Platoon Cooperation Across Carriers: From System Architecture to Coordination

Alexander Johansson, Ting Bai, Karl Henrik Johansson, and Jonas Mårtensson

Are with the Integrated Transport Research Lab, Digital Futures, and Division of Decision and Control, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden.

E-mail: alexjoha@kth.se; tingbai@kth.se; kallej@kth.se; jonas1g@kth.se.

xxxxxxx

Abstract—Truck platooning is a well-studied technology that has the potential to reduce both the environmental impact and operational costs of trucks. The technology has matured over the last 20 years, and the commercial rollout of platooning is approaching. Cooperation across carriers is essential for the viability of platooning; otherwise, many platooning opportunities are lost. We first present a cross-carrier platooning system architecture in which many carriers cooperate in forming platoons through a platoon-hailing service. Then, we present a cross-carrier platoon coordination approach in which each carrier optimizes its platooning plans according to the predicted plans of other carriers. A profit-sharing mechanism to even out the platooning profit in each platoon is embedded in the platoon coordination approach. Finally, a simulation study over the Swedish road network is performed to evaluate the potential of platooning under realistic conditions. The simulation study shows that the energy consumption of trucks in Sweden can be reduced by 5.4% due to platooning and that cooperation across carriers is essential to achieve significant platooning benefits.

Digital Object Identifier 10.1109/MITS.2022.3219997
Date of current version: 8 December 2022

1939-1390/23©2023IEEE

Platooning is when a group of trucks drives in a string formation on the road with small distances in between the trucks, as shown in Figure 1. Platooning reduces the environmental impact of trucks by improving the aerodynamics, especially for the follower trucks. The authors of [1], [2], [3], [4], and [5] demonstrated reduced energy consumption of follower trucks by around 10%. Moreover, the enabling automation technologies for platooning reduce the maneuvering of drivers, which significantly reduces the operational cost of trucks if drivers can perform other duties while in platoons or if some drivers can be removed. Other potential benefits of platooning are safer driving, increased road capacity, and reduced congestion. These benefits were studied by the authors of [6], [7], and [8]. Business opportunities for platooning have been investigated in [9], [10], [11], [12], [13].

Trucks need in-platoon coordination for cohesive, safe, and efficient platoon driving. The in-platoon coordination includes deciding reference speeds, accelerations, and intervehicular distances of platooning trucks. In-platoon coordination was studied in, for example, [14], [15], and [16]. Trucks also need coordination on a higher level to form platoons considering different routes and schedules. The high-level coordination includes matching trucks that will form platoons based on their routes and time schedules and deciding how the platoons will form. Platoons can form on roads by trucks slightly speeding up or slowing down. Due to the speed adjustments, on-road platoon formation may disturb or be disturbed by surrounding traffic. An alternative to on-road platoon formation is to form platoons at places along roads where trucks can wait for others and depart in the form of platoons. Such places where platoons can form along roads are called *hubs* and can be, for example, gas stations, charging stations, resting areas, and freight terminals. The coordination approach presented in this article is designed for platoon formation at hubs. Overviews of platoon coordination strategies were provided in [17] and [18].

The main focus of this article is platoon cooperation and high-level coordination across carriers. This is challenging because carriers have different objectives, are unwilling to share route and time schedules directly with other carriers, and are unwilling to leave control of their trucks to a third-party coordinator. The main contribution of this article is a cross-carrier platooning system that takes the challenges mentioned regarding cross-carrier platoon cooperation into account. First, we give an overview of research targeting high-level platoon coordination as well as an overview of experimental research projects on platooning. We then describe the layered structure of the platooning system and propose a functional system architecture of a platoon-hailing service that enables platoon cooperation across carriers by storing platooning plans of trucks and providing feasible platoons for trucks to join. Then, a coordination approach for hub-based platoon formation is presented where carriers make platooning decisions based on information from the platoon-hailing service.

The material presented in this article is based on our contributions to the research projects Sweden4Platooning and ENSEMBLE, which involved truck manufactures, suppliers of automotive equipment and technology, and academic partners. The Sweden4Platooning closing conference homepage, with links to presentations, is available at https://sites.google.com/view/s4pcc. The ENSEMBLE homepage, with links to deliverables and project information, is available at https://platooning ensemble.eu/.)

This article is organized as follows. A review of works on high-level platoon coordination and a brief overview of research projects on platooning is provided in the "Related Work" section. The "Cross-Carrier Platooning System" section presents the layered structure of the platooning system and our proposed cross-carrier platooning system architecture. The "Cross-Carrier Coordination Method" section gives the approach for coordinating platoon formation based on information from the platoon-hailing service. Results from a simulation study over the Swedish road network are presented in the "Simulation Study" section, and the article is concluded in the "Conclusions and Future Work" section.

Related Work

High-level platoon coordination has been studied in the literature quite extensively recently, and multiple experimental research projects on platooning have been conducted over the years.

(a)

(b)

FIG 1 A multibrand platooning demonstration in the ENSEMBLE project.

Review of High-Level Platoon Coordination

Coordination of on-road platoon formation where platoons form by adjusting the speeds of trucks was studied by, for example, in [19], [20], [21], and [22]. These works have different assumptions regarding their system models and complexity. However, they have in common that a platoon coordinator, having full access to routes and schedules, controls all trucks in the system and aims to maximize the overall profit. These assumptions may be unrealistic when multiple carriers are involved in the system.

This article focuses on platoon formation at hubs, where trucks can wait for others. Coordination of hub-based platoon formation was studied, for example, by the authors in [12], [23], [24], [25], [26], [27], [28], [29], and [30]. The majority of the work on hub-based platoon formation also assumes that a coordinator controls all trucks in the system, has access to their time schedules and routes, and aims to optimize the overall platooning profit in the system.

The authors of [27] proposed a cross-carrier platoon cooperation platform for when platooning is used as a transfer mode between a port and an industrial area. The platform decides the transportation schedules and service fees to minimize costs. Based on the platform's decisions, the carriers decide whether to use the platooning mode for their transportation tasks. The strategic interaction between the platform and the carriers is modeled as a two-level Stackelberg competition where the platform is the leader, and the carriers are the followers. In this work, we also consider cross-carrier platoon cooperation but develop a coordination method for when trucks have arbitrary routes in a network of hubs and carriers do not leave the scheduling of trucks to a third-party coordinator. We believe that considering Stackelberg competition among carriers in such a scenario would come with a high computational load, as it would require backward induction in a multistep game with as many steps as carriers.

The authors of [31] studied platoon coordination on a single road segment when trucks have individual preferences and trucks with the same speeds were assumed to form a platoon. The authors proposed a solution to maximize the total profit of all trucks. A profit-sharing mechanism was also proposed to incentivize trucks to accept the solution in a coalition game framework. Profit allocations based on coalition game concepts often have a high computational load. We believe coalition game concepts would imply a high computational load, even for the cross-carrier platoon coordination problem in a network of hubs. It is worth noting that the literature on collaborative transportation without platooning is extensive. Many of these works explore coalition game solutions for cooperation and profit sharing; see, for example, [32]. Other works consider auction-based methods that facilitate cooperation; see, for example, [33] and [34]. Profit sharing for collaborative transportation was reviewed in [35].

Hub-based coordination methods also explicitly addressing platoon cooperation across carriers were developed for the Sweden4Platooning, and ENSEMBLE projects [12], [28], [29], [30]. The authors of [29] assume that each truck controls its departure times from hubs and aims to maximize its individual platooning profit. The strategic interaction among trucks is modeled as a noncooperative game, and Nash equilibrium is considered the solution concept. This approach also comes with a high computational load due to the many iterations required for finding equilibrium when the trucks are many. The work of [28] proposes a Pareto-improving cross-carrier coordination solution, where each carrier is guaranteed to increase its profit by cooperation compared to when only forming platoons within its fleet. This approach requires the carriers to leave control of their trucks to a third-party coordinator.

The works of [12] and [30] consider a noncooperative scenario, where each truck aims to maximize the profit of its carrier. Instead of using game theoretic concepts for coordination and profit sharing, which often come with a high computational load, the departure times of trucks are computed based on the predicted departure times of others in a decoupled manner. The profit of each formed platoon is shared evenly among the trucks, and the proposed profit-sharing scheme falls into the class of proportional profit-sharing schemes discussed in [35]. In this way, trucks with individual preferences can cooperate efficiently in forming platoons without leaving the control of trucks to a third-party platoon coordinator. The loss of not considering game theoretic concepts for coordination and profit sharing is that collaboration incentives, stability of solutions, rationality, etc. are hard to analyze quantitatively.

