrivals at the destination. Constraints sets 32 and 33 are the supply and demand constraints. Constraints set 34 estimates the arrival time of a truck at the destination point while constraint sets 35 and 36 calculate the truck travel time and hours of delayed arrival.

5 NUMERICAL EXPERIMENTS OF *STCM*

Various numbers of origin, destination, and (de)coupling nodes, and demand were used to develop 36 test networks to explore the potential cost savings from the proposed truck caravanning freight operations concept. From problem instances 1 to 18 and 9 to 36 the demand is 100 and 200 trucks respectively. It is assumed that the supply is equal to the demand (truck units). Error! Reference source not found. summarizes these data for each problem instance. Next, we discuss the selection for the values of the *STCM* parameters (i.e., travel times, driver compensation, caravan size and arrival time deadlines at the destination nodes).

Travel Times

Travel times between all possible origin-destination pairs in the *STCM* were generated using two uniform probability distributions. For the *STCM* links that connect the origins to the coupling nodes and the decoupling to the destination nodes, travel times were generated based on a uniform distribution of U [2,3] in hours while travel times between caravanning nodes (K_1 and K_2) based on a uniform distribution of U [9,11] in hours. The uniform distribution ranges between caravanning nodes were selected to comply with the HOS regulations (Federal Motor Carrier Safety and Administration (FMCSA), 2020). These predetermined travel time ranges result in trucks engaging in caravans between 60% to 73% of their total travel time (excluding any delays at the (de)coupling nodes). For the BNM travel times between an origin-destination (OD) pair, were calculated as a percentage of the shortest path travel time in the *STCM*. For each problem instance in **Table 2** we considered two cases, where travel times between the OD pairs in the *BN*, are reduced by 20% and 40% respectively, as compared to the shortest paths in the *STCM*. For example, if the shortest path between origin node 1 and destination node 2 in the *STCM* is 14 hours then the travel time in the BN between origin node 1 and destination node 2 would be 11.2 and 8.4 hours for case 1 and 2 respectively. We also considered three different Arrival Time Deadlines (ATD) for the trucks at their destinations. For each O-D pair we calculated the shortest path in the BNM network. We then set the ATD to be a multiple of that shortest path travel time based on three uniform distributions of U [1, 1.5], U [1.5, 2], U [2, 2.5]. For example, assume that the shortest path travel time between an origin and a destination is 12 hours. We consider three ATD cases where in the first case the deadline at this specific destination would be between 12 and 18 hours; in the second case between 18 and 24 hours, and in the third case between 24 and 30 hours respectively.

Table 2: Test Network Instances of STCM

Network Instance	Demand (trucks)	Origin Nodes (O)	Coupling Nodes (K1)	Decoupling Nodes (K2)	Destination Nodes (D)
1/19	100/200	4	2	2	4
2/20	100/200	6	2	2	6
3/10	100/200	8	2	2	8
4/22	100/200	4	3	3	4
5/23	100/200	6	3	3	6
6/24	100/200	8	3	3	8
7/25	100/200	2	2	2	4
8/26	100/200	2	2	2	6
9/27	100/200	2	2	2	8
10/28	100/200	2	3	3	4
11/29	100/200	2	3	3	6
12/30	100/200	2	3	3	8
13/31	100/200	4	2	2	2
14/32	100/200	6	2	2	2
15/33	100/200	8	2	2	2
16/34	100/200	4	3	3	2
17/35	100/200	6	3	3	2
18/36	100/200	8	3	3	2

Truck Driver Compensation

The caravanning concept is based on the idea that trained caravan drivers will take responsibility for a convoy of trucks between nodes K_1 and K_2. In this research we consider two cases with respect to the truck caravan driver compensation where the hourly compensation is set to two ($^{DC_2}/_{DC_1} = 2$) and three times ($^{DC_2}/_{DC_1} = 3$) higher than that of a truck driver (from now on referred to as Driver Compensation Ratio or DCR).

Caravanning Size

Another parameter that will affect profitability of the proposed concept is the number of trucks that participate in a caravan (i.e., *cs* parameter value in the *STCM*). In this research we considered four different caravan sizes of 2, 4, 5, and 10 trucks with the rational that *cs* values of 2 and 10 represent the extreme cases (worst- and best-case scenarios) while values for *cs* of 4 and 5 are more realistic. This assumption is in line with what has been presented in the literature (Boysen, Briskorn and Schwerdfeger, 2018; Adler, Miculescu and Karaman, 2020; Minnesota Statute, 2020). Additionally, big caravan sizes could create issues of traffic disruption (e.g., at on-ramp/off-ramp areas), traffic safety (e.g., moving bottleneck), and pavement damage especially if the vehicles do not have a lateral offset between them (Gungor and Al-Qadi, 2020; Song, Chen and Ma, 2021). At this point we underline the importance of truck allocation in every caravan/platoon. Sun and Yin (Sun and Yin, 2019) proposed a cooperative platooning game theory model to identify behavioral instability and reallocate the benefit among platoon members to incentivize drivers to form and maintain the optimal platoon formation. Future research should focus on developing a mathematical model with variable caravan sizes (with a preset upper bound).

