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A third-party platoon coordination service: Pricing under government subsidies

Ting Bai[1,2] | Alexander Johansson[1] | Shaoyuan Li[3,4] | Karl Henrik Johansson[1,5] | Jonas Mårtensson[1,2]

[1]School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden

[2]Integrated Transport Research Lab (ITRL), KTH Royal Institute of Technology, Stockholm, Sweden

[3]Department of Automation, Shanghai Jiao Tong University, Shanghai, China

[4]Key Laboratory of System Control and Information Processing, Shanghai Jiao Tong University, Shanghai, China

[5]Digital Futures, Stockholm, Sweden

Correspondence
Ting Bai, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden.
Email: tingbai@kth.se

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Abstract

This paper models a platooning system consisting of trucks and a third-party service provider (TPSP), which performs platoon coordination, distributes the platooning profit in platoons, and charges trucks in exchange for the services. Government subsidies used to incentivize platooning are also considered. We propose a pricing rule for the TPSP, which keeps part of the platooning profit including the subsidy each time a platoon is formed. In addition, a platoon coordination solution based on the distributed model predictive control (MPC) is proposed, in which the pricing rule under government subsidies is integrated. We perform a realistic simulation over the Swedish road network to evaluate the impact of the pricing rule and subsidies on the achieved profits and fuel savings. Our results show that subsidies are an effective mean to boost fuel savings from platooning. Moreover, the simulation study indicates that high pricing corresponds to a low platooning rate of the system, as trucks' incentives for platooning decrease.

KEYWORDS

distributed model predictive control, government subsidies, platoon coordination, pricing rules

1 | INTRODUCTION

Truck platooning is an advanced technology in transportation systems, which allows trucks to be lined up on roads and drive in formation with small intervehicle distances. Compared to driving individually, driving in platoons help trucks save fuel consumption and decrease greenhouse gas emissions, due to the reduced aerodynamic drag experienced by the follower trucks. As has been shown by the field test on a four-truck automated platoon in the Energy ITS Project [1], platooning yields average fuel savings of 15% with 4-m intervehicle gaps. Another field test in [2] demonstrated that the leader truck of a platoon can achieve 4%–5% of fuel savings and the follower trucks can achieve 10%–14% of fuel savings. In addition to improving fuel economy, truck platooning contributes to increasing road capacity, reducing traffic jams, enhancing driving safety, cutting laboring costs, and alleviating driver shortages (see, e.g., [3–6]). In the past decades, platooning technology has been actively researched in both industry and academia, for example, in the research projects CHAUFFEUR [7], SARTRE [8], COMPANION [9], and ENSEMBLE [10].

Platoon coordination is critical for trucks that have different routes and time schedules to form platoons and enjoy platooning benefits. To date, there have been extensive achievements in coordination schemes to facilitate the formation of platoons, including optimizing the transport routes [11], adjusting trucks' driving speeds on routes [12], scheduling trucks' waiting and departure times at hubs [13–16], and co-design of the routes and travel times required to traverse the routes [17]. However, most of the existing coordination schemes have been developed in a centralized framework, where the goal is to maximize the platooning profits of all trucks in the system. These methods become inapplicable to large-scale networks consisting of a vast number of trucks from different carriers, due to the heavy computational load and noncooperative optimization targets. To deal with this scenario, the authors in [18] proposed a noncooperative game-theoretic approach to optimally schedule trucks' waiting times for forming platoons. However, since their method is based upon a Nash equilibrium solution of a platoon coordination game, it requires a large number of iterations when considering many trucks and thus, may also face the challenge of low computational efficiency. In [19], a distributed model predictive control (MPC) approach for addressing the hub-based platoon coordination problem was developed, where trucks schedule their waiting times independently given the predicted departure times of others. Such a coordination mechanism allows for distributing the computation load and is suitable for platoon coordination in large networks, but it requires full communication among trucks. The information shared among trucks includes their delivery routes, predicted arrival and departure times at hubs, and the achieved platooning benefits. In practice, trucks owned by different carriers may not share travel information and platooning profits with others due to privacy concerns. To avoid direct information-sharing among carriers and trucks, a third-party service provider (TPSP) is needed, which performs platoon coordination, distributes platooning profits among trucks, and takes a service fee in exchange for offering the coordination service.

Today, to cope with global climate change, more than 190 countries have signed the Paris Agreement with the common goal of achieving carbon neutrality by 2050. Since transportation is responsible for approximately 20% of the greenhouse gas emissions worldwide [20], governments have enacted a number of policies and measures to reduce carbon emissions resulting from the transport sector, including the establishment of carbon emission trading systems [21], the provision of tax breaks to encourage the use of renewable fuels [22], and the promotion of the electrification of fuel-powered vehicles with subsidies [23]. In this context, governments may also be interested in subsidizing truck platooning. Given government subsidies, how the TPSP determines its pricing rule for providing platoon coordination services to trucks, and how the government subsidy and pricing rule affect trucks' platooning behaviors have not been studied in the existing literature.

The profit-sharing schemes within platoons have attracted increasing attention recently. In [24], a noncooperative game modeling truck platooning was presented and three different schemes to share profit were developed. On the contrary, the authors in [25] modeled the behaviors of trucks in a cooperative game, where the proposed profit-sharing scheme makes trucks have no incentive to not follow the system-optimal solution. Different from these works, in this paper, a large-scale platooning system is considered and the profit-sharing scheme between trucks and the TPSP with government subsidies is taken into account. More specifically, we study a class of pricing rules for the TPSP, which provides platoon coordination service to individual trucks, shares platooning profit among trucks in platoons, and charges trucks service fees in exchange for offering the service while taking into account government subsidies.

As shown in Figure 1, the working scheme of the platooning system model developed for the TPSP can be divided into two phases: Offline evaluation and online optimization. (i) Offline evaluation phase: given the government subsidies and travel plans of trucks, including trucks' delivery routes, starting travel times, deadlines, etc., the TPSP could evaluate its profit and decide properly the pricing rule. (ii) Online optimization phase: The TPSP could then collect live data from trucks, including trucks' dynamic locations, travel times on routes, and waiting and departure times at hubs. Based on trucks' travel plans and the pricing rule determined offline, the TPSP could offer real-time platoon coordination service to every truck arriving at a hub, where the service refers to the optimal suggested waiting time for each truck. Meanwhile, in exchange for providing the service, the TPSP could charge the truck a service fee or compensate the truck to balance the platooning profits among trucks. Here, we note that the platooning system model in Figure 1 is developed from the viewpoint of the TPSP, where we assume that trucks will be willing to use the platoon coordination service if every truck has a non-negative profit from platooning. In addition, the government subsidy on truck platooning is assumed to be known by the TPSP. We also note that this paper is an extension of our previous work in [26], where a pricing rule of the TPSP was studied, without considering the interaction and influences of the government subsidies. To summarize, the major contributions of this paper are as follows.

