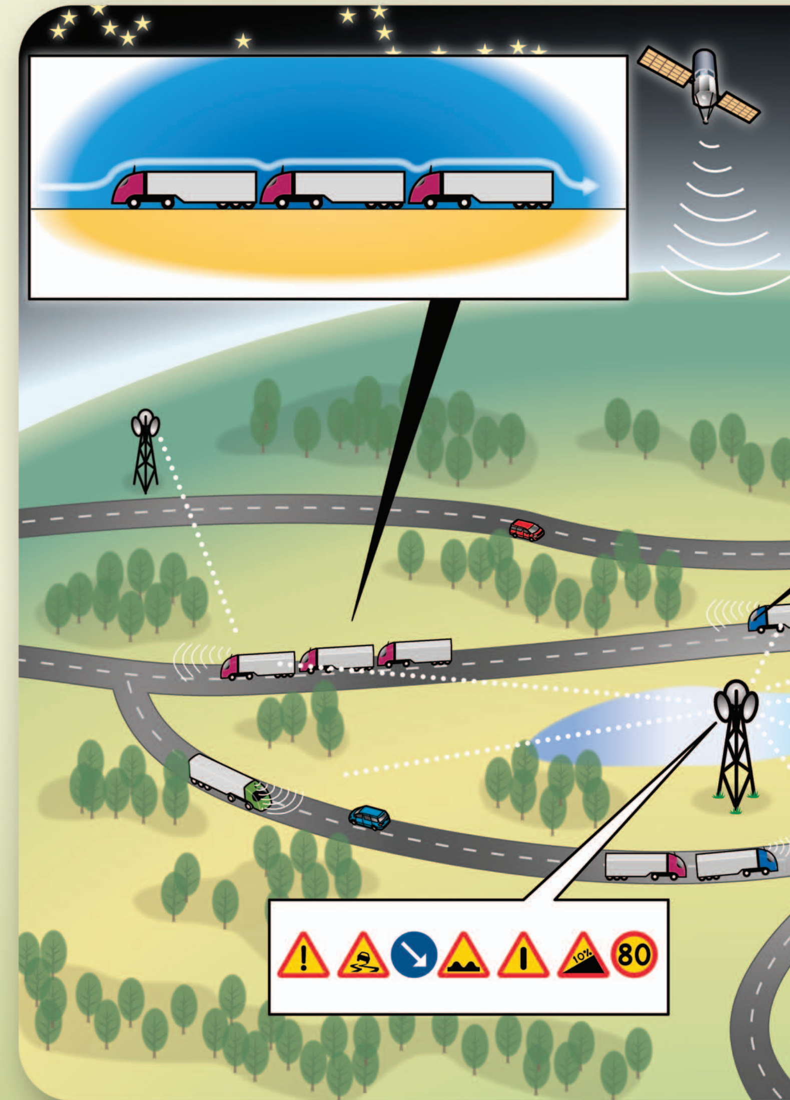
Heavy-Duty Vehicle Platooning for Sustainable Freight Transportation

A COOPERATIVE METHOD TO ENHANCE SAFETY AND EFFICIENCY

ASSAD ALAM, BART BESSELINK,
VALERIO TURRI, JONAS MÅRTENSSON,
and KARL H. JOHANSSON



The current system of global trade is largely based on transportation and communication technology from the 20th century. Advances in technology have led to an increasingly interconnected global market and reduced the costs of moving goods, people, and technology around the world [1]. Transportation is crucial to society, and the demand for transportation is strongly linked to economic development. Specifically, *road* transportation is essential since about 60% of all surface freight transportation (which includes road and rail transport) is done on roads [2]. Despite the important role of road freight transportation in the economy, it is facing serious challenges, such as those posed by increasing fuel prices and the need to reduce greenhouse gas emissions. On the other hand, the integration of information and communication technologies to transportation systems—leading to intelligent transportation systems—enables the development of cooperative