5.1 Input Data Summary

In total, 1,728 different network instances (i.e., different combination of network size, travel times, arrival deadlines, cs and DCR values) were evaluated. We grouped the various networks into six sets based on the arrival deadline, *BNM* to *STCM* travel times, network size and demand, caravan size and DCR values. **Table 3** summarizes the values and ranges of these parameters for every one of the six sets. CPLEX/GAMS (version 25.1.3) state of the art dual simplex algorithm (GAMS, no date) was used to solve all optimization problems on an Intel(R) Core (TM) i7-8700 CPU @ 3.20GHz and 16GB of memory, with CPU times averaging 33 min for the *STCM* and 1 second for the *BNM*. Both models are solved with an optimality gap of less than 1%. Next, we present and discuss the results from the numerical experiments. The *STCM* requires significantly higher CPU times mainly due to the introduction of variables y_{jk}^{cp} and f_{jk}^{p} and the additional constraints required to form the caravans and estimate the hours of delayed arrivals.

Table 3: Test Network Instances of *STCM*

	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**
Arrival Time Deadline (ATD)	[1-1.5]	[1.5-2]	[2-2.5]	[1-1.5]	[1.5-2]	[2-2.5]
Travel time reduction (*BNM* VS STCM)	20%			40%		
Network Instance	1-36					
Caravan Size (cs)	[2,4,5,10]					
Driver Compensation Ratio (DCR)	[2,3]					

5.2 Overall Cost Savings

In this subsection we present and discuss the results (summarized in **Table** *4***)** on the mean, median, and standard deviation of cost savings between the *STCN* and *BN*. As expected, cost savings reduced with the increase of the DCR and shortest path travel times difference between the *STCN* and *BN*. In the case where the *BNM* shortest path travel time is 40% less than the *STCM* (Sets 4, 5 and 6), a caravan of 10 trucks is required to achieve any substantial cost savings. We observe significant losses for the *STCN* when the caravan size is limited to two trucks (cs=2) which is to be expected due to the delays at (de)coupling nodes. However, for the more realistic cases where the cs values are either 4 or 5, the DCR value is 2, and the travel time reduction between the *BN* and *STCN* is 20%, the average cost savings, when using the *STCN*, range between 9% and 33%.

When the caravan size is 10, average cost savings range between 24% and 46%. As a sidenote, it is unlikely that caravan sizes larger than 5 will be feasible (due to safety and operational efficiency of the highways) unless dedicated truck corridors are in place. In North America, standard lengths of semi-trailers range from 28 ft to 53 ft. which means that a caravan of 10 trucks could stretch between 280 ft to 530 ft back from the lead tractor. Additionally, as the caravan size increases over five trucks there is a diminishing trend of cost savings because of the increased waiting time at coupling points. Median and mean cost values are relatively similar with a low standard deviation (that also decreases with the increase of cost savings) across all sets which points to a low dispersion and more robust savings as the caravan size increases. More specifically, the fact that no problem instance of any set differs more than 18% from the mean value, renders a clear tendency of clustered cost savings around central values (mean and median). Consequently, the results are robust irrespective of the network size and parameter values (e.g., demand, travel time, ATD etc.).

5.3 Cost Savings and Arrival Time Deadlines

ATD is a crucial parameter as it affects the profitability of the caravan concept and has significant implications on the models' complexity (i.e., when ATD is increased computational times reduce significantly). Results in

Table *4* highlighted the importance of ATD to cost savings being realized by the *STCN* as sets with higher ATDs showed improved cost saving between sets (i.e., sets 1, 2 and 3, and sets 4, 5, and 6) ranging from 2% to 17% for the mean and 0% to 17% for the median. For the standard deviation, we observe the same patterns to the overall cost savings (discussed in the previous subsection) albeit with a smaller range between 0% and 6%.

5.4 Cost Savings and Travel Time

In this subsection, we provide a discussion of the effects of travel time on cost savings based on the results from the numerical experiments. **Table 5** reports the average, median, and standard deviation cost savings difference for each one of the two shortest path travel time cases where we compare cost savings between sets one and four, two and five, and three and six. For these pairs of sets the only difference is the shortest path travel time (i.e., the *BN* shortest path travel time is 20% lower for sets one, two and three, and 40% lower for sets four, five and six for the *STCN*). Results for all cases illustrate that although higher travel times (in the *STCN* when compared to the *BN*) reduce cost savings (as expected), the *STCN* still provides significant savings ranging between 25% and 64%. Like previous results, average and median cost savings are similar, and the STD is low, which provided confidence that the results are not affected by the parameter values.