- We model a platooning system consisting of trucks and a third-party platoon coordination service provider with subsidy support from the government. A pricing rule

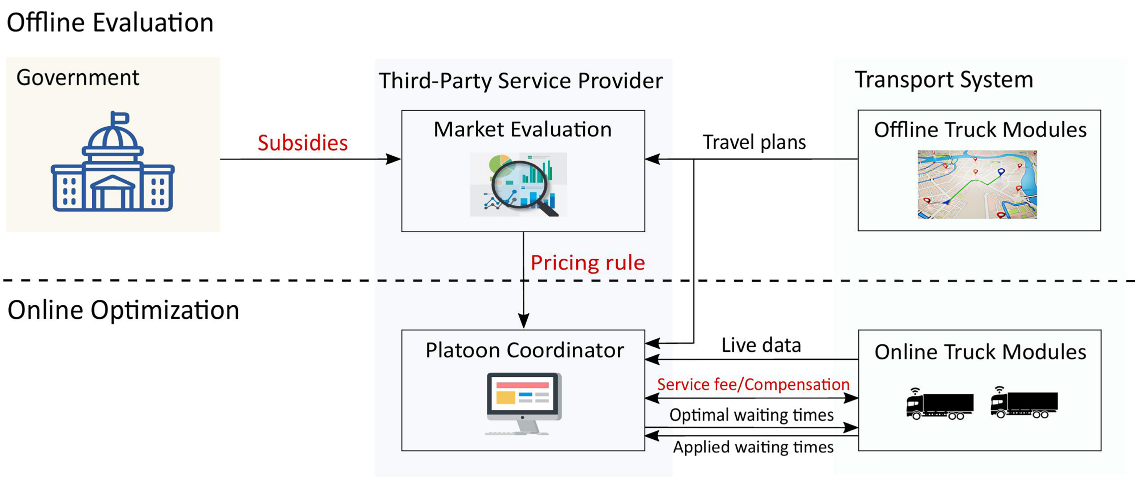


FIGURE 1 Illustration of the platooning system model developed for the TPSP, which consists of the offline evaluation phase and online optimization phase.

of the TPSP is developed to charge trucks that use the platoon coordination service.

- We propose a distributed platoon coordination approach for the TPSP based on the MPC scheme, in which the pricing rule of the TPSP under government subsidies is integrated.
- We perform a realistic simulation study over the Swedish road network to evaluate the impact of the pricing rule and subsidies on the profit distribution between trucks and the TPSP, and on trucks' platooning behaviors. Our simulation results show that subsidies are effective in boosting fuel savings from platooning and can increase both the profits of trucks and TPSP.
- We present the simulation where we study the trade-off between the profits of trucks and TPSP. The results show that TPSP should determine the pricing rule carefully as a high service price decreases trucks' incentives to form platoons and corresponds to a low platooning rate.

The rest of the paper is structured as follows. Section 2 proposes the pricing rule of the service provider that takes into account government subsidies. Section 3 introduces the distributed MPC-based platoon coordination approach wherein the pricing rule is integrated. Section 4 provides the simulation study and evaluation results. Finally, in Section 5, we conclude this paper and discuss the directions for future work.

2 | PRICING RULE UNDER GOVERNMENT SUBSIDIES

This section presents the pricing rule of the third-party platoon coordination service provider that considers the government subsidies to incentivize platooning. First of all, we make use of Figure 2 to illustrate the financial flow among the government, the service provider, and trucks in a platoon.

As shown in Figure 2, the TPSP receives subsidies from the government and uses them to increase the platooning profit. Meanwhile, the TPSP charges trucks service fees for offering the platoon coordination service each time a platoon is formed and distributes the remaining platooning profit among trucks in the platoon. In the following, we will introduce in detail the platooning profit under government subsidies, the pricing rule to charge trucks, and the compensation rule to balance the profit sharing among trucks.

2.1 | Platooning profit under subsidies

Trucks traveling in platoons can save fuel due to the reduced aerodynamic drag. As reported in [27–29], it is known from the field tests on truck platooning that every follower truck in a platoon has approximately the same fuel savings while the leader truck has significantly lower fuel savings. For simplification, we assume that every follower truck has the same platooning profit while the leader truck does not directly benefit from platooning (i.e., it has zero profit). We denote by B_f the platooning profit of each follower truck obtained by forming platoons with other trucks, which can be depicted by

$$B_f = \xi c, \tag{1}$$

where ξ denotes the platooning profit per follower truck per unit of travel time and c denotes the travel time of the follower truck. With government subsidies, the TPSP could increase the platooning profit of every follower truck in platoons to incentivize platooning. The new platooning

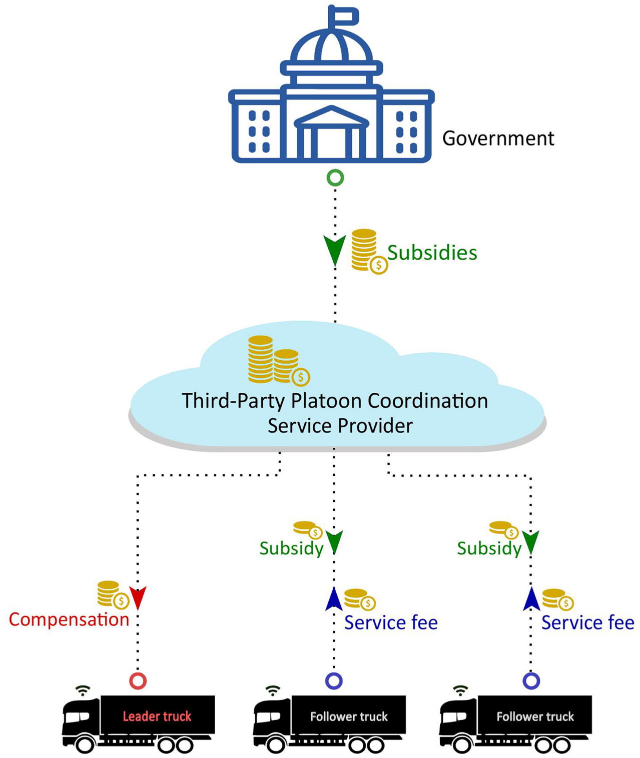


FIGURE 2 The financial flow among the government, the TPSP, and trucks in a platoon.

profit of each follower truck under government subsidies is denoted by

$$B^s_f = (\xi + \gamma)c, \tag{2}$$

where γ represents the government subsidy per follower truck per travel time unit. This indicates that the longer the travel time c and the more follower trucks in the platoon, the higher platooning profit can be achieved by trucks.

Remark 1. Increasing the subsidies γ in Equation (2) is mathematically equivalent to increasing the platooning profit ξ. In this paper, we study the role of the subsidies γ in promoting platoon formation and fuel savings while assuming that the value of ξ is fixed. In reality, the fluctuation of fuel prices, technological improvements in platooning, and other platooning benefits such as less labor costs can also bring changes in the platooning profits and the platooning incentives of trucks.

2.2 | Pricing rule

The pricing rule is set by the TPSP to charge trucks using the platoon coordination service. In this paper, we propose a pricing rule for the TPSP, where the TPSP charges every follower truck a service fee each time a platoon is formed and compensates the leader truck to offset the disparity between the leader's earnings and those of follower trucks.