The platoon coordination approach used in [12] and [30] inspired the coordinated system proposed in this article. The profit-sharing mechanism used in this article is inspired by one of the profit-sharing schemes developed in [36]. Other works developed under the ENSEMBLE project, but not presented in this article, regarding platoon coordination and business uptake of platooning are presented in [37] and [38], respectively.

Brief Overview of Research Projects on Platooning

Truck platooning has been studied and demonstrated by academic and industrial actors in various research projects since the early 2000s. The first projects studying truck platooning include PATH [1] in the United States, the Japanese Intelligent Transportation Systems project [39], and the European project CHAUFFEUR [40] as well as, in the late 2000s, the projects KONVOI [41] and SARTRE [42]. These projects focused on developing architectures and control schemes for safe and efficient platoon driving. In the early 2010s, the COMPANION project [43] and European Truck Platooning Challenge [44] were launched. COMPANION broadened the platooning research by including the high-level coordination of platoon formation in its scope. The European Truck Platooning Challenge project demonstrated platooning across borders, and the truck manufacturers DAF, Daimler, IVECO, MAN, Scania, and Volvo separately developed and demonstrated platoon functionalities.

The projects Sweden4Platooning [45] and ENSEMBLE [46] were launched in the late 2010s. Sweden4Platooning demonstrated platooning with Volvo and Scania trucks and became the first to develop multibrand platooning functionality, i.e., platooning with trucks of different brands. In the ENSEMBLE project, multibrand functionality was jointly developed by the seven truck manufacturers: DAF, Daimler, IVECO, MAN, Scania, Volvo, and Renault. Besides demonstrating multibrand platooning, Sweden4Platooning and ENSEMBLE have studied coordination for forming platoons, especially for trucks owned by competing carriers with self-interests. This article presents a cooperative platooning system, developed under the Sweden4Platooning and ENSEMBLE projects, where multiple carriers cooperate to form cross-carrier platoons.

Cross-Carrier Platooning System

The platooning system includes both on- and offboard systems. The layered structure of the platooning system and the functional system architecture of the platoon-hailing service through which carriers can cooperate in forming platoons are presented. Finally, we also describe the decision-making procedure triggered when a truck arrives at a hub.

Layered Structure of the Platooning System

The platooning system consists of layers needed to integrate platooning technology into today's transportation system, form platoons seamlessly, and maintain safe and efficient platoon driving. The layered structure shown in Figure 2 was developed in the ENSEMBLE project and shows the primary function of each layer. The layers are categorized as the service, strategic, tactical, and operational layers, where the former two layers are offboard systems, and the latter two layers are onboard systems.

The tactical and operational layers are the systems needed for safe and efficient platoon driving. Trucks in platoons communicate through vehicle-to-vehicle communication. The tactical layer includes the in-platoon coordination to maintain platoon cohesion and perform safe maneuvers, such as opening up intervehicular gaps when trucks join or leave platoons. The outputs from the tactical layer passed on to the local controllers of trucks are reference accelerations, speeds, and intervehicular distances. The operational layer includes the local control of individual trucks. In today's platooning technology, the local control includes longitudinal control to track the reference signals from the tactical layer, and future platooning technology with a higher degree of automation will also include latitudinal control.

The service and strategic layers are the systems needed for trucks with different routes and schedules to form platoons, integrate platooning into the transportation system, and enable carrier cooperation. The strategic and service layers communicate through cellular communication, long-distance communication, and cloud services. The strategic and tactical layers communicate through so-called infrastructure-to-vehicle and vehicle-to-everything communications. The strategic layer includes the high-level coordination of platoons, and its primary function is to match trucks into platoons based on their routes and mission constraints. The strategic layer also computes how platoons will form, for example, by syncing departure times at hubs or adjusting speed profiles on roads.

The service layer includes services that provide the high-level platoon coordination in the strategic layer with inputs and constraints. For example, carrier services provide the high-level coordination with routes and mission constraints used to match trucks into platoons. Other

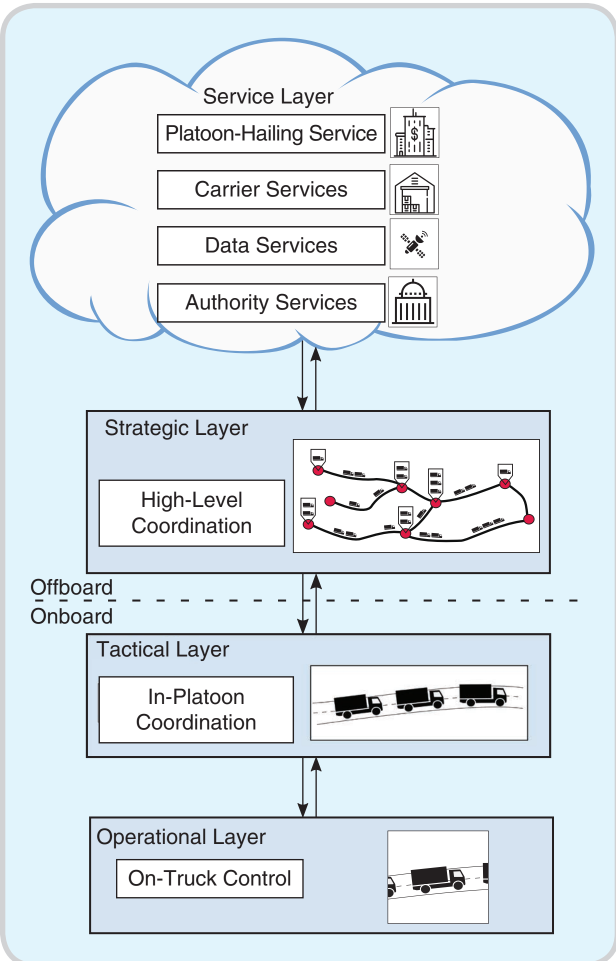

FIG 2 The layered structure of the platooning system.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

services useful for high-level coordination are data services, such as travel time and weather predictions, and authorities services, providing traffic management inputs and platooning restrictions. The service layer in Figure 2 also includes a platoon-hailing service that stores platooning plans and informs which platoons are feasible for trucks to join.

The Sweden4Platooning and ENSEMBLE projects have targeted both on- and offboard functionalities. The developed onboard functionalities in the ENSEMBLE project were demonstrated in real-traffic conditions [47], as shown in Figure 1. Details on the developed onboard functionalities are reported in [48]. The projects have also contributed to researching the offboard functionalities, especially when different carriers participate in the platooning system. The report in [37] discussed essential services and potential issues related to multibrand and multicarrier platooning, and information sharing and heterogeneous return of investments were identified as the main challenges. The work of [36] proposed profit-sharing mechanisms to distribute the profits within platoons. The works [12], [28], [29], and [30] developed cross-carrier platoon coordination methods. This article presents a coordinated system, developed in the Sweden4Platooning and ENSEMBLE projects, where different carriers cooperate.

Functional System Architecture of a Platoon-Hailing Service

We consider a platooning system where carriers cooperate in forming platoons, but each carrier keeps control of its truck fleet. Each carrier employs a carrier-specific coordinator with access to routes and timing constraints of the carrier's trucks and aims to optimize their platooning plans. We consider a system where carriers enumerated one to F participate. We call the carrier-specific coordinator of carrier f as coordinator f.

Cooperation across carriers is enabled by a platoon-hailing service, which stores the platooning plans of trucks and informs the carrier-specific coordinators which platoons their trucks can join along their routes. The functional system architecture of the platoon-hailing service is shown in Figure 3. The input to coordinator f from carrier f's module is the routes and timing constraints of trucks from carrier f, and the input from the platoon-hailing service is the platooning plans of other carriers that are stored in the platooning plan database. Coordinator f uses this information to optimize the platooning plans of carrier f's trucks. The optimized platooning plans are then reported back to the platooning plan database for other carrier-specific coordinators to use when making platooning decisions.

We consider the case when platoons form at hubs where trucks can wait for others, and a group of trucks forms a platoon when they depart from a hub and enter the road simultaneously. Thus, the platooning plans of trucks consist of departure times from hubs. As already mentioned, two general challenges with cross-carrier platoon cooperation are that each carrier is interested in maximizing its own profit and may be unwilling to leave the scheduling of its trucks to a third-party coordinator. Our proposed mechanism overcomes these challenges by each carrier employing a carrier-specific coordinator to maximize the carrier's profit under the premise that the profit of each formed platoon is shared evenly among trucks.