Table 4: *STCN* Average, Median, and Standard Deviation of Cost Savings

Sets	Average Cost Difference							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	-22%	9%	16%	30%	-41%	-1%	8%	24%
2	-12%	21%	27%	42%	-33%	9%	19%	38%
3	-8%	26%	33%	46%	-30%	15%	24%	42%
4	-73%	-35%	-27%	-9%	-99%	-49%	-38%	-14%
5	-69%	-24%	-13%	4%	-97%	-37%	-25%	-1%
6	-52%	-8%	1%	21%	-81%	-22%	-12%	16%

Sets	Median Cost Difference							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	-16%	12%	20%	30%	-37%	4%	12%	27%
2	-9%	22%	29%	42%	-31%	12%	20%	38%
3	-7%	27%	33%	47%	-29%	15%	24%	42%
4	-65%	-27%	-20%	-6%	-91%	-39%	-29%	-10%
5	-62%	-19%	-10%	5%	-91%	-33%	-22%	1%
6	-49%	-5%	4%	22%	-77%	-21%	-9%	17%

Sets	Standard Deviation Cost Difference							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	12%	10%	9%	4%	12%	11%	11%	7%
2	7%	4%	5%	2%	9%	8%	6%	2%
3	5%	3%	3%	2%	5%	3%	3%	2%
4	16%	15%	14%	10%	18%	15%	15%	11%
5	16%	12%	9%	7%	16%	12%	11%	6%
6	11%	10%	8%	5%	11%	7%	9%	2%

Table 5: Travel time effects: Average, median, and standard deviation of cost savings

	DCR =2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
SET 1 VS 4								
Average	50%	44%	44%	38%	58%	48%	46%	39%
Median	48%	41%	41%	36%	53%	44%	42%	37%
STD	10%	10%	10%	8%	15%	11%	11%	9%
SET 2 VS 5								
Average	57%	45%	41%	38%	64%	46%	45%	38%
Median	50%	41%	39%	37%	58%	44%	42%	38%
STD	15%	12%	9%	7%	16%	12%	13%	6%
SET 3 VS 6								
Average	44%	35%	32%	25%	51%	37%	35%	26%
Median	44%	33%	31%	24%	51%	37%	35%	26%
STD	11%	11%	9%	5%	12%	8%	11%	2%

5.5 Cost Savings and Demand

In this subsection, we analyze the impact on demand to cost savings with results reported in **Table 6**. Increasing the number of trucks should reduce arrival time delays at the destination as it increases the opportunity for caravan formation (and in turn reduces waiting times at the coupling nodes K_1) and thus, one would expect higher cost savings as demand increases. However, as Nourmohammadzadeh and Hartmann (Nourmohammadzadeh and Hartmann, 2019) observed, "*when a larger number of trucks are released on the road network, the platooning potential has already been used, and as a result, the positive influence of more trucks is reduced*". This positive influence could be translated as fuel cost reduction but in this case, it is labor cost reduction.

Results shown in **Table 6,** do not support either assumption (i.e., both statements are partially true). The parameter which emerges to affect cost savings the most is the ATD at the destination. When the ATD value is high, the caravanning scheduling is more flexible as the cost from arrival time deadline violations is minimized. In these cases (sets 3 and 6) the increase in demand (from 100 to 200 trucks) does not result in significant cost savings and, in some cases, results in a cost increase (set 3, *cs* of two and four, DCR of two). On the other hand, when the ATD value is small (i.e., sets 1 and 4) demand plays a key role to profitability with cost savings differences ranging from 4% (for a caravan size of ten) to 25% (for a caravan size of two). Based on the latter observation, the authors suggest that networks with higher demand be tested to provide more robust insight on a possible connection of demand and cost savings. To perform this analysis a heuristic or hybrid solution algorithm would need to be developed since the *STCM* cannot be solved efficiently for a demand of 300 trucks and above.

Table 6: Demand effects (200 VS 100 trucks): Average, median, and standard deviation of cost savings

Sets	DCR = 2				DCR = 3			
Average Savings: 200 VS 100 Trucks								
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	18%	13%	10%	4%	16%	13%	12%	8%
2	5%	3%	3%	1%	5%	5%	2%	1%
3	-1%	-1%	0%	0%	0%	0%	0%	0%
4	24%	22%	20%	11%	25%	24%	23%	12%
5	19%	17%	12%	8%	22%	16%	12%	7%
6	10%	7%	7%	3%	5%	5%	7%	1%
Median Savings: 200 VS 100 Trucks								
Sets	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	16%	9%	5%	4%	12%	6%	4%	5%
2	3%	0%	1%	0%	3%	1%	1%	0%
3	0%	0%	1%	0%	0%	0%	-1%	1%
4	23%	22%	25%	8%	20%	27%	26%	7%
5	15%	14%	10%	5%	17%	12%	8%	6%
6	6%	4%	4%	2%	-1%	2%	3%	1%
Savings Standard Deviation: 200 VS 100 Trucks								
Sets	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	11%	10%	11%	5%	12%	13%	13%	8%
2	7%	6%	6%	2%	11%	11%	8%	3%
3	8%	3%	4%	4%	4%	3%	4%	3%
4	14%	13%	12%	10%	17%	13%	13%	13%
5	18%	11%	9%	7%	16%	12%	11%	7%
6	14%	13%	11%	7%	15%	9%	12%	3%

5.6 Cost Savings, Caravan Size & Driver Compensation

In this subsection, the analysis is focused on the effects of caravan size to cost savings and results are summarized in **Table 7, Table 8,** and **Table 9**. We observe significant cost saving differences between or within each set when we vary the values of DCR, with the highest cost savings between caravans of size 2 and 10 (as expected), and declining cost saving differences as caravan size increases (e.g., from 4 to 5 trucks) (**Table 7**). For example, when the caravan size doubles from five to ten (100% increase in caravan size) the cost savings increase ranges from 14% to 28%. We also observe a significant reduction in profits when DCR increases from two and three (**Table 8**) but an insignificant change in the average hours of delayed arrivals per truck between and within each set when we vary either cs or DCR (**Table 9**). The combined results from **Table 7, Table 8,** and **Table 9** leads to the conclusion that driver compensation is the most critical component affecting profitably of the caravanning concept although its influence decreases significantly with the caravan size.