Let us consider a platoon comprised of n trucks where each truck cares about its own platooning profit. The service fee used to charge each follower truck in the platoon is denoted by F_f, and there is no service fee for the leader truck. In order to balance the platooning profits among all trucks in the platoon, the TPSP keeps part of the service fee as its profit and uses the other part of the service fee to compensate the leader truck. That is,

$$F_f = F_{sf} + F_{lf}, \tag{3}$$

where F_{sf} denotes the part of the service fee from one follower truck kept by the TPSP as its profit, and F_{lf} denotes the rest part of the service fee per follower used to compensate the leader truck. For a platoon of n trucks, the remaining platooning profit after the payment of the service fee is $(B^s_f - F_{sf})(n-1)$, where $(n-1)$ is the number of follower trucks in the platoon. To make sure that the leader and follower trucks can equally share the remaining platooning profit, we divide the remaining profit among n trucks and each truck achieves

$$\bar{B}_t = \frac{(n-1)(B^s_f - F_{sf})}{n}. \tag{4}$$

Therefore, by setting $(n-1)F_{lf} = \bar{B}_t$, we can obtain that

$$F_{lf} = \frac{B^s_f - F_{sf}}{n}. \tag{5}$$

In this way, the TPSP can keep the profit of $(n-1)F_{sf}$ from a platoon of n trucks by charging each follower truck a service of F_f, and the remaining platooning profit is shared evenly among trucks in the platoon. In this paper, we consider F_{sf} as the following form:

$$F_{sf} = \alpha B^s_f, \tag{6}$$

where $0 \leq \alpha \leq 1$ is the adjustable parameter that regulates the profit sharing between trucks and the service provider. Given the above, the service fee of each follower truck in a platoon is obtained as

$$F_f = \frac{1 + (n-1)\alpha}{n} B^s_f. \tag{7}$$

The total profit of the service provider obtained from the platoon of n trucks is denoted as

$$P_s = \alpha(n-1)B^s_f. \tag{8}$$

Remark 2. As seen in Equation (8), the TPSP can adjust the proportion of the platooning profit it charges by varying the value of α, which in turn changes the remaining platooning profits kept by the trucks and affects their incentives to platoon. That is, there exists a trade-off between the profits of trucks and the service provider. In addition, the government subsidies will lead to a higher B_f^s compared to B_f, which has a positive impact on both the profits of the trucks and the TPSP.

2.3 | Compensation rule

The compensation rule is employed by the TPSP to determine the compensation for the leader truck each time a platoon is formed. As proposed in Equation (5), the profit of the leader truck obtained from the platoon of n trucks, that is, the compensation offered by the TPSP, has the following form:

$$P_l = (n-1)F_{lf} = \frac{(n-1)(1-\alpha)}{n}B_f^s, \tag{9}$$

which is equal to the average platooning profit $\bar{B}_t$ kept by every truck in the platoon and is equal to the platooning profit P_f saved by each follower truck. Namely,

$$P_f = B_f^s - F_f = P_l. \tag{10}$$

3 | DISTRIBUTED PLATOON COORDINATION

This section presents the MPC-based platoon coordination approach integrated with the proposed pricing rule. First, the model of the transport system is introduced, including the road network and the dynamic models of trucks. The utility function of every truck is then proposed. Finally, the distributed platoon coordination problem for determining the optimal waiting times of trucks is provided.

3.1 | System model

We consider a transport system that consists of M trucks, where every truck travels from its origin hub to its destination hub to fulfill a delivery task. Each truck $i \in \mathcal{M} = \{1, \dots, M\}$ has a fixed route and can form platoons at hubs along its route. We index the origin hub of truck i as the first hub and index its destination hub as the N_i-th hub. The route of truck i can be denoted by the set

$$\mathcal{E}_i = \{e_i(1), \dots, e_i(N_i - 1)\}, \tag{11}$$

where $e_i(k)$ denotes the k-th route segment of truck i connecting its k-th and $(k+1)$-th hub.

To proceed, we denote by $a_i(k+h|k)$ and $w_i(k+h|k)$ the predictions of the arrival and waiting times of truck i at its $(k+h)$-th hub predicted at its k-th hub, where $h \in \{0, \dots, N_i - k\}$. The travel time on the route segment $e_i(k)$ is denoted by $c_i(k)$. Then, the arrival times of truck i at hubs can be computed by the following equations:

$$a_i(1) = t_{i,start} \tag{12}$$

$$a_i(k+h+1|k) = a_i(k+h|k) + w_i(k+h|k) + c_i(k+h), \quad h = 0, \dots, N_i - 1 - k, \tag{13}$$

where, in particular, the arrival time of truck i at its origin hub, denoted by $a_i(1)$, is given by $t_{i,start}$. Since every trip has its delivery deadline to respect, it requires that $a_i(N_i|k) \leq t_{i,end}$, where $a_i(N_i|k)$ is the predicted arrival time of truck i at its destination hub and $t_{i,end}$ represents its latest time allowed to reach the destination.

3.2 | Utility of trucks

The utility of a truck includes the reward that the truck gains from forming platoons and the loss caused by waiting at hubs. In this paper, we assume that every truck is owned by a different carrier and aims at optimizing its own utility. Below we start by presenting the reward function of each truck.

3.2.1 | Reward function

According to Equations (9) and (10), the remaining platoon profit is distributed evenly between the leader and follower trucks in each platoon. That is, for any truck i traveling in a platoon on its route segment $e_i(k)$, no matter whether it is a follower or a leader truck, its platooning profit is the same. By Equation (2), the platooning profit of each follower truck on $e_i(k)$ under government subsidies is

$$B_f^s = (\xi + \gamma)c_i(k), \tag{14}$$

where, as previously defined, ξ is the platooning profit per follower truck per travel time unit and γ is the government subsidy to each follower truck per travel time unit. Moreover, $c_i(k)$ denotes the travel time on the route segment $e_i(k)$, which is given by the dynamic model in (13).

To form a platoon at a hub, the departure times and the routes of trucks in the platoon must be synchronized. Next, the size of a platoon formed at a hub is characterized. The dynamic models of individual trucks in Equation (13) indicate that the arrival time of a truck at its $(k+1)$-th hub is predictable given its arrival and waiting times at its k-th hub. In other words, with the knowledge of other trucks' predicted departure times from hubs, the service provider could predict the platooning partners for each truck at every hub along its route.

Let $\mathcal{R}_i(k+h|k)$ be the set of the predicted platooning partners of truck i on its $(k+h)$-th route segment, which is predicted by the service provider to decide truck i's waiting times at its k-th hub. More precisely, $\mathcal{R}_i(k+h|k)$ includes trucks that are predicted to depart from the $(k+h)$-th hub in the route $\mathcal{E}_i$ at the same time as truck i and have the next route segment in common with truck i, including truck i. To represent $\mathcal{R}_i(k+h|k)$, we denote by $\mathcal{P}_i(k+h) = \{j \in \mathcal{M} : e_i(k+h) \in \mathcal{E}_j\}$ the group of trucks that have the route segment $e_i(k+h)$ in their routes. Then mathematically, $\mathcal{R}_i(k+h|k)$ can be denoted by

$$\mathcal{R}_i(k+h|k) = \{j \in \mathcal{P}_i(k+h) : a_i(k+h|k) + w_i(k+h|k) = d_{ji}(k+h|k)\}, \tag{15}$$

where $d_{ji}(k+h|k)$ denotes the predicted departure times of other trucks $j \in \mathcal{P}_i(k+h)$ at the $(k+h)$-th hub of truck i when truck i makes the waiting time decision at its k-th hub. On this basis, the size of the platoon formed by truck i and other trucks on $e_i(k+h)$ equals the cardinality of its predicted platooning partner set, that is, $n = |\mathcal{R}_i(k+h|k)|$. Truck i can choose which trucks to form platoons with at each of its hubs $(k+h)$ by controlling its waiting times $w_i(k+h|k)$, and forming platoons with different trucks can lead to different platooning profits for truck i.