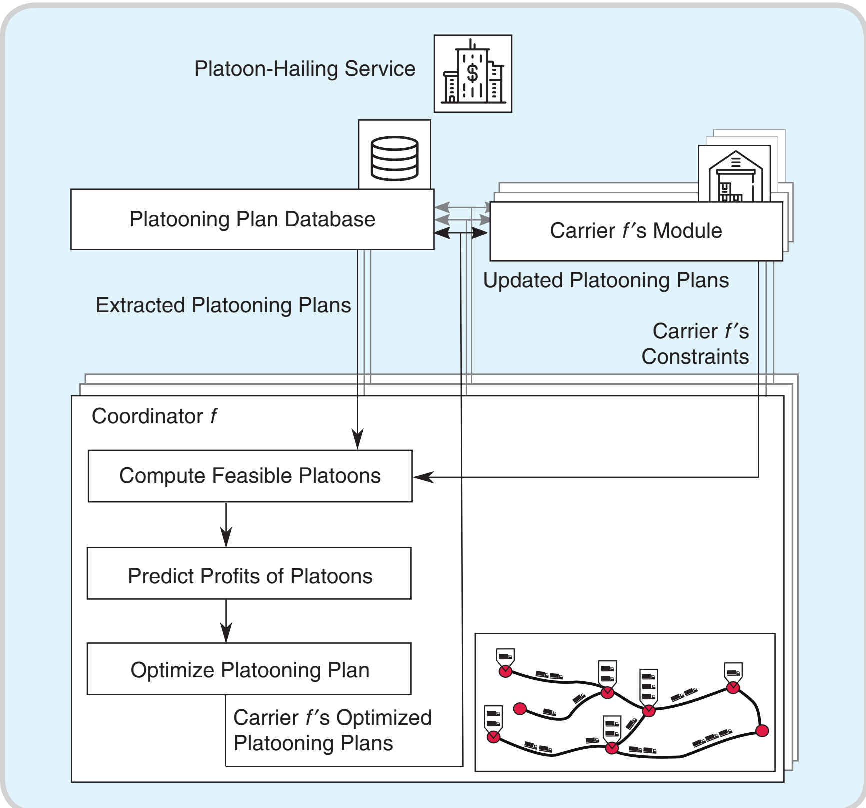

FIG 3 The functional system architecture of the platoon-hailing service.

Decision-Making Procedure

The decision-making procedure of the platooning system is illustrated in Figure 4. The decision-making procedure of a carrier-specific coordinator is triggered when one of its trucks arrives at a hub. The carrier-specific coordinator then requests the platooning plans of other trucks along the route of the arrived truck from the platoon-hailing service. The carrier-specific coordinator decides which platoons the arrived truck will join based on the truck's route, timing constraints, and platooning plans of others. The arrived truck will depart at the decided departure time at the current hub, and the platoon-hailing service is informed about the decided departure at the hubs of the arrived truck. We assume that trucks and already formed platoons stop at every hub on their routes. When a platoon arrives at a hub, the carrier-specific coordinator of each truck decides whether to continue with the same platoon, form a new platoon with others, or depart alone.

Cross-Carrier Coordination Method

We present the method used by each carrier-specific coordinator to compute the platoons that one of its trucks will join when it triggers decision making. We start by giving necessary notations regarding trucks and carriers connected to the system as well as information stored and shared by the platoon-hailing service. Then, we present a model of how the departure times at hubs are controlled by the waiting times at hubs, and we give the platooning reward function in which a profit-sharing mechanism that evens out the platooning profit in each platoon is embedded. Finally, we present the optimization problem that each carrier-specific coordinator aims to solve when one of its trucks triggers decision making.

Carriers and Trucks Connected to the System

Multiple carriers with truck fleets are connected to the platooning system. The index set of trucks is $\mathcal{N} = \{1, \ldots, N\}$, and the index set of trucks from carrier f is $\mathcal{F}_f \subseteq \mathcal{N}$. Each truck belongs to precisely one of the carriers enumerated 1 to F, and carrier f's coordinator is called coordinator f. The trucks have routes in a region including a network of hubs and road segments connecting the hubs. The set of hubs in the region is $\mathcal{V}$, and the set of road segments is $\mathcal{E}$, where each road segment is directed and connects two hubs. The route of each truck $i \in \mathcal{N}$ is a sequence of road segments and is denoted $\mathcal{P}^i \subseteq \mathcal{E}$. The kth road segment in the route of truck i is $e_k^i \in \mathcal{P}^i$. The predicted time of truck i to depart from a hub and enter road segment e_k^i is $\hat{t}_k^i$.

Information Shared by the Platoon-Hailing Service

The platoon-hailing service stores platooning plans in the form of predicted departure times at hubs of trucks connected to the service. For each road segment in the region over which the platoon-hailing service operates, the platoon-hailing service stores the predicted departure times of trucks that will depart from a hub and enter the road segment. The set of stored departure times at road segment $e \in \mathcal{E}$ is $\mathcal{D}_e$. The elements of $\mathcal{D}_e$ are repeatedly updated when the carrier-specific coordinators update the predicted departure times of trucks.

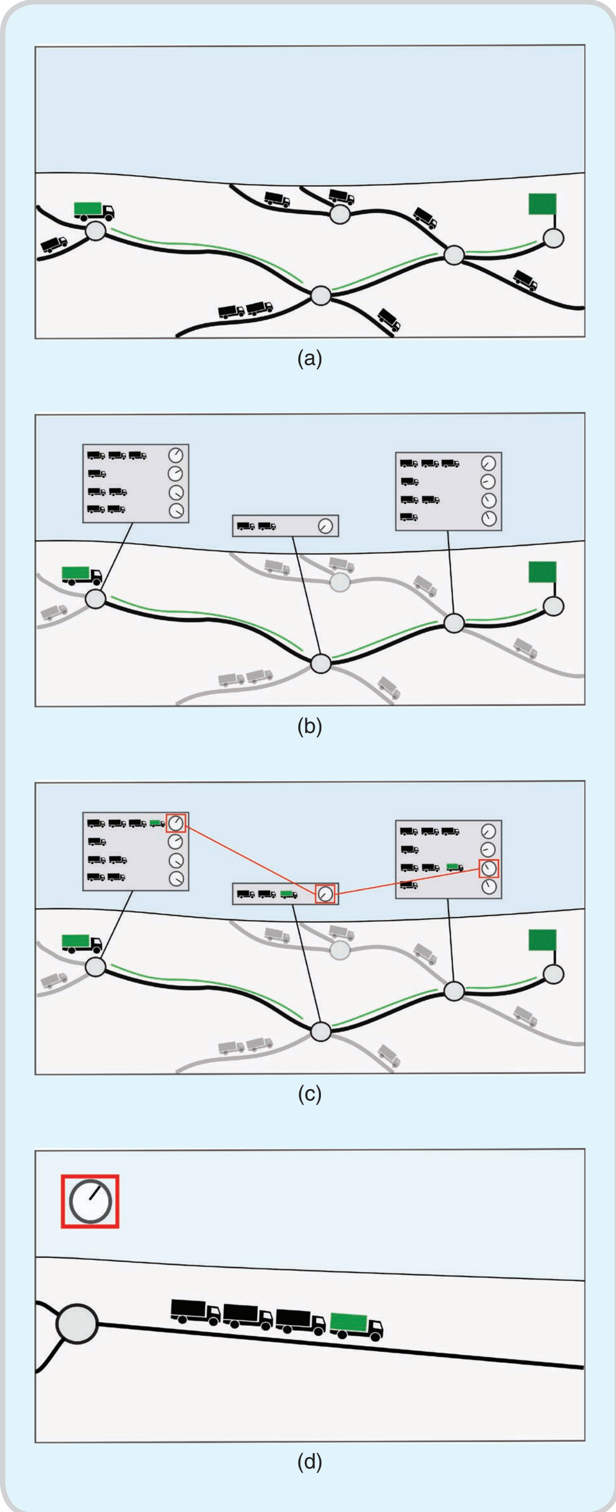

FIG 4 The decision-making procedure. (a) A truck arrives at a hub and the decision-making procedure is triggered. (b) The carrier-specific coordinator of the arrived truck receives the departure times of other trucks at the hubs along the arrived truck's remaining route from the platoon-hailing service. (c) The carrier-specific coordinator computes the optimal platoons for the truck to join and informs the platoon-hailing service about the decision. (d) The truck departs with its platooning partners at the computed departure time.