Table 7: Cost savings differences between caravan sizes

Set	Cost Savings Difference DCR : 2					
	cs: 2 VS 4	cs: 2 VS 5	cs: 4 VS 5	cs: 2 VS 10	cs: 4 VS 10	cs: 5 VS 10
1	31%	39%	8%	52%	21%	13%
2	38%	45%	8%	64%	26%	19%
3	33%	39%	6%	54%	21%	15%
4	45%	56%	11%	73%	28%	17%
5	34%	41%	7%	54%	20%	14%
6	44%	54%	9%	73%	29%	20%
Set	**Cost Savings Difference DCR : 3**					
	cs: 2 VS 4	**cs: 2 VS 5**	**cs: 4 VS 5**	**cs: 2 VS 10**	**cs: 4 VS 10**	**cs: 5 VS 10**
1	41%	49%	8%	66%	25%	17%
2	42%	52%	10%	71%	29%	19%
3	45%	54%	9%	72%	27%	18%
4	51%	61%	10%	85%	34%	24%
5	60%	72%	12%	96%	36%	25%
6	59%	69%	10%	97%	38%	28%

Table 8: DCR effects: Average, median, and standard deviation of cost savings differences

Sets	Average Cost Difference DCR = 2 VS 3			
	cs=2	cs=4	cs=5	cs=10
1	16%	11%	11%	8%
2	15%	10%	9%	5%
3	20%	16%	12%	8%
4	17%	11%	11%	5%
5	21%	15%	14%	9%
6	19%	13%	13%	7%

Sets	Median Cost Difference DCR = 2 VS 3			
	cs=2	cs=4	cs=5	cs=10
1	17%	11%	11%	7%
2	15%	10%	8%	5%
3	19%	14%	12%	8%
4	18%	12%	10%	5%
5	20%	15%	13%	8%
6	18%	14%	13%	8%

Sets	Standard Deviation Cost Difference DCR = 2 VS 3			
	cs=2	cs=4	cs=5	cs=10
1	0%	0%	1%	0%
2	0%	0%	0%	0%
3	1%	2%	1%	0%
4	1%	1%	0%	0%
5	0%	0%	0%	0%
6	0%	0%	0%	0%

Table 9: Average, median, and standard deviation of delayed arrivals (in hours per truck)

Sets	Average Delayed Arrivals								
	DCR = 2				DCR = 3				BN
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	6.07	6.15	5.85	5.71	5.94	6.00	5.96	5.96	2.69
2	1.54	1.69	1.73	1.43	1.53	1.85	1.66	1.46	0.05
3	0.05	0.04	0.05	0.05	0.06	0.05	0.05	0.05	-
4	9.84	10.21	10.32	10.02	9.86	10.27	10.38	10.05	3.70
5	5.56	5.51	5.34	5.37	5.53	5.36	5.38	5.21	0.48
6	2.10	2.20	2.02	2.55	2.13	2.20	2.29	1.61	-
Sets	**Median Delayed Arrivals**								
	DCR = 2				DCR = 3				BN
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	5.38	5.66	5.39	5.54	5.70	5.35	5.18	5.58	2.58
2	1.47	1.63	1.65	1.45	1.49	1.51	1.50	1.51	0.02
3	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	-
4	9.23	9.48	9.73	9.64	9.56	9.66	9.67	9.63	3.41
5	5.20	4.91	4.82	5.18	5.25	4.83	5.06	4.83	0.45
6	2.02	1.94	1.82	2.22	2.00	2.11	2.06	1.58	-
Sets	**Standard Deviation Delayed Arrivals**								
	DCR = 2				DCR = 3				BN
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	1.78	1.77	1.76	1.00	1.61	1.90	1.92	1.42	1.10
2	0.74	0.62	0.62	0.25	0.87	1.07	0.73	0.24	0.06
3	0.10	0.06	0.07	0.05	0.06	0.06	0.07	0.06	-
4	1.63	1.90	1.88	1.37	1.62	1.93	1.98	1.56	1.31
5	1.60	1.52	1.37	1.06	1.49	1.53	1.42	1.03	0.30
6	0.83	0.93	0.87	1.47	0.78	0.66	0.89	0.17	-

5.7 Truck Travel Times

In this subsection, we present results and a discussion on the truck travel times between the two networks for the various sets. **Table 10** reports the average, median, and standard deviation truck travel time (in hours) between the origin and the destination for both the *STCN* and *BN*. **Table 11** provides the average, median, and standard deviation of waiting time (in hours) at the coupling nodes K_1. The average total travel time (**Table 10**) fluctuated between 15 and 18 hours depending on the case for the *STCN*. This means an increase in truck travel times (when compared to the shortest path in the *BN*) anywhere between 4 and 9 hours (**Table 10).** For sets 1, 2, and 3, the mean or median truck travel time in the *STCM* increases anywhere between 38% and 66% when compared to the *BN*. For sets 4, 5, and 6, the mean or median truck travel time in the *STCN* increases anywhere between 85% and 104% when compared to the *BN*. These data can be used in the selection of commodities/shippers that can be shipped using the caravan network, as some commodities/shippers may not be able to accept such travel time increases.