By Equations (9), (14), and (15), the platooning profit of truck i on its route segment $e_i(k+h)$ predicted at its k-th hub is of the following form:

$$R_i(k+h|k) = (1-\alpha)(\xi+\gamma)c_i(k)\frac{|\mathcal{R}_i(k+h|k)|-1}{|\mathcal{R}_i(k+h|k)|}, \tag{16}$$

where $\mathcal{R}_i(k+h|k)$ includes all the trucks predicted to form a platoon with truck i at its $(k+h)$-th hub.

For any truck i arriving at its k-th hub, considering all the platooning profits on its remaining route segments, that is, from its k-th to (N_i-1)-th route segment, the profit that truck i predicts to achieve is

$$R_i(k) = \sum_{h=0}^{N_i-1-k} R_i(k+h|k), \tag{17}$$

which gives the reward function of truck i at its hub k.

3.2.2 | Loss function

Waiting at hubs increases the probability of joining platoons for trucks but may also increase their waiting loss during the entire journey due to the extra labor costs and the higher risk of being delayed. For any truck i at its k-th hub, the predicted waiting loss at all its remaining hubs, from the k-th to (N_i-1)-th hub, can be denoted by

$$L_i(k) = \sum_{h=0}^{N_i-1-k} \epsilon w_i(k+h|k), \tag{18}$$

where ϵ denotes the monetary loss per waiting time unit and $w_i(k+h|k)$ is truck i's waiting time at its $(k+h)$-th hub predicted at its k-th hub.

3.2.3 | Utility function

Given the above, the utility function of truck i at its k-th hub, including the predicted platooning reward and the waiting loss at all its remaining hubs, can be denoted as

$$J_i(k) = R_i(k) - L_i(k). \tag{19}$$

By maximizing the utility $J_i(k)$ for every truck i arriving at one of its hubs, the service provider is able to provide the optimal waiting time for each truck to form platoons.

3.3 | Platoon coordination problem

In the following, the platoon coordination problem of individual trucks is presented. Given the routes, dynamic models, and delivery deadlines of every truck, the service provider could suggest an optimal waiting time for each truck arriving at a hub. To provide satisfactory coordination service to each truck while making the problem computationally tractable, the platoon coordination problem of truck i at its k-th hub is formulated as the following distributed MPC problem:

$$\max_{w_i(k),\, b_i(k)} \; J_i(k) = \sum_{h=0}^{N_i-1-k} (1-\alpha)(\xi+\gamma)c_i(k)\frac{\|b_i(k+h|k)\|_1}{\|b_i(k+h|k)\|_1+1} - \sum_{h=0}^{N_i-1-k} \epsilon w_i(k+h|k), \tag{20a}$$

$$\text{s.t. } a_i(k|k) = t_{i,arr}(k), \tag{20b}$$

$$a_i(k+h+1|k) = a_i(k+h|k) + w_i(k+h|k) + c_i(k+h),\; h = 0, \dots, N_i-1-k, \tag{20c}$$

$$\left|a_i(k+h|k) + w_i(k+h|k) - d_{ji}(k+h|k)\right| \le \delta_i\left(1 - b_{ij}(k+h|k)\right),\; j \in \mathcal{P}_i(k+h),\; h = 0, \dots, N_i-1-k, \tag{20d}$$

$$b_{ij}(k+h|k) \in \{0,1\},\; j \in \mathcal{P}_i(k+h),\; h = 0, \dots, N_i-1-k, \tag{20e}$$

$$b_i(k+h|k) = [b_{ij}(k+h|k)]_{j\in\mathcal{P}_i(k+h)},\; h = 0, \dots, N_i-1-k, \tag{20f}$$

$$a_i(N_i|k) - t_{i,end} \le 0, \tag{20g}$$

where (20b) denotes truck i's arrival time at its k-th hub and (20c) is its dynamic model used to predict its arrival time at each hub. The optimization variables of the problem (20) include the waiting times $w_i(k)$ and the integer variables $b_i(k)$, which have the following forms:

$$w_i(k) = [w_i(k|k), w_i(k+1|k), \ \dots \ , w_i(N_i - 1|k)],$$
$$b_i(k) = [b_i(k|k), b_i(k+1|k), \ \dots \ , b_i(N_i - 1|k)].$$

As given in (20e) and (20f), $b_i(k+h|k)$ denotes the vector composed of the binary variables $b_{ij}(k+h|k) \in \{0,1\}$ with $j \in \mathcal{P}_i(k+h)$ and $h = 0, \dots, N_i - 1 - k$, where each binary variable captures if truck i forms a platoon with other trucks j.

The predicted platooning partner set $\mathcal{R}_i(k+h|k)$ defined in (15) is denoted by (20d), where $\delta_i > 0$ is a sufficiently large relaxation parameter. By (20d), we have $b_{ij}(k+h|k) = 1$ if truck i has the same predicted departure time as truck j at its $(k+h)$-th hub. The cardinality of $\mathcal{R}_i(k+h|k)$ can be then represented as $\|b_i(k+h|k)\|_1$, where the 1-norm $\|v\|_1$ denotes the sum of the absolute values of all the elements in the vector v. Finally, the constraint (20g) ensures that truck i respects its delivery deadline at its destination. By solving problem (20), the optimal waiting time $w_i^*(k|k)$ computed by the TPSP will be used as the optimal waiting time provided to truck i. The other optimal waiting times $[w_i^*(k+1|k), \dots, w_i^*(N_i - 1|k)]$ computed for the remaining hubs will be saved by the service provider and used as the predicted waiting times of truck i when scheduling the waiting times of other trucks.

In (20a), the objective is to maximize the utility of truck i, including its predicted platooning reward and waiting loss at all hubs in its remaining route. It is worth noting that, maximizing the profit of the TPSP is equivalent to maximizing the platooning reward of the truck i. The reason for not using the profit of the TPSP as the objective is that it may result in a waiting time decision for truck i leading to a negative utility $J_i(k)$. As a result, truck i may not follow the suggested waiting time and decrease its incentive to use the service.

Remark 3. The problem in (20) is a mixed-integer nonlinear program, which is difficult to solve by existing solvers, especially when considering large-scale transport networks with a vast number of trucks. In this paper, we resort to the dynamic programming (DP) method to address it. Specifically, given the predicted departure times of other trucks, the decision-making of each truck is decoupled, and the decision and state space of each truck can be discretized accordingly. This allows us to generate a DP graph for every truck arriving at each hub and solve the problem (20) by the DP method [30].

