World Academy of Science, Engineering and Technology
International Journal of Transport and Vehicle Engineering
Vol:16, No:6, 2022

Truck Routing Problem Considering Platooning and Drivers' Breaks

Xiaoyuan Yan, Min Xu

***Abstract*—**Truck platooning refers to a convoy of digitally connected automated trucks traveling safely with a small inter-vehicle gap. It has been identified as one of the most promising and applicable technologies towards automated and sustainable freight transportation. Although truck platooning delivers significant energy-saving benefits, it cannot be realized without good coordination of drivers' shifts to lead the platoons subject to their mandatory breaks. Therefore, this study aims to route a fleet of trucks to their destinations using the least amount of fuel by maximizing platoon opportunities under the regulations of drivers' mandatory breaks. We formulate this platoon coordination problem as a mixed-integer linear programming problem and solve it by CPLEX. Numerical experiments are conducted to demonstrate the effectiveness and efficiency of our proposed model. In addition, we also explore the impacts of drivers' compulsory breaks on the fuel-savings performance. The results show a slight increase in the total fuel costs in the presence of drivers' compulsory breaks, thanks to driving-while-resting benefit provided for the trailing trucks. This study may serve as a guide for the operators of automated freight transportation.

***Keywords*—**Truck platooning, route optimization, compulsory breaks, energy saving.

I. Introduction

TRUCKING is the most used transport mode to deliver goods, especially in the long-haul freight transport service with randomly distributed delivery requests. However, it causes substantial fuel consumption and greenhouse emissions, which require urgent improvement on the fuel efficiency and operation characteristics of trucks. Recently, with the development of connected and automated vehicle (CAV) technology, truck platooning emerges and is regarded as the most promising and applicable technology towards automated and sustainable freight transportation in the near future. Truck platooning is a string of moving trucks that follow one another with minimum inter-vehicle gaps (see Fig. 1 for an example), enabled by the advanced and reliable vehicle-to-vehicle communication system and control technologies [2]. The main benefit of platooning is the reduction in fuel consumption allowed by the reduced air drag experienced by trucks in a platoon. However, the energy-saving benefits cannot be realized without good coordination of drivers' shifts to lead the platoons subject to their mandatory breaks.

A. Literature Review

Attracted by the promised benefits, an increasing amount of research has explored different aspects of platooning problems to fully exploit the positive effects of platooning. Most of the existing related studies mainly fall into two categories: one is the technical aspects of platooning, such as adaptive cruise control, safe driving, and automation technology for platoons [3]-[7]; the other concerns field tests to identify the factors influencing the fuel-saving effects [8], [9].

Fig. 1 Illustration of a three-truck platoon [1]

The platooning-related performance is not only affected by the technical aspects but is significantly influenced by the operational strategies of platooning, such as the coordination and optimization of platoons. Nevertheless, such planning and optimization problem concerned with platooning is still at the premature stage of investigation and has received insufficient attention. Among the limited related studies, Larson et al. firstly used the local controllers to facilitate the vehicles to form platoons with others by compromising their speeds to minimize the total fuel consumption [10]. However, they merely coordinate the trucks approaching the road intersections rather than all the trucks involved in the network. Liang then investigated the platooning problem from a larger perspective and proposed a path-inference algorithm to help recognize potential platooning opportunities by adjusting speeds or selecting paths [4]. Later, Larsson et al. [1] formally formulated the truck platooning problem as a mixed-integer linear programming model to optimize the routing and platooning plans of a truck fleet to minimize their total fuel costs. This work was followed by many studies. For instance, Luo et al. further extended the platooning model by considering multiple speed options for each vehicle and proposed an efficient heuristic algorithm to accelerate the solution process [11]. Boysen et al. further proposed a cubic algorithm to handle larger-sized instances [12].

Though the platooning optimization problem has received increasing investigation, little attention has been paid to the impact of human involvement on platooning performance. However, special attention should be paid to the very important

Min Xu is with The Hong Kong Polytechnic University, Hong Kong (e-mail: min.m.xu@polyu.edu.hk).

aspect in routing and planning that all truck drivers must obey the legislation on mandatory break times during their trips to comply with the Hours of Service (HOS) for safety reasons [13]. Note that the routing plans and platooning strategies for truck drivers can be applied in the real world only if the strict regulation on drivers' compulsory break time is considered in the platooning model