The platoon-hailing service shares platooning plans when decision making is triggered, as illustrated in Figure 4. Assume truck i from carrier f, that is, $i \in \mathcal{F}_f$, arrives at its kth hub. Then, as illustrated in Figure 4(b), coordinator f receives the predicted departure times of other trucks at the hubs along the remaining route of truck i, that is, the road segments $e^i_k, \ldots, e^i_{|\mathcal{P}_i|}$. The predicted departure times of others are given in the form of the functions $N^f_l(t)$ and $N^{-f}_l(t)$ for $l = k, \ldots, |\mathcal{P}_i|$. The function $N^f_l(t)$ is the number of trucks from carrier f predicted to enter road segment e^i_l at time t, and the function $N^{-f}_l(t)$ is the number of trucks from other carriers that are predicted to enter road segment e^i_l at time t. The functions $N^f_l(t)$ and $N^{-f}_l(t)$ are obtained by the platoon-hailing service by $\mathcal{D}_e$ for $e = e^i_l$.

Waiting and Departure Times

A platoon is formed when a group of trucks departs from a hub and enters a road segment simultaneously. Thus, the platoons a truck will join are determined by its departure times at the hubs along its route, which are controlled by its waiting times. Assume truck $i \in \mathcal{F}_f$ arrives at its kth hub; then, its waiting times at the remaining hubs are $w^i_k, \ldots, w^i_{|\mathcal{P}_i|}$, and the departure times are $t^i_k, \ldots, t^i_{|\mathcal{P}_i|}$. Moreover, assume the arrival time at the kth hub is $\tau^\star$; then, the departure time at the kth hub is computed as $t^i_k = \tau^\star + w^i_k$, and the departure times at the other hubs are computed as

$$t^i_{l+1} = t^i_l + \tau^i_l + w^i_{l+1}$$

for $l = k, \ldots, |\mathcal{P}_i| - 1$, where τ^i_l is the travel time on the lth road segment.

The trucks are constrained to arrive at their destination before a deadline. The deadline of truck i is $\bar{t}^i$, and, therefore, we require $t^i_{|\mathcal{P}_i|} + \tau^i_{|\mathcal{P}_i|} \leq \bar{t}^i$. We also assume a cost for waiting due, for example, to overtime for drivers or the risk of being delayed. The cost of waiting for truck i at its lth hub is $\Lambda_l(w^i_k)$.

Platooning Reward and Profit Sharing

The platooning benefit differs between platoon members and is typically higher for the follower trucks than for the lead truck, for example, if the reduced energy consumption or reduced workload are considered platooning benefits. Profit sharing is therefore needed for different carriers to cooperate in forming platoons. We propose a simple profit-sharing mechanism where compensations even out the platooning profits. This profit-sharing mechanism falls into the class of proportional profit-sharing methods discussed in [35].

The total platooning profit of a platoon in our model is a function of the number of platoon members. This is accurate if the platooning benefit only depends on the platoon length and is independent of the platoon members' types, brands, freight, and other individual characteristics. The platooning benefit at a road segment with index k of a truck driving in a platoon at position j in a platoon of n members, counted from the lead truck to the last truck, is denoted as $b_k(n, j)$. The total platooning benefit of the platoon is

$$b_k(n) = \sum_{i=1}^{n} b_k(n, j)$$

and, typically, $b_k(n) = 0$ for $n < 2$, and $b_k(n, j) \geq 0$ otherwise.

The average platooning benefit in the platoon is $\bar{b}_k(n) = b_k(n)/n$ for $n > 0$, which is the profit of each truck; after that, the profit is evened out by compensations. The compensation that the truck at position j either sends or receives is $c_k(n, j)$. More precisely, $c_k(n, j)$ is positive if the truck at position j receives compensation and is otherwise negative. The compensation of the truck at position j is computed by

$$\bar{b}_k(n) = b_k(n, j) + c_k(n, j) \Rightarrow c_k(n, j) = \bar{b}_k(n) - b_k(n, j).$$

Given this profit-sharing mechanism, the platooning profit for carrier f of a platoon including n^f trucks from carrier f and n^{-f} trucks from other carriers is

$$R_k(n^f, n^{-f}) = n^f \bar{b}_k(n^f + n^{-f})$$

for $n^f + n^{-f} > 0$, and $R_k(0, 0) = 0$. The incremental profit of carrier f if one more truck from carrier f is joining the platoon is

$$\begin{aligned} \Delta R_k(n^f, n^{-f}) = {} & (n^f + 1)\bar{b}_k(n)(n^f + 1 + n^{-f}) \\ & - n^f \bar{b}_k(n)(n^f + n^{-f}). \end{aligned}$$

In the simulation study later, the platooning benefit is considered the monetary savings due to reduced energy consumption. However, our platooning reward model can capture any other quantifiable benefits, such as the reduced workload of drivers. Next, we formulate the optimization problem where carrier-specific coordinators maximize the incremental profit by deciding which platoons their trucks will join along their routes under the premise that the profit of each platoon is shared equally. The compensations will not explicitly be part of the optimization problem, as the objective function captures the average profit of platoon members. In practice, the average profit can be achieved by the compensations after platoons are formed.

Optimization Problem

Assume truck $i \in \mathcal{F}_f$ arrives at its kth hub at time $t^\star$. Then, coordinator f computes the optimal waiting and departure times at the hubs along the remaining route of truck i, which includes its road segments indexed k to $|\mathcal{P}^i|$. The optimization problem of coordinator f is

$$\max_{w_l^i,\ l=k,\dots,|\mathcal{P}_i|} \quad \sum_{l=k}^{|\mathcal{P}_i|} \Delta R_l(S_l^f, S_l^{-f}) - \Lambda_l(w_l^i) \tag{1a}$$

$$\text{s.t.} \quad t_k^i = t' + w_k^i \tag{1b}$$

$$t_{l+1}^i = t_l^i + \tau_l^i + w_{l+1}^i,\ l = k,\dots,|\mathcal{P}_i|-1 \tag{1c}$$

$$t_{|\mathcal{P}_i|}^i + \tau_{|\mathcal{P}_i|}^i \le \bar{t}^i \tag{1d}$$

$$w_l^i \ge 0,\ l = k,\dots,|\mathcal{P}_i| \tag{1e}$$

$$S_l^f = N_l^f(t_l^i),\ l = k,\dots,|\mathcal{P}_i| \tag{1f}$$

$$S_l^{-f} = N_l^{-f}(t_l^i),\ l = k,\dots,|\mathcal{P}_i|. \tag{1g}$$

The objective function in (1a) includes the incremental platooning profit and waiting cost over the remaining route of truck i. The constraints (1b) and (1c) determine how the departure times at hubs are affected by the waiting times at hubs. The constraint (1d) restricts the arrival time at the destination-to-be before the deadline. The constraint (1e) restricts the waiting times to be positive. The constraints (1f) and (1g) determine the number of trucks that truck i is predicted to platoon with over its remaining route from its carrier f and of other carriers, respectively. Note that the platooning partners are determined by the departure times from hubs. The functions $N_l^f(t)$ and $N_l^{-f}(t)$ for $l = k,\dots,|\mathcal{P}_i|$ are obtained from the platoon-hailing service.

The optimal waiting times are denoted $\hat{w}_l^i$ for $l = k,\dots,|\mathcal{P}_i|$, and the corresponding departure times are denoted $\hat{t}_l^i$ for $l = k,\dots,|\mathcal{P}_i|$. Truck i will depart from its kth hub at time $\hat{t}_k^i$, and the departure times at the other hubs on its route are updated once it arrives at its next hub. The computed departure times are communicated to the platoon-hailing service and used as predicted departure times by others when they make platooning decisions. The optimization problem in (1) is solved by a dynamic programming technique where there is one decision step for each hub. The state at each decision step is the arrival time, and the decision is the waiting time. The waiting time at each decision step is either zero or another feasible waiting time such that the truck joins a platoon. A comprehensive review of dynamic programming was given in [49].

Simulation Study

We investigate the potential of cross-carrier platooning and study platooning patterns in the Swedish road network. We give the setup of the simulation study before giving the results.

Setup

Many inputs to the simulation study are outputs from the national freight model in Sweden, called *Samgods* [50]. The Samgods model is a tool that public authorities use to analyze and predict the modal split and geographic distribution of freight transportation flows in Sweden. The input to the SAMGODS model includes real data on where goods are produced and consumed and the costs of using different modes. The output from the SAMGODS model is realistic freight transportation flows between zones in Sweden. The Swedish road network with 105 hubs, at which trucks can wait and form platoons, is shown in Figure 5. The hub locations are real road terminal locations and are obtained from the SAMGODS model. The roads between hubs and their travel times are obtained from the open source mapping service OpenStreetMap [51].