Depending on the case, trucks wait to form a caravan, on average, anywhere between 1 and 4 hours (**Table 11**). The waiting times at the coupling nodes translate anywhere between 6% and 22% of the total travel times in the *STCN*. This means, that better coordination to form caravans and reduce wait times may not result in significant increase of savings.

Table 10: Average, median, and standard deviation of total travel time from origin to destination (in hours per truck)

Sets	DCR = 2				DCR = 3				BN
	Average Total Travel Time								
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	15.61	15.86	15.77	15.67	15.67	15.91	15.82	15.61	11.30
2	15.83	16.37	16.47	17.11	15.85	16.37	16.62	17.04	11.06
3	16.29	17.04	17.38	17.82	16.29	17.27	17.30	17.97	11.12
4	15.46	15.98	16.15	16.26	15.34	15.90	15.92	16.26	8.30
5	15.37	15.42	15.33	15.34	15.43	15.76	15.41	15.34	8.25
6	15.99	16.37	16.64	16.92	15.96	16.47	16.61	17.03	8.34
	Median Total Travel Time								
Sets	DCR = 2				DCR = 3				BN
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	15.38	15.58	15.48	15.48	15.43	15.83	15.41	15.31	10.98
2	15.74	16.27	16.51	17.10	15.74	16.37	16.59	17.02	11.02
3	16.40	17.32	17.67	18.27	16.40	17.43	17.67	18.27	11.00
4	15.38	15.72	15.73	16.34	15.23	15.57	15.65	15.88	8.27
5	15.12	15.16	15.12	15.05	15.20	15.64	15.05	15.17	8.16
6	16.27	16.26	16.51	16.74	16.25	16.21	16.38	16.85	8.25
	Standard Deviation Total Travel Time								
Sets	DCR = 2				DCR = 3				BN
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10	
1	0.88	1.02	0.94	0.90	0.95	0.99	1.04	0.87	0.72
2	0.94	0.94	0.81	0.81	0.92	1.02	0.94	0.84	0.50
3	0.78	1.05	0.95	1.18	0.78	0.81	1.15	0.99	0.53
4	1.15	1.39	1.42	1.26	1.09	1.40	1.37	1.40	0.37
5	0.85	0.96	0.89	0.74	0.81	0.97	0.99	0.79	0.35
6	0.94	0.84	0.90	0.84	0.91	0.92	0.90	0.83	0.40

Table 11: Waiting time at coupling points K_1(in hours per truck)

Sets	Average Waiting Time							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	1.14	1.45	1.26	1.34	1.16	1.50	1.30	1.28
2	1.29	2.18	2.41	3.04	1.30	2.16	2.44	3.02
3	3.06	3.42	3.62	3.86	3.06	3.51	3.54	3.93
4	0.96	1.52	1.72	1.98	0.99	1.46	1.57	1.82
5	1.08	1.32	1.31	1.38	1.21	1.65	1.39	1.35
6	1.30	2.17	2.43	2.96	1.30	2.22	2.40	3.00

Sets	Median Waiting Time							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	1.22	1.44	1.23	1.23	1.27	1.52	1.25	1.09
2	1.30	2.17	2.44	3.07	1.31	2.28	2.47	3.02
3	3.02	3.52	3.64	3.92	3.02	3.53	3.64	3.95
4	0.98	1.43	1.57	1.55	1.03	1.52	1.38	1.54
5	1.14	1.14	1.17	1.12	1.24	1.52	1.23	1.19
6	1.32	2.22	2.53	3.03	1.33	2.23	2.45	3.08

Sets	Standard Deviation Waiting Time							
	DCR = 2				DCR = 3			
	cs=2	cs=4	cs=5	cs=10	cs=2	cs=4	cs=5	cs=10
1	0.30	0.68	0.84	0.90	0.30	0.65	0.82	0.91
2	0.13	0.26	0.27	0.30	0.12	0.38	0.27	0.34
3	0.22	0.38	0.25	0.35	0.22	0.18	0.46	0.23
4	0.38	0.72	0.88	0.96	0.35	0.75	0.79	0.87
5	0.27	0.48	0.63	0.63	0.19	0.43	0.53	0.56
6	0.17	0.28	0.34	0.32	0.19	0.27	0.35	0.39

6 NUMERICAL EXPERIMENTS OF *YTCM*

To quantify the *YTCM* we developed 54 test networks, summarized in **Table 12** with various numbers of origin, destination, (de)coupling nodes, and demand assuming (without loss of generality) that the supply is equal to the demand. For example, problem instance 1, 19, and 37 corresponds to a network with four origins and destination nodes, two coupling and decoupling nodes, and a demand of 50, 75, and 100 trucks respectively. It is already discussed the rationale behind the selection for the parameter values used in *STCM* at the previous section. Most of those parameters remain the same with the only difference that at this section we evaluate more cases of travel time reduction, less cases of arrival time deadline and some different cases of caravan size.