B. Objectives and Research Gap

To bridge the above gaps, this paper investigates the truck platooning optimization problem under the consideration of drivers' mandatory breaks, referred to as the TPOB hereafter. We consider the semi-autonomous truck platooning mode, in which the leading driver is in control of the platoon and carries out the traditional driving task, while the drivers of the trailing trucks can handle alternative non-driving tasks, which can be regarded as valid breaks. We assume that the leading truck in a platoon as well as trucks traveling alone experience no fuel savings. The objective of this study is to minimize the total amount of fuel consumed by the fleet of trucks across a highway network by optimizing their rout es, schedules, and platooning plans. We formulate it as a mixed-integer programming model (MIP) and solve it with CPLEX. Numerical experiments are conducted to demonstrate the efficiency and effectiveness of our proposed model. In addition, we explore the impact of mandatory breaks on fuel-savings performance.

II. Problem Description

We define the TPOB over a highway network represented by an undirected and connected graph $\mathbf{G} = (\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is the set of nodes in the graph and $\mathbf{E} \subset \mathbf{V} \times \mathbf{V}$ is the set of undirected edges. Let $\mathbf{N}$ denote the set of involved trucks. Each truck is assigned a transport mission, consisting of an origin node O_n, a destination node d_n, and a service time window, i.e., the earliest departure time σ_n and latest arrival time τ_n. For simplicity, we assume that all the trucks can travel at free-flow speed on any edge $(i, j) \in \mathbf{E}$ and the required travel time for edge $(i, j) \in \mathbf{E}$ is denoted by w_{ij}. Besides, the unit fuel cost of traversing an edge $(i, j) \in \mathbf{E}$ for a truck is denoted by c_{ij}. A fraction η of the normal fuel used by trucks traveling alone can be saved by the trailing trucks in platoons. To exactly build the platooning model considering mandatory breaks, we will elaborate on the truck platooning and driver's mandatory breaks in the following subsections.

A. Truck Platooning

To mathematically formulate the platooning model, we should first specify the truck platooning process in this study. Each truck is assigned a transport mission and reports the information to the central coordinator before the departure. Trucks are digitally connected to the central coordinator via a communication system and thus able to share their transport assignment information. The platoon coordinator then computes and optimizes fuel-efficient routes and schedules for the fleet of trucks. These instructions will be sent to the trucks and assumed to be successfully executed.

Regarding platooning, we consider that a fleet of trucks can form fuel-efficient platoons while traveling across a highway network to save fuel. We assume that only the trucks arriving at a node of the network at the same time can form a platoon. Besides, the trucks are allowed to take detours or wait at nodes for some time u_i^n to form or join a platoon. To plan routes for the trucks, we introduce the binary decision variable x_{ij}^n to indicate whether truck n covers the edge $(i, j) \in \mathbf{E}$ on its trip. This routing decision is made along with the platooning plan, represented by the binary decision variable p_{ij}^{nm} to indicate whether truck n follows truck m over edge $(i, j) \in \mathbf{E}$.

B. Platooning Formations under the Mandatory Regulations on Drivers' Breaks

Social regulations on mandatory breaks are the issues that drivers must respect for safety reasons. The truck platooning incorporating the consideration of drivers' mandatory breaks requires routing all the trucks to their destinations under each own break time restriction. Fortunately, with the development of connected and automated technology, the drivers of the trailing trucks in a platoon may have a valid rest. In this way, we denote the driving time w_{ij} of a truck from node i to node j as a trailer in the platoon can be counted as his/her break time, so does the time u_i^n that truck n waits at node i for joining a platoon. In this study, we stipulate that an accumulated break time for the driver of truck n throughout his/her trip should be at least totaling T_n to meet the strict regulations on breaks.

III. Optimization Model Building

A. Assumptions

We make the following assumptions to underlie our exact model. All the trucks in this study are assumed to be homogeneous and are ready to platoon with others once informed by the central coordinator. We assume that trucks are numbered and those with larger indices will follow the ones with smaller indices if in a platoon. We also assume that the trucks leading the platoon and traveling alone experience no fuel savings, and all the trailing trucks in the platoons benefit from the same fuel-saving rate regardless of their positions.

B. Model Sets, Parameters, and Variables

To formulate our mathematical model, the notations are summarized in Table I.