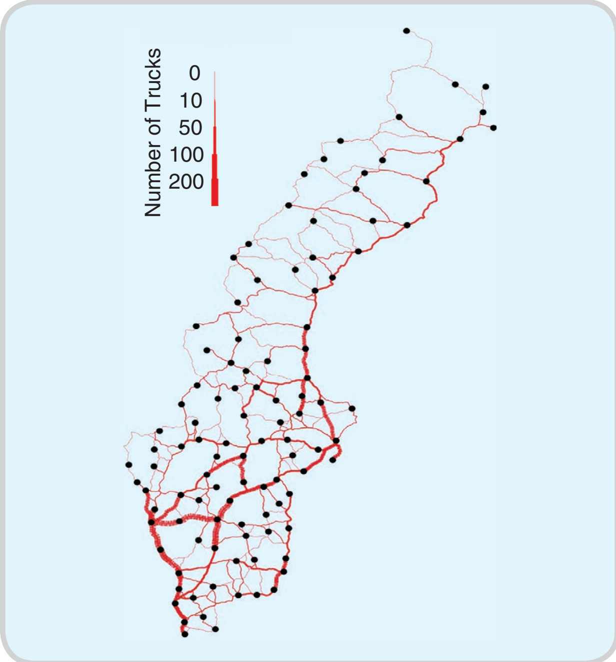

FIG 5 The Swedish road network and the number of trucks traveling between hubs per hour. The hub locations and the number of trucks traveling between hubs are obtained from the SAMGODS model.

The SAMGODS model output gives a realistic distribution of the origin–destination pairs of trucks. We use this distribution as input to our simulation study to randomize the origin–destination pairs of each truck. In Figure 5, the width of each road indicates the average number of trucks traveling on the road per hour in both directions. We compute the average number of trucks traveling on each road per hour from the SAMGODS model output and the routing between hubs from OpenStreetMap.

The trucks in the simulation study start their trips within 1 h, and the starting time of each truck is uniformly randomized within the 1-h period. The platooning system is evaluated for 1,000 trucks, 3,000 trucks, and 5,000 trucks, which corresponds to 20%, 60%, and 100%, respectively, of all trucks starting their trips on average in Sweden during the 1-h period [52].

The trucks belong to different carriers, and Figure 6 shows the percentages of trucks that belong to carriers of different sizes. The carrier size distribution in Figure 6 is obtained from the data in [53], which give the distribution of the number of employees of transportation companies in Sweden, and we generate the carrier size distribution by assuming the number of trucks of a carrier is proportional to its number of employees.

The benefit of platooning is assumed to be the monetary savings from reducing energy consumption, and the profits of the trucks in each platoon are evened out through compensations, as already mentioned. The energy consumption of each follower truck is assumed to be reduced by 10%, which is realistic according to the field tests in [4].

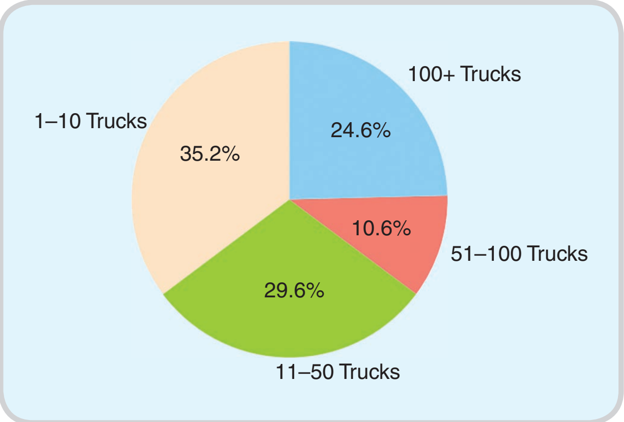

FIG 6 The percentages of trucks that belong to carriers of different sizes.

The energy price per kilometer of other trucks is assumed as SEK7.2, which is realistic if considering diesel trucks. Moreover, we assume that the waiting cost per hour is SEK260, which is approximately the average price of drivers in Sweden [54]. We set the deadlines of trucks by assuming that each truck is allowed to increase its trip time by 10% due to waiting.

Evaluation of the Platooning System

The platooning system is evaluated in terms of reduced energy consumption; profit of trucks, including saved energy expenses and increased waiting cost; and the trip delay caused by waiting at hubs to form platoons.

Figure 7 shows the reduced energy consumption on the roads in the Swedish road network for 1,000; 3,000; and 5,000 trucks connected to the cross-carrier platooning system. The reduced energy consumption on each road is aggregated in both directions. Figure 7 shows that more roads generally have a high energy consumption reduction when more trucks are connected to the system. On a few roads, the percent energy reduction is decreased when the number of trucks is increased. This is possible if, by chance, the new trucks drive alone, decreasing the percent energy reduction due to platooning. We see from Figures 5 and 7 that roads where many trucks travel generally have a higher reduction in energy consumption.

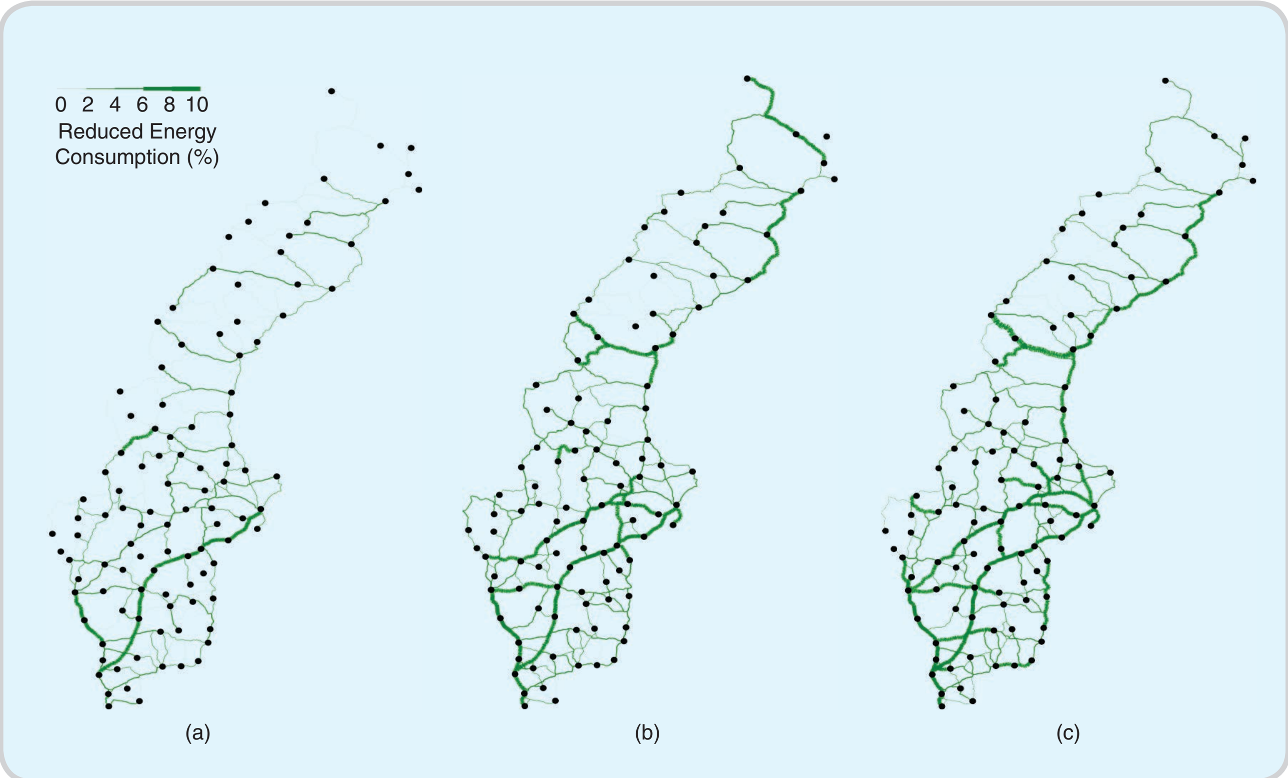

FIG 7 The reduced energy consumption on the road segments in the Swedish road network when (a) 1,000 trucks, (b) 3,000 trucks, and (c) 5,000 trucks participate in the platooning system.