Remark 4. The optimal waiting time $w_i^*(k|k)$ is computed based on the predicted departure times of other trucks. As trucks can change/update their waiting decisions at each hub, the proposed platoon coordination approach cannot guarantee that every truck will join a platoon by waiting at its k-th hub for $w_i^*(k|k)$. To make sure that trucks can achieve non-negative platooning profits and thus enhance their willingness to use the coordination service, we consider the case where the service provider would afford trucks' waiting loss if they fail to form platoons with others by applying the suggested waiting times.

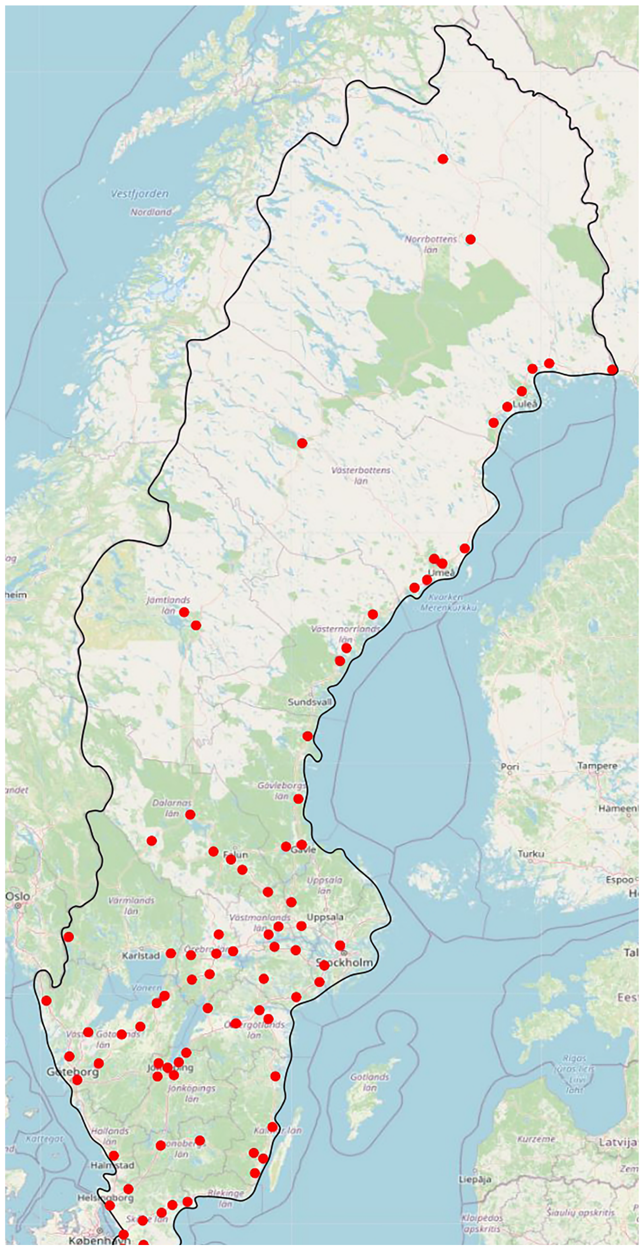


FIGURE 3 The Swedish road network, where the considered hubs are shown by the red nodes.

4 | SIMULATION STUDY

In this section, a realistic simulation study is conducted to evaluate the impact of the pricing rule and the government subsidies on the platooning system. The parameter settings of the simulation are introduced first. Next, the evaluations of the pricing rule and government subsidies are provided, respectively.

4.1 | Parameter settings

We consider a transport system of Sweden with hundreds of trucks. The origin and destination hubs for each trip are randomly selected from 84 hubs in the Swedish road network, as shown in Figure 3. The routes of trucks and their travel times on the route segments are obtained from *OpenStreetMap* [31]. We assume that trucks start their trips at any time between 08:00 and 12:00 and each truck travels with a speed of 80 km/h. The maximum travel time of a truck per day is 9 h. The allowed waiting time for each truck at all hubs in its route is assumed as 10% of its total travel time. Furthermore, we assume that the fuel saving of each follower truck is 10% of its fuel consumption. Based on these assumptions, the parameter ξ is obtained as 5.5€ per follower truck per hour. According to the driver's salary in Sweden, the waiting loss of every truck at hubs is set as $\epsilon = 25$€ per hour.

4.2 | Evaluation of the pricing rule

First, the pricing rule is evaluated. In Equation (8), the adjustable parameter α regulates the profit sharing between trucks and TPSP. To evaluate the influence of α on the platooning system, we test five scenarios in the simulation study, where the number of trucks in the system is varied from 100 to 500, and in each scenario, the value of α is varied from 0 to 1, with an increment interval of 0.1. A fixed initial system setting is adopted in each scenario while only the value of α is varied in the multiple simulation tests, that is, the routes, the starting times of trips, the delivery deadlines, and the waiting time constraints are exactly the same in each scenario.

We show the evaluation results in Figures 4–7. Specifically, Figure 4 shows the total profit of the TPSP achieved from the platooning system, without taking into account

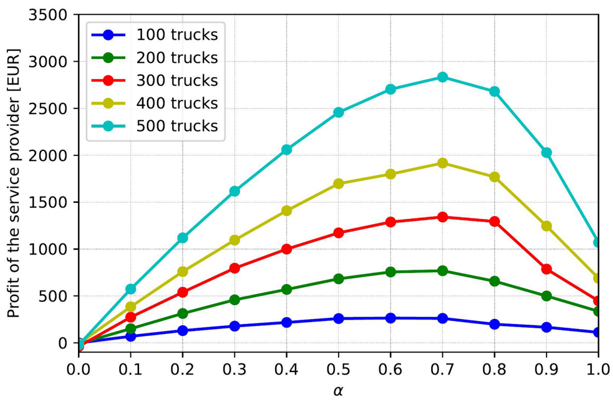


FIGURE 4 The profit of the service provider.

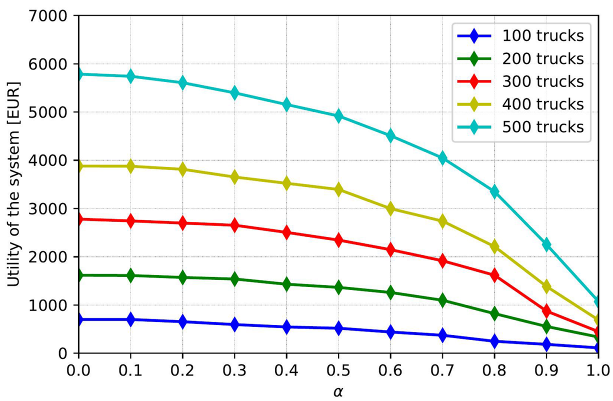


FIGURE 5 The utility of the platooning system.