Table 12: Test Network Instances of YTCM

Network Instance	Demand (trucks)	Origin Nodes (O)	Coupling Nodes (K1)	Decoupling Nodes (K2)	Destination Nodes (D)
1/19/37	50/75/100	4	2	2	4
2/20/38	50/75/100	6	2	2	6
3/21/39	50/75/100	8	2	2	8
4/22/40	50/75/100	4	3	3	4
5/23/41	50/75/100	6	3	3	6
6/24/42	50/75/100	8	3	3	8
7/25/43	50/75/100	2	2	2	4
8/26/44	50/75/100	2	2	2	6
9/27/45	50/75/100	2	2	2	8
10/28/46	50/75/100	2	3	3	4
11/29/47	50/75/100	2	3	3	6
12/30/48	50/75/100	2	3	3	8
13/31/49	50/75/100	4	2	2	2
14/32/50	50/75/100	6	2	2	2
15/33/51	50/75/100	8	2	2	2
16/34/52	50/75/100	4	3	3	2
17/35/53	50/75/100	6	3	3	2
18/36/54	50/75/100	8	3	3	2

6.1 Input Data Summary

In total, 3,456 different network instances (i.e., different combination of network size, travel times, arrival deadlines, cs and DCR values) were evaluated. We grouped the various networks into eight sets based on the arrival deadline, *BNM* to *YTCN* travel times, network size and demand, caravan capacity and DCR values. **Table 13** summarizes the values and ranges of these parameters (ATD, cs, DCR, travel time reduction) for every one of the eight sets. CPLEX/GAMS (version 25.1.3) state of the art dual simplex algorithm (GAMS, no date) was used to solve all optimization problems on an Intel(R) Core (TM) i7-8700 CPU @ 3.20GHz and 16GB of memory. Next, we present and discuss the results from the numerical experiments of *YTCN*.

Table 13: Test Network Instances of YTCM

	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**	**Set 7**	**Set 8**
Travel time reduction (BNM VS YTCN)	10%	20%	30%	40%	10%	20%	30%	40%
Arrival Time Deadline (ATD)	[1.5-2]				[2-2.5]			
Network Instance	1-54							
Caravan Size (cs)	[3,5,8,10]							
Driver Compensation Ratio (DCR)	[2,3]							

6.2 Overall Cost Savings

The main contribution of this research was the quantification of any cost savings from implementing a truck caravanning scheduling. Average cost savings from the proposed *YTCM* as compared to the *BNM* are presented in **Table 14**. As expected, cost savings reduce as the DCR and the shortest path travel times difference between the *YTCN* and *BN* increase and increase with the caravan capacity. More specifically from the results it seems that the cost savings difference between DCR:2 and DCR:3 is very low for the two examined cases of ATD, for the different cases of number of trucks, when caravan capacity is high (e.g., cs=8 and cs=10). The three different cases of examined number of trucks (e.g., 50,75 and 100 trucks) have not any significant impact on the cost saving. For better insight between cost savings and the number of trucks, the *YTCM* has to been solved for bigger demand. We observe that once the caravan capacity exceeds five trucks the cost reduction margins reduce. If one takes under consideration safety concerns of large size caravans and the complexities of (de)coupling (nodes K_1 and K_2) the optimal capacity for the caravan, based on these experiments, is five. We note that the standard deviation of cost savings was less than 3% for any set.

Table 14: YTCM Average, Median, and Standard Deviation of Cost Savings

Sets	DCR: 2											
	50 Trucks				75 Trucks				100 Trucks			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
1	26%	42%	49%	53%	26%	42%	50%	53%	26%	42%	50%	53%
2	15%	33%	41%	45%	16%	33%	42%	45%	15%	32%	42%	45%
3	2%	17%	26%	30%	2%	17%	27%	30%	1%	17%	27%	30%
4	0%	1%	6%	9%	0%	0%	5%	8%	0%	0%	4%	8%
5	26%	42%	49%	53%	26%	42%	49%	52%	26%	41%	49%	53%
6	17%	34%	42%	47%	17%	34%	43%	46%	17%	35%	44%	47%
7	5%	25%	35%	39%	5%	25%	35%	39%	5%	25%	36%	40%
8	0%	9%	35%	24%	0%	9%	20%	24%	0%	8%	19%	24%
Sets	**DCR: 3**											
	50 Trucks				**75 Trucks**				**100 Trucks**			
	cs=3	**cs=5**	**cs=8**	**cs=10**	**cs=3**	**cs=5**	**cs=8**	**cs=10**	**cs=3**	**cs=5**	**cs=8**	**cs=10**
1	14%	34%	44%	49%	14%	34%	44%	49%	14%	34%	45%	49%
2	2%	24%	35%	40%	2%	24%	36%	40%	2%	24%	36%	41%
3	0%	8%	21%	25%	0%	8%	21%	25%	0%	7%	20%	25%
4	0%	0%	2%	5%	0%	0%	1%	3%	0%	0%	0%	3%
5	13%	34%	44%	49%	14%	34%	44%	48%	14%	34%	44%	49%
6	3%	26%	37%	43%	3%	26%	37%	42%	3%	26%	38%	43%
7	0%	15%	29%	34%	0%	15%	29%	34%	0%	15%	29%	35%
8	0%	1%	13%	18%	0%	1%	13%	19%	0%	1%	13%	18%