This is because the number of platooning opportunities increases with the number of trucks. The number of trucks in single platoons is not constrained in our formulation; however, when 5,000 trucks are considered in the simulation study, more than 95% of the platoons have six or fewer trucks, and more than 50% of the platoons have two trucks.

Figure 8 shows the total reduced energy consumption in the Swedish road network due to platooning, the total profit, and the average trip delay per truck due to waiting. These measures are evaluated for 1,000; 3,000; and 5,000 trucks. The cross-carrier platooning system is compared to a single-carrier platooning system where each truck is only allowed to form platoons with trucks from the same carrier.

Figure 8(a) and (b) shows that the energy consumption is decreased and the total profit due to platooning is increased with more trucks connected to the system, which is in line with the patterns seen in Figure 7. These figures show that cross-carrier platooning can achieve significant environmental benefits and that the monetary benefit of platooning in the simulation study is relatively low compared to the operational cost of trucks. However, if considering other profits than monetary savings due to reduced energy consumption or if considering the accumulated profit over time, the platooning profits can still be substantial. Figure 8(a) and (b) also shows that cooperation across carriers is essential to achieve significant benefits from platooning. This is due to the carrier size distribution in Figure 6, which shows that many trucks belong to carriers with few trucks in their fleets, causing a massive loss in platooning opportunities when cross-carrier platooning is not allowed.

Figure 8(c) shows that the average waiting time per truck is small compared to the trucks' total travel times; trucks only need to delay their trip times by a few percent. This indicates that platoons can form relatively seamlessly without considerable trip delays.

Figure 9 shows the average profit from platooning per truck for carriers with fewer than 100 trucks and more than 100 trucks when 5,000 trucks participate in the platooning system. The figure shows that the profit per truck under cross-carrier cooperation is approximately the same

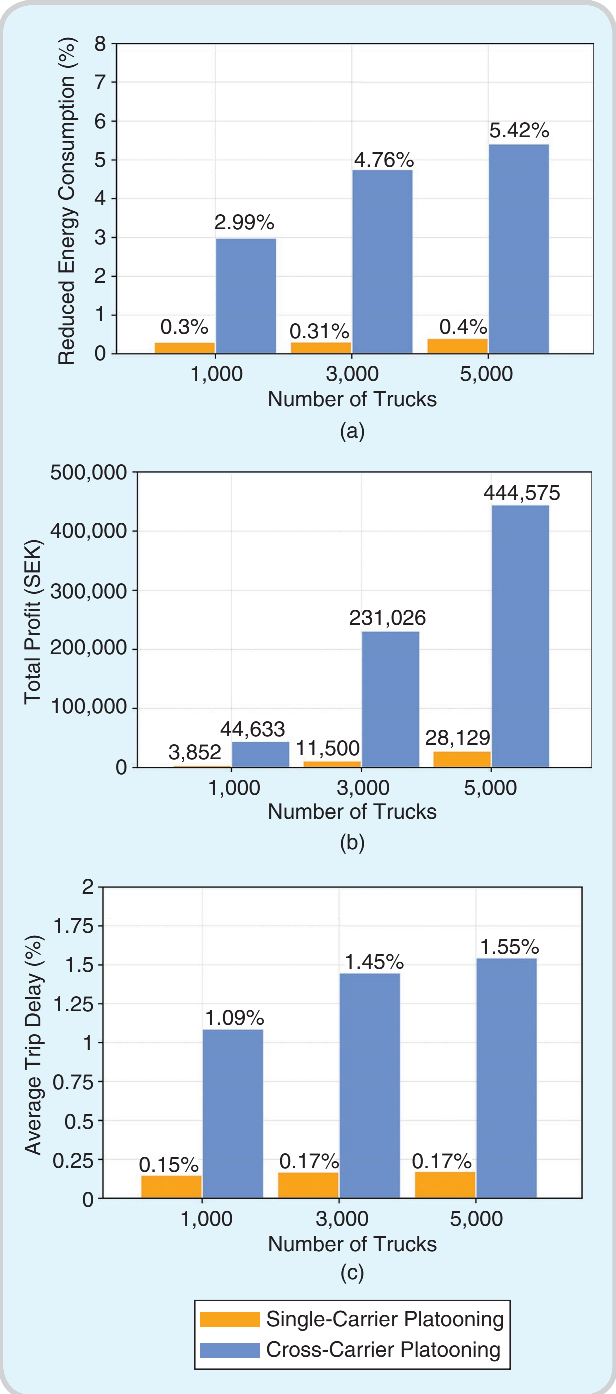

FIG 8 The (a) reduced energy consumption in the Swedish road network; (b) total profit due to platooning; and (c) average trip delay per truck due to waiting when 1,000; 3,000; and 5,000 trucks participate in the platooning system.

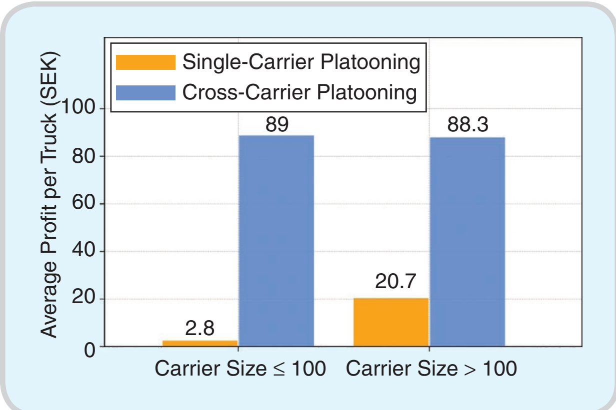

FIG 9 The average profit from platooning per truck for carriers with fewer than 100 trucks and more than 100 trucks when 5,000 trucks participate in the platooning system.

for the carriers with fewer than 100 trucks as for the carriers with more than 100 trucks. The figure also shows that the incentive to cooperate with others is higher for the smaller fleets, and this is because they have few single-carrier platooning opportunities. However, the carriers with more than 100 trucks also significantly increase their profits per truck by cooperation.

Conclusions and Future Work

This article presented a platooning system where carriers cooperate in forming platoons. We proposed a cross-carrier platooning system architecture where the carriers keep control of their trucks but cooperate through a platoon-hailing service. The function of the platoon-hailing service is to inform each carrier about the feasible platooning options for its trucks, and each carrier decides which platoons its trucks will join. We also presented a coordination approach that each carrier uses when computing the platooning decisions for its trucks.

The cross-fleet platooning system was evaluated in a simulation study. The simulations showed substantial energy savings in Sweden due to platooning for a sufficiently high penetration rate of platooning technology. More precisely, the energy consumption was reduced by 3%, 4.8%, and 5.4% for 1,000; 3,000; and 5,000 trucks connected to the platooning system, respectively. This suggests that energy savings thanks to platooning will increase over time as more trucks get equipped with platooning technology. The simulations also showed significant energy savings on roads where many trucks travel, even for low penetration rates of platooning technology.

We also compared the cross-carrier platooning system with a system where trucks are only allowed to platoon with trucks from the same carrier. According to the simulation study, the energy consumption was only reduced by 0.4% due to platooning for 5,000 when only single-carrier platoons were formed. This suggests that cross-fleet platoon cooperation is essential to obtain significant savings from platooning. The average profit per truck for carriers with fewer than and more than 100 trucks was compared under cross-carrier platooning and single-carrier platooning. The results show that smaller carriers are more incentivized to cooperate with others than larger carriers. This indicates that larger carriers might require a larger share of the platooning profit to accept cooperation with smaller carriers. This can be achieved through a simple proportional profit-sharing mechanism, as in this article, giving a larger share to larger carriers, or by a profit-sharing mechanism based on a game theoretic concept.

The simulation study used realistic distributions of trucks' origins and destination pairs as well as the carrier sizes. However, the benefits of platooning remain to be shown in case studies where real mission data from carriers are used. In the simulation study, the trucks' routes were fixed, and the decision variables were the waiting times at hubs. In the future, we plan to study the achieved benefits when the routing is included in the platooning decisions. In our formulation, several assumptions were made that might be unrealistic in practice; for example, the number of trucks in single platoons was not constrained, there were no driving and resting time regulations, already formed platoons stopped at hubs, and trucks could stop at every hub on their routes. Thus, we plan to extend the work in this article to include such constraints and study their consequences. We also plan to capture in our reward model that trucks are heterogeneous, for example, in the brands, types, and freight they transport. Finally, another promising direction is to explore auction-based methods for cross-carrier platoon cooperation, as it is common for collaborative transportation.