C. Model Formulation

Based on the descriptions and analysis above, the problem in this paper can be formulated by the following optimization model:

[TPOB]

$$\min_{x,p,t,u,g} \sum_{(i,j)\in\mathbf{E}} c_{ij} \cdot g_{ij} \tag{1}$$

TABLE I
NOTATIONS USED IN THE MODEL BUILDING

Symbol	Description
Indices and sets:	
$\mathbf{G}=(\mathbf{V},\mathbf{E})$	Graph with node set $\mathbf{V}$ and edge set $\mathbf{E}$
$\mathbf{V}$	Set of network nodes
$\mathbf{E}$	Set of network edges
$\mathbf{N}$	Set of trucks
(i,j)	Index for edge
i,j	Indices for nodes
n,m	Indices for trucks
Known parameters:	
o_n	Origin node for truck $n\in\mathbf{N}$
d_n	Destination node for truck $n\in\mathbf{N}$
w_{ij}	The time required to traverse the edge $(i,j)\in\mathbf{E}$
σ_n	Earliest departure time for truck $n\in\mathbf{N}$
τ_n	Latest arrival time for truck $n\in\mathbf{N}$
T_n	Mandatory minimum break time for the driver in the truck $n\in\mathbf{N}$ during his/her entire travel journey
c_{ij}	Unit fuel cost of traversing edge $(i,j)\in\mathbf{E}$
η	Fuel reduction rate for the trailing trucks in a platoon
M	A sufficiently large enough positive number
Decision variables:	
x_{ij}^n	Binary variable indicating whether truck $n\in\mathbf{N}$ travels on the edge $(i,j)\in\mathbf{E}$
p_{ij}^{nm}	Binary variable indicating whether truck $n\in\mathbf{N}$ follows truck $m\in\mathbf{N}$ over the edge $(i,j)\in\mathbf{E}$
t_{ij}^n	The time when the truck $n\in\mathbf{N}$ starts traversing an edge $(i,j)\in\mathbf{E}$
u_i^n	Waiting time at the node $i\in\mathbf{V}$ of the driver in the truck $n\in\mathbf{N}$
g_{ij}	Joint fuel consumption for the trucks traversing the edge $(i,j)\in\mathbf{E}$

$$\sum_{j\in\mathbf{V}} x_{ij}^n - \sum_{j\in\mathbf{V}} x_{ji}^n = \begin{cases} 1 & \text{if } i=o_n \\ -1 & \text{if } i=d_n \\ 0 & \text{otherwise} \end{cases}, \forall\, i\in\mathbf{V},\ n\in\mathbf{N} \tag{2}$$

$$t_{ij}^n - t_{ki}^n \ge w_{ij} + u_i^n - M(2 - x_{ij}^n - x_{ki}^n), \forall (i,j)\in\mathbf{E}, (k,i)\in\mathbf{E}, n\in\mathbf{N}, i\ne o_n \ne d_n \tag{3}$$

$$t_{o_n i}^n \ge \sigma_n + u_{o_n}^n - M\cdot(1 - x_{o_n i}^n), \forall (o_n,i)\in\mathbf{E}, n\in\mathbf{N} \tag{4}$$

$$\tau_n \ge t_{id_n}^n + w_{id_n} + u_{d_n}^n - M\cdot(1 - x_{id_n}^n), \forall (i,d_n)\in\mathbf{E}, n\in\mathbf{N} \tag{5}$$

$$t_{ij}^n \le M\cdot x_{ij}^n, \forall (i,j)\in\mathbf{E},\ n\in\mathbf{N} \tag{6}$$

$$u_i^n \le M\cdot(\sum_{j\in\mathbf{N}} x_{ij}^n + x_{ji}^n), \forall i\in\mathbf{V},\ n\in\mathbf{N} \tag{7}$$

$$-M(1-P_{ij}^{nm}) \le t_{ij}^n - t_{ij}^m \le M(1-P_{ij}^{nm}), \forall (i,j)\in\mathbf{E}, n,m\in\mathbf{N}, n\ge m \tag{8}$$

$$2P_{ij}^{nm} \le x_{ij}^n + x_{ij}^m, \forall (i,j)\in\mathbf{E}, n,m\in\mathbf{N}, n\ge m \tag{9}$$

$$\sum_{n\in N} P_{ij}^{nm} \le 1, \forall (i,j)\in\mathbf{E}, m\in\mathbf{N} \tag{10}$$

$$\sum_{m\in N} P_{ij}^{nm} \le 1, \forall (i,j)\in\mathbf{E}, n\in\mathbf{N} \tag{11}$$

$$P_{ij}^{nm} + P_{ij}^{mn} \le 1, \forall (i,j)\in\mathbf{E}, n,m\in\mathbf{N} \tag{12}$$