6.3 Truck Caravan Utilization

Table 15 reports the average number of trucks using a caravan. We observe a pattern where the number of trucks that do opt for the caravan is analogous to caravan capacity and inverse to the shortest path travel time. In other words, the higher the number of trucks allowed to form a caravan the higher the number of trucks that will utilize this option and the higher the difference of travel time between the *BNM* and *YTCM* the less the number of trucks using the caravan option.

Table 15: Average Number of Trucks Using Caravans

Sets	DCR : 2											
	50 Trucks				75 Trucks				100 Trucks			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
1	50	50	50	49	75	75	75	75	99	100	100	100
2	48	50	49	49	74	75	75	75	99	100	100	100
3	28	48	49	49	48	72	74	74	80	97	98	100
4	3	27	39	41	11	48	63	66	1	72	92	93
5	50	50	50	49	75	75	75	75	99	100	100	100
6	49	0	0	0	75	75	75	75	99	100	100	100
7	47	50	48	49	74	75	74	75	96	100	100	100
8	3	43	47	49	3	65	73	74	1	90	98	99
Sets	DCR : 3											
	50 Trucks				75 Trucks				100 Trucks			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
1	48	50	48	49	75	75	75	75	99	100	100	100
2	40	50	48	49	62	75	75	75	86	100	100	100
3	3	41	47	49	1	66	72	74	2	91	97	99
4	3	15	33	39	1	21	56	64	1	40	82	87
5	48	50	48	49	75	75	75	75	99	100	100	100
6	47	50	48	49	71	75	74	75	96	100	100	100
7	3	50	48	49	1	75	72	75	1	100	99	100
8	3	24	46	48	1	46	70	71	1	62	95	95

6.4 Effects Of Caravan Capacity to Cost Reduction

Table 15 reports the average number of trucks that form a caravan. We observe that in all cases the model chooses to create caravans with, almost, the maximum number of trucks allowed. However, the zero values of trucks in some sets it was expected and interprets that the simple origin destination policy was the best option in order the cost to be minimized. Therefore, those cases observed when the travel time reduction was more than 20% (e.g., Set 3 and Set 4). If the number of average trucks per caravan at **Table 16** is the same with the corresponding caravan size, then all trucks participated in caravans to reach their final destination. This is an important result as one would not necessarily expect for all the caravans to utilize the caravan's capacity. These results provide insight for policy makers, when setting limits for the caravan capacity, as they should expect whatever capacity they choose to be fully utilized.

Table 16: Average, Maximum, and Minimum Number of Trucks in Each Caravan

	DCR : 2															
	Set 1				Set 2				Set 3				Set 4			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
Average	2.98	5.00	7.45	9.79	2.99	5.00	7.57	9.67	3.00	4.99	7.65	9.39	0.00	4.98	7.76	9.56
Max	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	0.00	5.00	8.00	10.00
Min	2.61	5.00	5.22	9.15	2.85	5.00	5.07	8.28	2.91	4.85	5.93	7.17	0.00	4.80	6.48	7.80
	Set 5				Set 6				Set 7				Set 9			
Average	3.00	5.00	7.69	10.00	3.00	5.00	7.69	10.00	3.00	5.00	7.77	9.79	0.00	4.99	7.81	9.68
Max	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	0.00	5.00	8.00	10.00
Min	3.00	5.00	4.00	10.00	3.00	5.00	6.00	10.00	2.94	4.98	6.59	7.17	0.00	4.96	6.76	8.28
	DCR : 3															
	Set 1				Set 2				Set 3				Set 4			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
Average	3.00	5.00	7.71	9.79	3.00	5.00	7.70	9.72	0.06	5.00	7.88	9.73	0.00	4.35	7.89	9.79
Max	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	0.06	5.00	8.00	10.00	0.00	4.35	8.00	10.00
Min	3.00	4.91	6.44	9.06	3.00	5.00	5.56	8.56	0.06	4.96	7.11	8.26	0.00	4.33	7.30	8.74
	Set 6				Set 6				Set 7				Set 8			
Average	3.00	5.00	7.73	9.79	3.00	5.00	7.76	9.79	0.00	5.00	7.93	9.79	0.00	4.71	7.92	9.82
Max	3.00	5.00	8.00	10.00	3.00	5.00	8.00	10.00	0.00	5.00	8.00	10.00	0.00	4.72	8.00	10.00
Min	3.00	5.00	5.63	8.74	2.87	5.00	6.22	9.02	0.00	4.98	7.50	8.26	0.00	4.59	7.50	9.00