Acknowledgment

Thanks to all the partners in the Sweden4Platooning and ENSEMBLE projects for valuable discussions and cooperation. Thanks to Albin Engholm for providing us with data from the SAMGODS model. This work is supported by the Strategic Vehicle Research and Innovation Program through the project Sweden4Platooning, the Horizon 2020 through the project ENSEMBLE, the Knut and Alice Wallenberg Foundation, the Swedish Foundation for Strategic Research, and the Swedish Research Council.

About the Authors

Alexander Johansson (alexjoha@kth.se) earned his M.Sc. degree in applied mathematics in 2017 from KTH Royal Institute of Technology, Stockholm, Sweden. He is currently working toward his Ph.D. degree with the Division of Decision and Control Systems, Department of Intelligent Systems, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden. His research interests include optimization, game theory, and control for platoon coordination. He is a Student Member of IEEE.

Ting Bai (tingbai@kth.se) earned her Ph.D. 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 SE-100 44, Sweden, where she is a postdoctoral researcher. Her research interests include distributed model predictive control, control configuration design, and optimal

control of complex networks and transport systems. She is a Member of IEEE.

Karl Henrik Johansson (kallej@kth.se) earned his Ph.D. degree from Lund University. He is a professor with the School of Electrical Engineering and Computer Science at KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden, and the director of Digital Futures. His research interests include networked control systems and cyberphysical 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 International Federation of Automatic Control executive board, and he is currently vice president of the European Control Association. He is a Fellow of IEEE and the Royal Swedish Academy of Engineering Sciences, and he is an IEEE Control Systems Society Distinguished Lecturer.

Jonas Mårtensson (jonas1@kth.se) earned his Ph.D. degree in automatic control from KTH Royal Institute of Technology, Stockholm, Sweden, in 2007. 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, Stockholm SE-100 44, Sweden. He is also engaged as a program leader in the Integrated Transport Research Laboratory and is a thematic leader for the Transport in the Information Age area within the KTH Transport Platform. His research interests include cooperative and autonomous transport systems, particularly related to heavy-duty vehicle platooning. He is involved in several collaboration projects with Scania 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. He is a Senior Member of IEEE.

References

[1] F. Browand, J. McArthur, and C. Radovich, "Fuel saving achieved in the field test of two tandem trucks," Univ. of Southern California, Berkeley, CA, USA, Tech. Rep. UCB-ITS-PRR-2004-20, 2004.

[2] A. Davila, E. del Pozo, E. Aramburu, and A. Freixas, "Environmental benefits of vehicle platooning," in *Proc. Symp. Int. Automot. Technol.*, Jan. 2013, pp. 1–6, doi: 10.4271/2013-26-0142.

[3] A. Alam, B. Besselink, V. Turri, J. Mårtensson, and K. H. Johansson, "Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency," *IEEE Control Syst. Mag.*, vol. 35, no. 6, pp. 34–56, Dec. 2015, doi: 10.1109/MCS.2015.2471046.

[4] S. Tsugawa, S. Jeschke, and S. E. Shladover, "A review of truck platooning projects for energy savings," *IEEE Trans. Intell. Veh.*, vol. 1, no. 1, pp. 68–77, Mar. 2016, doi: 10.1109/TIV.2016.2577499.

[5] R. Bishop, D. Bevly, L. Humphreys, S. Boyd, and D. Murray, "Evaluation and testing of driver-assistive truck platooning: Phase 2 final results," *Transport. Res. Rec.*, vol. 2615, no. 1, pp. 11–18, 2017, doi: 10.3141/2615-02.

[6] P. A. Ioannou and C. C. Chien, "Autonomous intelligent cruise control," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 657–672, Nov. 1993, doi: 10.1109/25.260745.

[7] P. B. Fernandes and U. J. Nunes, "Platooning with IVC-enabled autonomous vehicles: Strategies to mitigate communication delays, improve safety and traffic flow," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 1, pp. 91–106, Mar. 2012, doi: 10.1109/TITS.2011.2179936.

[8] Y. Jo, J. Kim, C. Oh, I. Kim, and G. Lee, "Benefits of travel time savings by truck platooning in Korean freeway networks," *Transport Policy*, vol. 83, pp. 37–45, Nov. 2019, doi: 10.1016/j.tranpol.2019.09.003.

[9] G. R. Janssen, J. Zwijnenberg, I. Blankers, and J. de Kruijff, "Truck platooning: Driving the future of transportation," TNO, Delft, The Netherlands, 2015. Accessed: Jun. 27, 2022. [Online]. Available: http://publications.tno.nl/publication/34616035/dLIjFM/janssen-2015-truck.pdf

[10] A. Chottani, G. Hastings, J. Murnane, and F. Neuhaus, "Distraction or disruption? Autonomous trucks gain ground in US logistics," Mckinsey & Company, Atlanta, GA, USA, 2018. Accessed: May 6, 2020. [Online]. Available: https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/distraction-or-disruption-autonomous-trucks-gain-ground-in-us-logistics

[11] J. Axelsson, T. Bergh, A. Johansson, B. Mårdberg, P. Svenson, and V. Åkesson, "Truck platooning business case analysis," RISE Research Institutes of Sweden and S4P Partners, Sweden, 2020. [Online]. Available: http://ri.diva-portal.org/smash/get/diva2:1410842/FULLTEXT01.pdf

[12] F. Combes et al., "Analysis of market needs, business models and life-cycle environmental impacts of multi-brand platooning," ENSEMBLE, Cincinnati, OH, USA, Deliverable D4.3 of H2020 Project, 2022. Accessed: Jun. 27, 2022. [Online]. Available: https://platooningensemble.eu/library/deliverables

[13] F. Daems, "Platooning value and benefit analysis," ENSEMBLE, Cincinnati, OH, USA, D14.8 of H2020 Project, 2022. Accessed: Jun. 27, 2022. [Online]. Available: https://platooningensemble.eu/library/deliverables

[14] S. Darbha and J. K. Hedrick, "Constant spacing strategies platooning automated highway systems," *J. Dyn. Syst. Meas. Control*, vol. 121, no. 3, pp. 462–470, 1999, doi: 10.1115/1.2802497.

[15] J. Ploeg, N. Van De Wouw, and H. Nijmeijer, "Lp string stability of cascaded systems: Application to vehicle platooning," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 2, pp. 786–793, Mar. 2014, doi: 10.1109/TCST.2013.2258346.

[16] V. Turri, B. Besselink, and K. H. Johansson, "Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 12–28, Jan. 2017, doi: 10.1109/TCST.2016.2542044.

[17] A. K. Bhoopalam, N. Agatz, and R. Zuidwijk, "Planning of truck platoons: A literature review and directions for future research," *Transp. Res. B*, vol. 107, pp. 212–228, Jan. 2018, doi: 10.1016/j.trb.2017.10.016.

[18] V. Lesch, M. Breitbach, M. Segata, C. Becker, S. Kounev, and C. Krupitzer, "An overview on approaches for coordination of platoons," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 10,049–10,065, Aug. 2021, doi: 10.1109/TITS.2021.3115908.

[19] E. Larsson, G. Sennton, and J. Larson, "The vehicle platooning problem: Computational complexity and heuristics," *Transp. Res. C, Emerg. Technol.*, vol. 60, pp. 258–277, Nov. 2015, doi: 10.1016/j.trc.2015.08.019.

[20] K.-Y. Liang, J. Mårtensson, and K. H. Johansson, "Heavy-duty vehicle platoon formation for fuel efficiency," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 1051–1061, Apr. 2016, doi: 10.1109/TITS.2015.2492243.

[21] S. van de Hoef, K. H. Johansson, and D. V. Dimarogonas, "Fuel-efficient en route formation of truck platoons," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 1, pp. 102–112, Jan. 2018, doi: 10.1109/TITS.2017.2700021.

[22] X. Xiong, J. Sha, and L. Jin, "Optimizing coordinated vehicle platooning: An analytical approach based on stochastic dynamic programming," *Transp. Res. B, Methodol.*, vol. 150, pp. 482–502, Aug. 2021, doi: 10.1016/j.trb.2021.06.009.

[23] W. Zhang, E. Jenelius, and X. Ma, "Freight transport platoon coordination and departure time scheduling under travel time uncertainty," *Transp. Res. E, Logistics Transp. Rev.*, vol. 98, pp. 1–23, Feb. 2017, doi: 10.1016/j.tre.2016.11.008.