$$g_{ij} = \sum_{n\in\mathbf{N}}\left(x_{ij}^n - \eta \sum_{m\in\mathbf{N}} P_{ij}^{nm} \right), \forall (i,j)\in\mathbf{E} \tag{13}$$

$$T_n \le \sum_{(i,j)\in\mathbf{E}} \sum_{m\in\mathbf{N}} P_{ij}^{nm}\cdot w_{ij} + \sum_{i\in\mathbf{V}} u_i^n, \forall n\in\mathbf{N} \tag{14}$$

$$\begin{cases} x_{ij}^n \in \{0,1\}, P_{ij}^{nm}\in\{0,1\} \\ t_{ij}^n \ge 0, u_i^n \ge 0, g_{ij}\ge 0 \end{cases}, \forall (i,j)\in\mathbf{E}, n,m\in\mathbf{N} \tag{15}$$

IV. NUMERICAL EXPERIMENTS

In this section, we test the performance of our proposed model for TPOB by using CPLEX and the CPU time limit is set to 7200 seconds. Note that the platooning problem we investigated is computationally expensive due to the inherent complexity of platooning and the additional complexity caused by drivers' mandatory breaks. To this end, we only test the small-sized problem instances in this study.

A. Test Instances

Two randomly generated highway networks with different numbers of nodes, i.e., 10 and 20, are used to conduct the numerical experiments. As for the truck fleet, we consider two different fleet sizes, i.e., 5 and 10. The travel time on edge in the network is drawn randomly from [5,30]. Pair of origin/ destination nodes, i.e., o_n and d_n, for each truck is also randomly generated from the nodes of the networks. Besides, the origin time for each truck is drawn uniformly from [0,30], while the latest arrival times are calculated as:

$$\tau_n = \sigma_n + (1+\varphi)\cdot\zeta_n, \forall n\in\mathbf{N} \tag{16}$$

where ζ_n is the minimum time required to travel between the truck n's origin and destination along the shortest path. φ is a parameter to control the tightness of the time window for each truck and we set $\varphi = 1$ in this paper. Furthermore, the unit fuel cost c_{ij}, the mandatory break time T_n for truck n, and the fuel reduction rate η are set to 1, 45, and 10%, respectively, in the model.

B. Numerical Results

Assessment of the Model

To quantify the fuel-saving benefits from platooning, we benchmark the solution results of the model without considering platooning. Table II gives the average results of objective function values and CPU runtimes for both settings. An observation is that even a small increase in the number of trucks and the nodes of the highway networks would cause a significantly longer computational time for CPLEX. For example, we find that the instances with 5 trucks can be solved to optimality within dozens of seconds by CPLEX, whereas the runtimes for instances with 10 trucks would rise to averagely half an hour. Besides, for the fleet size of 10 trucks, the CPU runtimes required to solve the instances with 20 cities are almost 21 times longer than that with 10 cities. The exponential increase of CPU runtimes for the model indicates the computational complexity of the problem we investigate in this study. In addition, compared with the model with platooning, the model without platooning requires much shorter CPU runtimes to be solved to optimality. Besides, it seems that the runtimes for the platooning-forbidden model are insensitive to the increase in the size of the fleet or the network. In addition, we also find that substantial fuel reductions can actually be achieved by platooning. The average percentage of the fuel reduction is observed to be 6.22%. Moreover, another notable observation is that the fuel-saving effects increase with the size of the fleet, i.e., more trucks involved, more fuel can be saved.

TABLE II
NUMERICAL COMPARISON RESULTS

Fleet size	Node number	Computation results				
		With platooning		Without platooning		Comparison
5	10	156.87	1	162.91	1	-3.71%
	20	266.42	72	280.08	2	-4.88%
10	10	372.55	112	402.11	16	-7.35%
	20	543.84	2409	597.16	35	-8.93%
5	10	156.87	1	162.91	1	-3.71%
Average		334.92	648.5	359.675	13.5	-6.22%

Impacts of Drivers' Mandatory Breaks on Fuel-Saving Performance

To evaluate the impact of drivers' compulsory breaks on the fuel-saving performance of the model, we compare the solution results of the platooning model formulation including and excluding mandatory breaks. The results in Fig. 2 show a slight increase in the total fuel costs in the presence of drivers' compulsory breaks, indicating at least the predictable drawbacks of these breaks due to the reduced temporal flexibility for platooning coordination. On the other hand, such a small difference of the objective values also indicates that the breaks cast unexpectedly obscure negative impact on the platooning benefit in terms of fuel savings, which can be explained by the driving-while-resting benefit provided for the trailing trucks.