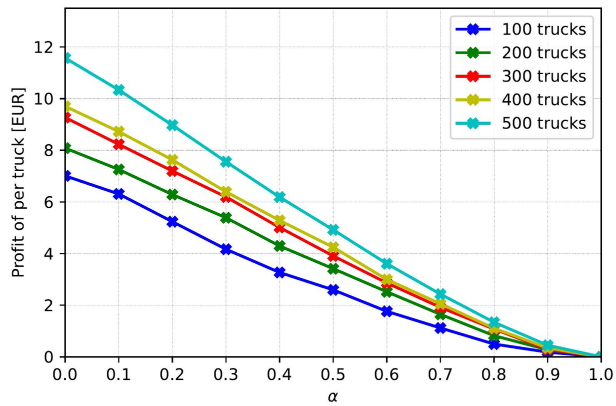


FIGURE 6 The average profit per truck.

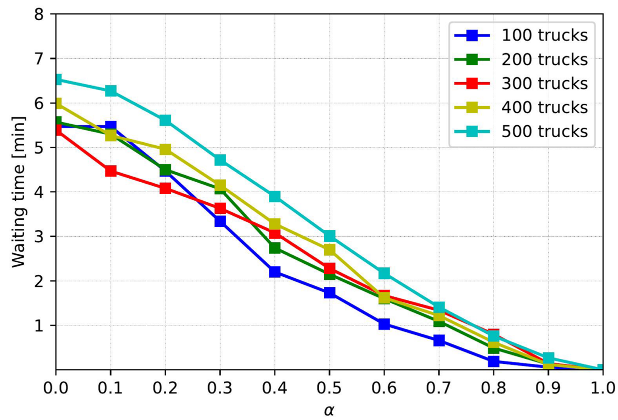
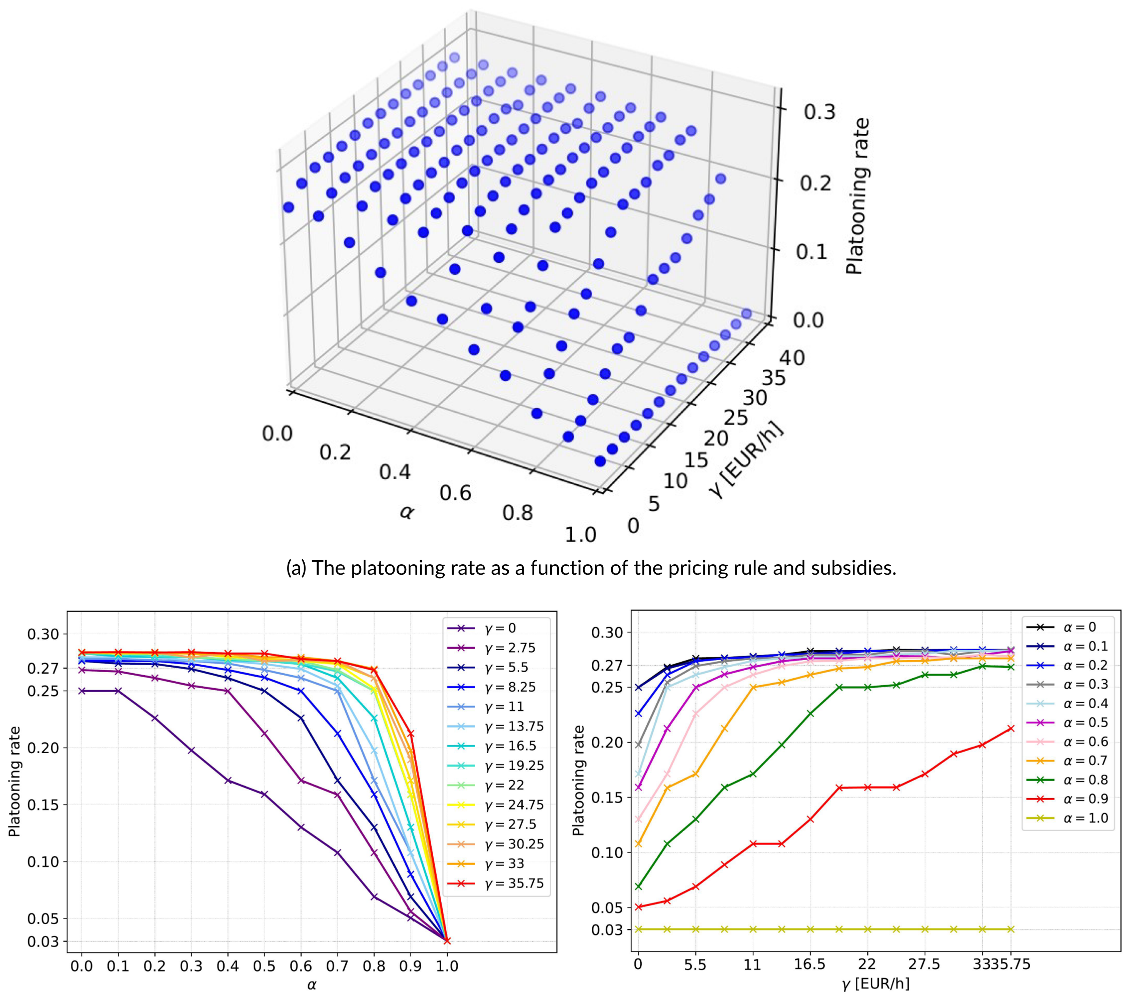


FIGURE 7 The average waiting time per truck.

the subsidy from the government, that is, $\gamma = 0$. As is shown in the figure, the profit of the service provider increases at first and then decreases as α increases. This result indicates that a decreased number of platoons are formed when the service fee is higher than a certain level. Moreover, for a fixed value of α, the more trucks in the system, the higher platooning profit the service provider can achieve. Figure 5 shows the utility of the platooning system. By "utility of the platooning system," we mean the sum of the utility achieved by all trucks in the system in their whole trips and the total profit kept by the service provider. As we can see, the system's utility is maximized when the service provider offers the platoon coordination service for free. As the proportion of the service fee in the platooning benefit increases, the utility of the system continues to decrease. Here, we note that the utility of the platooning system with $\alpha = 1$ is achieved by platoons formed spontaneously by trucks without waiting.

Figure 6 shows the average profit per truck in the system, that is, the average monetary gains of every truck after being charged a service fee. The results show that the profit of each truck tends to decrease as α increases, and the average profit approaches 0 when α approaches 1. We can also see from the simulation results that a platooning system with more trucks is beneficial to every truck to obtain a higher platooning profit. In addition, the average waiting time per truck at hubs during their whole trips is given in Figure 7. It shows that the average waiting time per truck is less than 7 min in the five scenarios and no truck decides to wait when α equals 1, in which case the service provider takes all the platooning profits. By comparing Figure 5 and Figure 7, we notice that some platoons can be formed spontaneously without coordination in particular cases. The more trucks in the system, the higher profit that the system obtains from the spontaneous platoons.

The above results indicate that the TPSP could obtain high platooning profit by setting a high service fee when



(a) The platooning rate as a function of the pricing rule and subsidies.

(b) The platooning rate of the system for different subsidies. (c) The platooning rate of the system for different pricing rules.

FIGURE 8 The platooning rate of the system as a function of the pricing rule and subsidies.

the service provider has its monopoly in the platooning system. If this is not the case, that is, the TPSP has competitors in the market, seeing that the utility of the system and the average utility of trucks will be decreasing as the service fee increases, the TPSP needs to select the service fee carefully to achieve a satisfactory profit.