6.5 Arrival Deadline Violations

In the proposed model we assumed an hourly penalty for late arrivals of trucks. In this subsection report (**Table 17)** the average late arrivals (hours per truck) as on-time arrivals are one of the most critical components of today's supply chains. As expected, the higher the capacity of the caravan and the shorter the shortest path travel time the higher the late arrivals for trucks using the caravan option. One interesting observation from these results (in combination with results presented in **Table 17**) is that the model chooses to form large caravans at the cost of increasing late arrivals. Future research should focus on performing a sensitivity analysis on the caravan size formed when the hourly late arrival penalty increases (i.e., will the model choose to form caravans of small sizes to meet the arrival deadlines or choose to have trucks wait at the coupling nodes and form larger size caravans). We note that, in the BN, delayed arrivals where less than 0.35 hours per truck.

Table 17: Average of delayed arrivals (in hours per truck)

Sets	DCR : 2											
	50 Trucks				75 Trucks				100 Trucks			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
1	0.05	0.12	0.05	0.09	0.15	0.11	0.04	0.04	0.08	0.13	0.05	0.11
2	0.31	0.44	0.38	0.53	0.42	0.42	0.39	0.44	0.49	0.50	0.47	0.54
3	0.33	1.83	1.94	2.06	0.66	1.66	1.87	2.05	1.29	1.87	2.01	2.02
4	0.34	1.72	3.01	3.29	0.39	2.47	3.22	3.64	0.34	3.00	3.92	3.87
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.01	0.02	0.00	0.03	0.02	0.02	0.00	0.00	0.01	0.02	0.00	0.02
7	0.12	0.12	0.01	0.10	0.11	0.12	0.03	0.04	0.10	0.12	0.04	0.11
8	0.01	0.46	0.84	1.13	0.01	0.47	0.87	0.91	0.01	0.70	0.92	0.97
Sets	DCR : 3											
	50 Trucks				75 Trucks				100 Trucks			
	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10	cs=3	cs=5	cs=8	cs=10
1	0.07	0.13	0.03	0.11	0.22	0.19	0.06	0.06	0.13	0.14	0.04	0.11
2	0.16	0.44	0.36	0.53	0.25	0.60	0.57	0.64	0.29	0.49	0.45	0.52
3	0.17	1.14	1.81	2.24	0.20	1.99	2.77	2.93	0.18	1.79	2.03	2.26
4	0.33	0.99	2.30	3.09	0.59	1.54	4.70	5.45	0.35	1.49	3.73	4.18
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.01	0.03	0.00	0.03	0.02	0.04	0.00	0.00	0.01	0.02	0.00	0.03
7	0.00	0.12	0.02	0.11	0.00	0.19	0.02	0.06	0.00	0.15	0.02	0.10
8	0.01	0.10	0.81	0.98	0.01	0.33	1.10	1.25	0.01	0.28	0.79	0.88

7 CONCLUSIONS AND FUTURE RESEARCH

In supply chain management, we typically categorize companies based upon their roles as suppliers, manufacturers, wholesalers, distributors, or retailers. This study investigates the equally important role of transporters. Among its theoretical contributions, this research investigated an important gap in our transportation knowledge and proposed an alternative to truck platooning known as truck caravanning where only a single driver is needed for each platoon (or caravan) of trucks. The motivation for introducing and evaluating the concept came from claims in the literature that truck platooning does not provide significant enough fuel savings to justify its relatively costly application. Truck caravanning on the other hand, as showcased by this research, potentially produces significant cost savings (stemming from less labor needs), especially in networks where the (de)coupling nodes are strategically placed so that they do not increase travel time significantly when compared to the base network (i.e., network with direct connections from the origins to the destinations). Results from this research also show that caravans with two trucks provide negative cost savings and that as the caravan size increases a diminishing rate of cost savings is observed. Results indicate that truck caravan driver compensation and arrival time deadlines are the most critical parameters affecting the concept's profitability.

Future research

In this research, fuel savings from the formation of caravans or cost and savings from the introduction of electric trucks was not considered. The proposed model is capturing the operational aspects of trucking, (de)coupling nodes are predetermined, and opening/maintaining/operating costs of these facilities is not considered. The rational is that the model proposed in this manuscript can be used to quantify monetary benefits from truck caravanning that can be used in a cost benefit analysis for the selection of the number and location of the facilities. As a next step the development of a bilevel network design model (a.k.a. Stackelberg or hierarchical) is warranted to capture both the tactical and operational levels. The tactical level (upper) would consider costs for opening/maintaining/operating the facilities at the (de)coupling nodes and the cost of purchasing electric trucks while the operational level (lower) would capture (similar to the model proposed in this manuscript). Ongoing research is evaluating more complex networks (e.g., the size of each caravan can be different and variable, higher supply and demand, larger networks), relaxed assumptions (e.g., a subset of trucks may be able to travel directly to the destination without joining a caravan), longer travel times with two or more alternating drivers (to comply with HOS regulations), caravanning when individual trucks are fully autonomous (SAE Level 5), and development of hybrid solution algorithms to handle large problem instances within acceptable computational times and optimality gaps.

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