V. CONCLUSIONS

In this paper, we explore the combinatorial problem of truck routing and platooning problem by comprising the restrictions on truck drivers' compulsory breaks. We formulate the problem as an MIP model and solve it by CPLEX. The effectiveness of the proposed model has been demonstrated by our numerical experiments. We also investigate the impact of compulsory breaks on platooning performance. Contrary to our prior expectations, however, mandatory breaks cast a small negative effect on the fuel-saving benefit of platooning. Nevertheless, this paper only deals with the small-sized instances of the proposed problem. To cope with the larger-sized platooning problems, more compact mathematical models and tailored-designed efficient algorithms are highly expected in future related research.

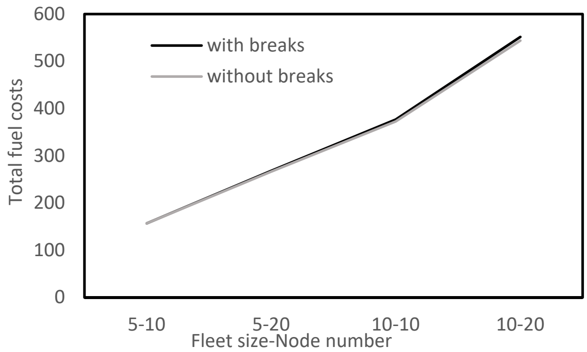

Fig. 2 Comparison between the model with and without the drivers' breaks

ACKNOWLEDGEMENT

The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (PolyU 15221821). We also appreciate the support from the Hong Kong Polytechnic University (UAKQ).

REFERENCES

[1] Larsson, E., Sennton, G., Larson, J., "The vehicle platooning problem: Computational complexity and heuristics," *Transportation Research Part C: Emerging Technologies*, 60, pp. 258-277, 2015.

[2] Bhoopalam, A.K., Agatz, N., Zuidwijk, R., "Planning of truck platoons: A literature review and directions for future research," *Transportation Research Part B: Methodological,* 107, 212-228, 2018.

[3] Hu, J., Wang, H., Li, X., Li, X., "Modelling merging behaviour joining a cooperative adaptive cruise control platoon," *IET Intelligent Transport Systems*, 14(7), pp. 693-701,2020.

[4] Liang, K.-Y., "Coordination and routing for fuel-efficient heavy-duty vehicle platoon formation," KTH Royal Institute of Technology, 2014.

[5] Alam, A., Besselink, B., Turri, V., Mårtensson, J., Johansson, K.H., "Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency," *IEEE Control Systems Magazine*, 35(6), pp. 34-56,2015.

[6] Chen, J., Bai, D., Liang, H., Zhou, Y, "A third-order consensus approach for vehicle platoon with intervehicle communication," *Journal of Advanced Transportation*,112, pp. 36-49, 2018.

[7] Jia, D., Ngoduy, D., "Platoon based cooperative driving model with consideration of realistic inter-vehicle communication," *Transportation Research Part C: Emerging Technologies*, 68, pp. 245-264, 2016.

[8] Bonnet, C., Fritz, H., "Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing", SAE Technical Paper,2000.

[9] Shladover, S.E., Lu, X.-Y., Yang, S., Ramezani, H., Spring, J., Nowakowski, C., Nelson, D., Thompson, D., Kailas, A., McAuliffe, B., "Partial Automation for Truck Platooning. United States", Federal Highway Administration Office of Research, 120, pp. 326-360, 2019.

[10] Larson, J., Kammer, C., Liang, K.-Y., Johansson, K.H. "Coordinated route optimization for heavy-duty vehicle platoons", *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, IEEE, pp. 1196-1202.

[11] Luo, F., Larson, J., Munson, T., "Coordinated platooning with multiple speeds", *Transportation Research Part C: Emerging Technologies*, 90, pp. 213-225, 2018.

[12] Boysen, N., Briskorn, D., Schwerdfeger, S., "The identical-path truck platooning problem", *Transportation Research Part B: Methodological*, 109, pp. 26-39, 2018.

[13] Goel, A., "A mixed-integer programming formulation and effective cuts for minimizing schedule durations of Australian truck drivers", *Journal of Scheduling*, 15(6), pp. 733-741, 2021.