[24] N. Boysen, D. Briskorn, and S. Schwerdfeger, "The identical-path truck platooning problem," *Transp. Res. B, Methodol.*, vol. 109, pp. 26–39, Mar. 2018, doi: 10.1016/j.trb.2018.01.006.

[25] R. Larsen, J. Rich, and T. K. Rasmussen, "Hub-based truck platooning: Potentials and profitability," *Transp. Res. E, Logistics Transp. Rev.*, vol. 127, pp. 249–264, Jul. 2019, doi: 10.1016/j.tre.2019.05.005.
[26] N. Pourmohammad-Zia, F. Schulte, D. Souravlias, and R. R. Negenborn, "Platooning of automated ground vehicles to connect port and hinterland: A multi-objective optimization approach," in *Proc. Int. Conf. Comput. Logistics*, Springer-Verlag, 2020, pp. 428–442, doi: 10.1007/978-3-030-59747-4_28.
[27] N. Pourmohammad-Zia, F. Schulte, and R. R. Negenborn, "Platform-based platooning to connect two autonomous vehicle areas," in *Proc. 2020 IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, pp. 1–6, doi: 10.1109/ITSC45102.2020.9294689.
[28] A. Johansson, X. Sun, J. Mårtensson, and Y. Yin, "Real-time cross-fleet pareto-improving truck platoon coordination," in *Proc. 2021 IEEE Int. Intell. Transp. Syst. Conf. (ITSC)*, pp. 996–1003, doi: 10.1109/ITSC48978.2021.9565048.
[29] A. Johansson, E. Nekouei, K. H. Johansson, and J. Mårtensson, "Strategic hub-based platoon coordination under uncertain travel times," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 8277–8287, Jul. 2021, doi: 10.1109/TITS.2021.3077467.
[30] T. Bai, A. Johansson, K. H. Johansson, and J. Mårtensson, "Event-triggered distributed model predictive control for platoon coordination at hubs in a transport system," in *Proc. 2021 60th IEEE Conf. Decis. Control (CDC)*, pp. 1198–1204, doi: 10.1109/CDC45484.2021.9683080.
[31] X. Sun and Y. Yin, "Behaviorally stable vehicle platooning for energy savings," *Transp. Res. C, Emerg. Technol.*, vol. 99, pp. 37–52, Feb. 2019, doi: 10.1016/j.trc.2018.12.017.
[32] M. A. Krajewska, H. Kopfer, G. Laporte, S. Ropke, and G. Zaccour, "Horizontal cooperation among freight carriers: Request allocation and profit sharing," *J. Oper. Res. Soc.*, vol. 59, no. 11, pp. 1483–1491, 2008, doi: 10.1057/palgrave.jors.2602489.
[33] M. Gansterer and R. F. Hartl, "Collaborative vehicle routing: A survey," *Eur. J. Oper. Res.*, vol. 268, no. 1, pp. 1–12, 2018, doi: 10.1016/j.ejor.2017.10.023.
[34] J. Los, F. Schulte, M. Gansterer, R. F. Hartl, M. T. J. Spaan, and R. R. Negenborn, "Large-scale collaborative vehicle routing," *Ann. Oper. Res.*, vol. 8, pp. 1–33, Apr. 2022, doi: 10.1007/s10479-021-04504-3.
[35] M. Guajardo and M. Rönnqvist, "A review on cost allocation methods in collaborative transportation," *Int. Trans. Oper. Res.*, vol. 23, no. 3, pp. 371–392, 2016, doi: 10.1111/itor.12205.
[36] A. Johansson and J. Mårtensson, "Game theoretic models for profit-sharing in multi-fleet platoons," in *Proc. 2019 IEEE Intell. Transp. Syst. Conf. (ITSC)*, pp. 3019–3024, doi: 10.1109/ITSC.2019.8917349.
[37] J. Lützner, "Service and strategic layer design," ENSEMBLE, Cincinnati, OH, USA, D4.2 of H2020 Project, 2021. Accessed: Jun. 27, 2022. [Online]. Available: https://platooningensemble.eu/library/deliverables
[38] E.-M. Aboulkacem and F. Combes, "Truck platooning technology diffusion: A micro-economic dynamic model of market uptake." SSRN. Accessed: Jun. 28, 2022. [Online]. Available: https://ssrn.com/abstract=3991838
[39] S. Tsugawa, "An overview on an automated truck platoon within the energy its project," *IFAC Proc. Volumes*, vol. 46, no. 21, pp. 41–46, 2013, doi: 10.3182/20130904-4-JP-2042.00110.
[40] H. Fritz, A. Gern, H. Schiemenz, and C. Bonnet, "Chauffeur assistant: A driver assistance system for commercial vehicles based on fusion of advanced ACC and lane keeping," in *Proc. IEEE Intell. Veh. Symp.*, 2004, pp. 495–500, doi: 10.1109/IVS.2004.1336433.
[41] R. Ramakers, K. Henning, S. Gies, D. Abel, and H. M. A. Max, "Electronically coupled truck platoons on German highways," in *Proc. 2009 IEEE Int. Conf. Syst., Man Cybern.*, pp. 2409–2414, doi: 10.1109/ICSMC.2009.5346393.
[42] T. Robinson, E. Chan, and E. Coelingh, "Operating platoons on public motorways: An introduction to the Sartre platooning programme," in *Proc. 17th World Congr. Intell. Transport Syst.*, 2010, vol. 1, p. 12.
[43] S. Eilers et al., "COMPANION–Towards co-operative platoon management of heavy-duty vehicles," in *Proc. 2015 IEEE 18th Int. Conf. Intell. Transp. Syst.*, pp. 1267–1273, doi: 10.1109/ITSC.2015.208.
[44] L. Aarts and G. Feddes, "European truck platooning challenge," in *Proc. 14th Int. Symp. Heavy Veh. Transp. Technol. (HVTT14)*, Nov. 2016, pp. 1–9.
[45] J. Dellrud and C. V. A. B. Scania, "Sweden4Platooning," Trafikverket, Borlänge, Sweden, Public Rep., 2021. Accessed: Jun. 27, 2022. [Online]. Available: https://bransch.trafikverket.se/om-oss/aktuellt-for-dig-i-branschen3/aktuellt-om-forskning-och-innovation2/2020-05/konvojkorningplatooning-med-lastbilar/
[46] "Platooning together." ENSEMBLE Project. Accessed: Apr. 18, 2022. [Online]. Available: https://platooningensemble.eu/
[47] J. Pont, "Public demonstration report," ENSEMBLE, Cincinnati, OH, USA, D5.6 of H2020 Project, 2021. Accessed: Jun. 27, 2022. [Online]. Available: https://platooningensemble.eu/library/deliverables
[48] A. Schmeitz, J. Verhaeg, and M. Fusco, "Detailed design of the unbranded Tactical Layer," ENSEMBLE, Cincinnati, OH, USA, D3.1 of H2020 Project, 2019. Accessed: Jun. 27, 2022. [Online]. Available: https://platooningensemble.eu/library/deliverables
[49] D. Bertsekas, *Dynamic Programming and Optimal Control*, vol. 1. Belmont, MA, USA: Athena Scientific, 2012.
[50] M. Bergquist, V. Bernhardsson, and E. Rosklint, "Representation of the Swedish transport and logistics system in Samgods v. 1.1.," Trafikverket, Borlänge, Sweden, 2016. Accessed: Jun. 27, 2022. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:1034226/FULLTEXT01.pdf
[51] Open Street Maps. Accessed: May 25, 2022. [Online]. Available: https://www.openstreetmap.org/#map=19/62.38384/17.31072
[52] "Lastbilstrafik 2020," Trafikanalys, Stockholm, Sweden, 2020. Accessed: Jun. 27, 2022. [Online]. Available: https://www.trafa.se/globalassets/statistik/vagtrafik/lastbilstrafik/2020/lastbilstrafik-2020.pdf
[53] "Transportbranschens ekonomi 1997-2015," Trafikanalys, Stockholm, Sweden, 2016. Accessed: Jun. 27, 2022. [Online]. Available: https://www.trafa.se/ovrig/transportbranschens-ekonomi/
[54] "Godstransporter i Sverige - en nulägesanalys," Trafikanalys, Stockholm, Sweden, Rapport 2016:7, 2016. [Online]. Available: https://www.trafa.se/globalassets/rapporter/2016/rapport-2016_7_godstransporter-i-sverige---en-nulagesanalys.pdf

ITS