4.3 | Evaluation of government subsidies

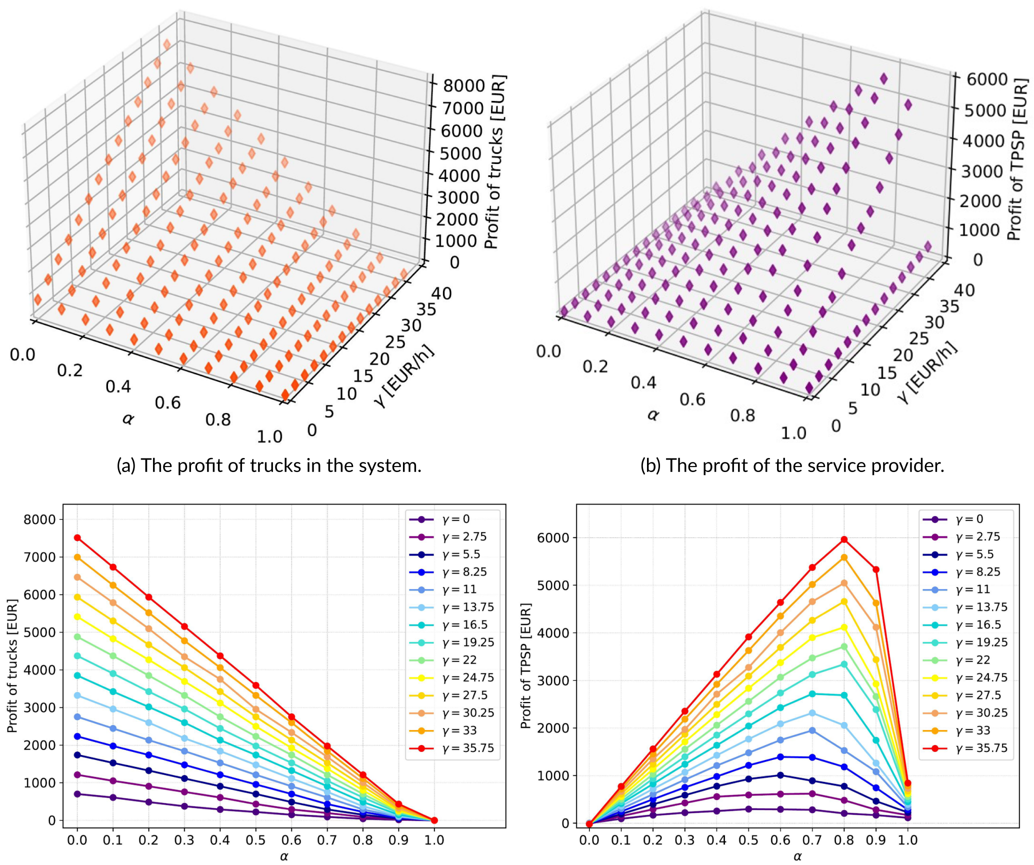
The impact of the government subsidies on the platooning system is then evaluated. We test the platooning performance in the first scenario with 100 trucks in the system and vary the government subsidies per follower truck per travel time unit linearly, that is, γ is selected by $\gamma = \beta\xi$ where β is varied from 0 to 6.5, with an increment interval of 0.5. That is, γ is selected from the set $\{2.75, 5.5, \dots, 37.5\}$. Notice that in the work, we model a platooning system from the perspective of the TPSP, without considering the modeling and optimization of the government subsidy decisions. In reality, the government subsidy plan can be made based on a variety of factors, including the financial budget, market demand, trucks' travel plans, and pricing rules, which is beyond the scope of this paper and not studied here. Today, 19 European countries have carbon taxes to limit carbon emissions and the carbon tax in Sweden is 116.33€ per tonne of carbon emissions [32], which is predicted to increase significantly by 2029 [33]. According to the carbon emissions of fuel trucks, which is 86.4-kg carbon emission per truck per hour, each truck has a carbon tax of approximately 10€ per hour without platooning. One can regard the government subsidy γ as a tax reduction for follower trucks in platoons. For example, a subsidy of 2.75€ per hour corresponds to a carbon tax reduction of 27.5%.

To evaluate the platooning efficiency, the platooning rate of a transport system with N trucks, denoted by $P_s(N)$, is defined by

$$P_s(N) = \frac{\text{Total travel time of follower trucks in platoons}}{\text{Total travel time of all trucks in the road network}}, \quad (21)$$

where N equals 100 in our simulation.

The platooning rate of the system with 100 trucks is shown in Figure 8, which is a function of the pricing rule



(a) The profit of trucks in the system.

(b) The profit of the service provider.

(c) The profit of trucks for different subsidies.

(d) The profit of the TPSP for different subsidies.

FIGURE 9 The profits of trucks and the service provider as a function of the pricing rule and subsidies.

TABLE 1 An example of the subsidy proposal to the government.

Platooning rate≥	Subsidy per travel time unitγ [EUR/h]	Fuel savings [L]	Subsidies [EUR]	Profit of TPSP [EUR]	Profit of trucks [EUR]
0.27	13.75	578	2485	2076	1100
0.25	11	562	1930	1748	960
0.20	8.25	537	1384	1390	700
0.15	5.5	486	836	1008	490
0.10	2.75	341	293	620	195
0.05	0	280	0	290	150

α and the subsidy γ. As shown in Figure 8a, the platooning rate $P_s(N)$ of the system is decreasing with the increase of the service pricing and is increasing with the increase of the subsidies. For an in-depth analysis of the trend, the platooning rates of the system for different subsidies and different pricing rules are provided in Figure 8b,c, respectively. Figure 8b shows that given a certain amount of subsidies, the platooning rate in the system decreases with the increase in α. The more subsidies from the government, the higher platooning rate can be achieved by the platooning system with the same pricing α. Moreover, the more subsidies the TPSP receives, the higher service pricing α can be selected to maintain the same level of platooning rate. The results in Figure 8c reveal that government subsidies fail to act as an incentive to truck platooning when $\alpha = 1$, meaning that the TPSP keeps all the platooning profits of trucks. For the other values of α (except for 1), the platooning rate of the system continues to grow and then reaches a peak with the increase of the subsidies. From the simulation results, we can also see that the maximum platooning rates of the system that can be reached by different α are similar. In other words, subsidies cannot increase the platooning rate indefinitely. The smaller the α, the fewer subsidies are required to reach the maximum platooning rate.

Under different pricing rules and government subsidies, the profits of trucks and the service provider are shown in Figure 9. Specifically, Figure 9a,b shows the profits of trucks and the profits of the TPSP as a function of the pricing rule α and subsidies γ, respectively. For better analysis, Figure 9c,d is used to show the profits of trucks and the TPSP under different subsidies. As we can see, the profits of trucks keep decreasing with the increase in pricing. In Figure 9d, it can be seen that subsidies also help the TPSP to increase its profit, and there exists a peak in the profit of the TPSP for a certain subsidy. Moreover, such a peak is moving toward a higher pricing α with the increase in the amount of the subsidies. This indicates that in a monopolized platooning market, the more subsidies the TPSP gets, the higher pricing can be set to maximize the TPSP's profit.

In light of the evaluation results in Figures 8 and 9, the TPSP could properly determine the pricing rule (i.e., the value of α) based on the given government subsidies and its optimization objectives, such as the maximum self-interest or the highest platooning rate of the system. For instance, if $\gamma = 11$€ per hour and the target is to maximize the profit of the TPSP, an appropriate α could be 0.7, according to Figure 9d. If the target is to maximize the platooning rate, which is beneficial for the TPSP to enhance trucks' incentives to use the service and improve its market share, then Figure 8c can be used to determine the pricing rule properly.

To conclude, the above evaluation results illustrate that government subsidies are effective in increasing the platooning rate of the system and thus boosting the fuel savings from platooning. In addition, government subsidies increase the profits of both the trucks and the TPSP. Given a certain amount of subsidies, a high service pricing corresponds to a low platooning rate in the system, as trucks' incentives to form platoons decrease.

Seeing that government subsidies play a crucial role in increasing the profits of trucks and TPSP, the TPSP could propose to the government to subsidize trucks to incentivize platooning. Based on the above simulation study, we provide in Table 1 an example of the subsidy proposal. More precisely, Table 1 shows the required subsidies to achieve certain levels of platooning rates and fuel savings. The first column of the table represents the lower bound of the platooning rate in the system, meaning that the platooning rate can be maintained at a level no lower than the given values by adjusting α. The subsidy per followed travel time unit γ is proposed by the TPSP, which is determined by studying the evaluation results in Figures 8b,c and 9d, and picking reasonable values of α and γ to maintain a certain platooning rate. The table also gives the total amount of fuel savings, subsidies, and the achieved profits of the TPSP and trucks under different platooning rates, where the fuel consumption is assumed as 0.4 L/km. Such a table can be used as a basis by the government when making subsidy plans.

5 | CONCLUSIONS AND FUTURE DIRECTIONS

This paper modeled a platooning system with a TPSP that coordinates trucks from different carriers to form platoons. A pricing rule for the service provider with subsidies provided by the government was proposed, in which every follower truck is charged a service fee while the leader truck is compensated. In addition, the pricing rule was integrated with a distributed MPC-based platoon coordination approach, by which the service provider schedules the waiting times of individual trucks and provides trucks with the optimal waiting times at hubs. A realistic simulation study was performed over the Swedish road network to evaluate the influences of the pricing rule and government subsidies on the achieved profits and fuel savings.

Our simulation results show that the platooning rate of the system highly relies on the service pricing. The higher the pricing, the lower the platooning rate. Additionally, the results show that government subsidies are effective in increasing the platooning rate and fuel savings from platooning, and the service provider can also benefit from the subsidies. Our simulation study also indicates that, if the TPSP takes a monopoly position in the market, for example, in the early stage of the commercialization of the platooning technology, it can achieve high profits by setting a high service price. If other competitors exist, the service provider needs to set the pricing carefully to maintain the trucks' willingness for using its service and to achieve satisfactory profits.

In the pricing rule proposed in this paper, trucks are charged a service fee each time a platoon is formed. In future work, it would be interesting to explore the pricing rule that allows for a subscription fee to trucks, in which trucks are charged weekly or monthly no matter how many times they use the services. Another possible extension is to study the pricing rules for a platooning system with competing service providers.

AUTHOR CONTRIBUTIONS

Ting Bai: Conceptualization; formal analysis; methodology; resources; software; validation; visualization; writing—original draft; writing—review and editing. **Alexander Johansson:** Formal analysis; writing—review and editing. **Shaoyuan Li:** Conceptualization; formal analysis; supervision; writing—review and editing. **Karl Henrik Johansson:** Conceptualization; formal analysis; supervision; writing—review and editing. **Jonas Mårtensson:** Conceptualization; formal analysis; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

Ting Bai https://orcid.org/0000-0002-1753-512X
Shaoyuan Li https://orcid.org/0000-0003-3427-2912

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AUTHOR BIOGRAPHIES

Ting Bai received a BSc degree in Automation from Northwestern Polytechnical University, Xi'an, China, in 2013, and a PhD degree in Electrical Engineering from Shanghai Jiao Tong University, Shanghai, China, in 2019. Since 2020, she has been with the Division of Decision and Control Systems, Department of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden, where she is a postdoctoral researcher. Her research interests include distributed model predictive control, optimization and control of complex networks, and platoon coordination in transport systems.

Alexander Johansson received an MSc degree in applied mathematics in 2017 from KTH Royal Institute of Technology, Stockholm, Sweden. In 2022, he received a PhD degree from the Division and Control Systems, Department of Intelligent Systems, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. His research interests are optimization, game theory, and control for platoon coordination.

Shaoyuan Li received BSc and MSc degrees in Automation from Hebei University of Technology, Tianjin, China, in 1987 and 1992, respectively, and a PhD degree from the Department of Computer and System Science, Nankai University, Tianjin, in 1997. Since July 1997, he has been with the Department of Automation, Shanghai Jiao Tong University, Shanghai, China, where he is currently a distinguished professor. His research interests include distributed model predictive control, dynamic system optimization, networked control systems, and system identification. He is a vice president of Asian Control Association (ACA) and a senior member of IEEE.

Karl Henrik Johansson is a professor with the School of Electrical Engineering and Computer Science at KTH Royal Institute of Technology in Sweden and Director of Digital Futures. He received MSc and PhD degrees from Lund University. He has held visiting positions at UC Berkeley, Caltech, NTU, HKUST Institute of Advanced Studies, and NTNU. His research interests are in networked control systems and cyber-physical systems with applications in transportation, energy, and automation networks. He is a member of the Swedish Research Council's Scientific Council for Natural Sciences and Engineering Sciences. He has served on the IEEE Control Systems Society Board of Governors and the IFAC Executive Board and is currently Vice-President of the European Control Association. He has received several best paper awards and other distinctions from IEEE, IFAC, and ACM. He has been awarded Distinguished Professor with the Swedish Research Council and Wallenberg Scholar with the Knut and Alice Wallenberg Foundation. He has received the Future Research Leader Award from the Swedish Foundation for Strategic Research and the triennial Young Author Prize from IFAC. He is Fellow of the IEEE and the Royal Swedish Academy of Engineering Sciences, and he is IEEE Control Systems Society Distinguished Lecturer.

Jonas Mårtensson received an MSc degree in vehicle engineering and a PhD degree in automatic control from KTH Royal Institute of Technology, Stockholm, Sweden, in 2002 and 2007, respectively. He was appointed as docent in 2016. He holds a tenure-track position as an Assistant Professor with the Department of Automatic Control, KTH Royal Institute of Technology. He is also engaged as a Program Leader in the Integrated Transport Research Laboratory and is a Thematic Leader for the area Transport in the Information Age within the KTH Transport Platform. His research interests are cooperative and autonomous transport systems, in particular related to heavy-duty vehicle platooning. He is involved in several collaboration projects with Scania CV AB, Södertälje, Sweden, dealing with collaborative adaptive cruise control, look-ahead platooning, route optimization and coordination for platooning, path planning and predictive control of autonomous heavy vehicles, and related topics.

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