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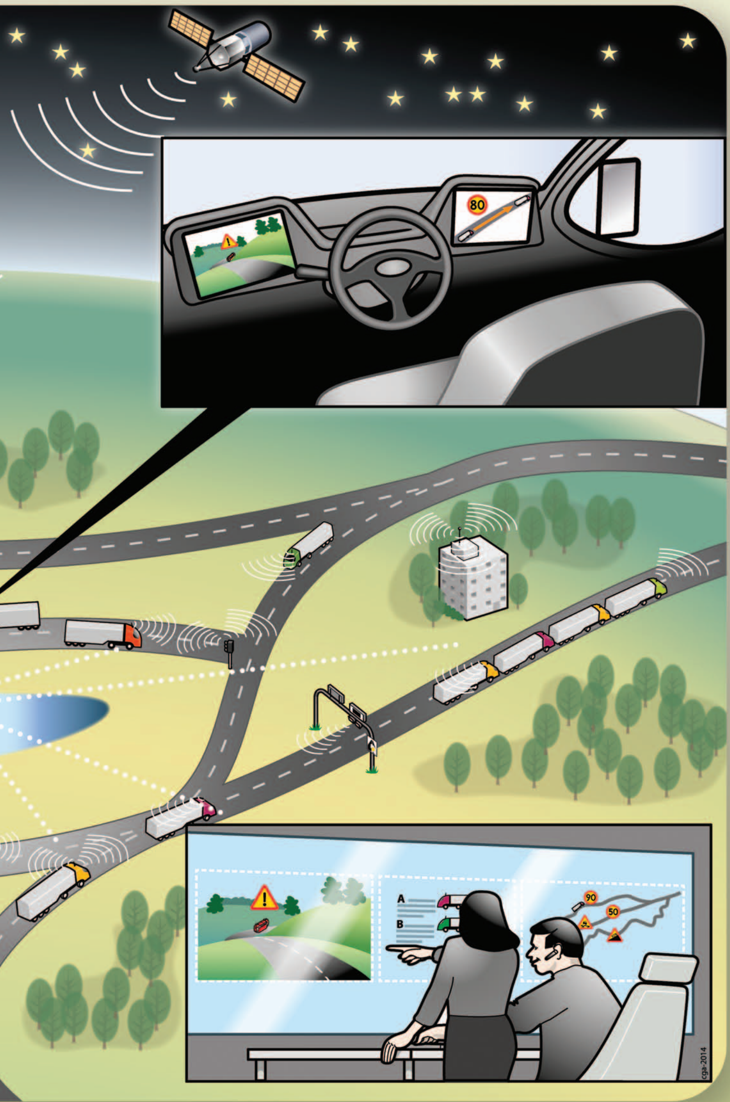
methods to enhance the safety and energy efficiency of transportation networks. This article focuses on one such cooperative approach, which is known as platooning. The formation of a group of heavy-duty vehicles (HDVs) at close intervehicular distances, known as a *platoon* (see Figure 1) increases the fuel efficiency of the group by reducing the overall air drag. The safe operation of such platoons requires the automatic control of the velocity of the platoon vehicles as well as their intervehicular distance. Existing work on platooning has focused on the design of controllers for these longitudinal dynamics, in which simple vehicle models are typically exploited and perfect environmental conditions, such as flat roads, are generally assumed. The broader perspective of how platooning can be effectively exploited in a freight transportation system has received less attention. Moreover, experimental validations of the fuel-saving potential offered by platooning have typically been performed by reproducing the perfect conditions as assumed in the design of the automatic controllers. This article focuses on these two aspects by addressing the following two objectives.



First, a vision of a future freight transportation system is given, in which cooperation and platooning play an important role. Namely, cooperation allows for a better utilization of the available goods transport capacity. It also enables the coordination of HDVs to form platoons and thereby collaboratively save fuel. We present a system architecture for such a transportation system. This three-layer architecture consists of a transport layer, which addresses transport planning and vehicle routing, a platoon layer, which handles the formation of platoons and the computation of fuel-optimal velocity trajectories using preview information, and a vehicle layer, which performs the real-time control of the vehicles to track the desired velocity profiles while guaranteeing safety.

The second objective of this article is to present an experimental evaluation of the fuel-saving potential as offered by platooning under realistic conditions. Contrary to many existing experimental studies on platooning, experiments in this article have been conducted on public roads with varying road grade, in the presence of traffic, and under varying weather conditions. Under these realistic conditions, two important aspects of HDV platooning can be observed. First, platooning can significantly reduce fuel consumption, providing a clear motivation for cooperative transportation systems. Second, the road grade has a large impact on the behavior of HDVs and the operation of platoons on roads

FIGURE 1 A platoon of three automatically controlled heavy-duty vehicles. The overall air drag is reduced as a result of small intervehicular distances, carefully regulated through vehicle-to-vehicle communication. (Image courtesy of Scania CV AB.)

with large road grades does not necessarily lead to the expected fuel savings. In fact, it is shown that more advanced control strategies should be used that exploit the use of preview information on the road topography. This aspect has not been observed in practice before and provides a strong motivation for future research on cooperative control of vehicle platoons.

The remainder of the article is organized as follows. The section "Future Freight Transport" presents a vision for a future freight transportation system, which is aimed at improving energy-efficiency and exploits the concept of platooning at its core. A layered system architecture for a future freight transportation system is presented in the section "Freight Transport System Architecture." The section "Fuel-Efficient Platoon Control" discusses the control implementation of the lower layers of this architecture, of which the performance is evaluated by means of experiments in the section "Experimental Evaluation." Finally, conclusions are stated in the section "Conclusions."

FUTURE FREIGHT TRANSPORT

A vision for future freight transport is presented in this section.

Incentives

As the world's population continues to increase and economies are projected to expand, the demand for goods transportation is expected to grow significantly over the next decades. In particular, the International Transport Forum [3] predicts that surface freight transport [that is, by road and rail, measured in tonne-kilometers (tkm)] in Organization for Economic Co-operation and Development (OECD) countries will increase between 40 and 125% by 2050 compared to 2010 levels [2]. For developing countries, an increase of up to 400% is predicted. Even though the share of rail transport is expected to increase slightly within the OECD (from 42 to 46%), it is clear that freight transport over roads will show a significant increase with respect to current levels. In 2011, road freight transport amounted to 1,734 billion tkm in the European Union [4] and 3,394 billion tkm in the United States [5], corresponding to 45 and 42% of the total freight transport in these regions, respectively.

The large expected increase in road freight transport presents great challenges with respect to energy consumption and emissions. Many industrialized countries agreed to reduce greenhouse gas emissions under the Kyoto protocol. In addition to this agreement, the European Union has set more ambitious targets and aims to reduce emissions by 80–90% by 2050 with respect to 1990 levels. This requires a 60% reduction (or 70% with respect to 2008 levels) in greenhouse gas emissions from the transportation sector [6]. In 2010, the transportation sector accounted for 33% of the total energy use and 24% of the total greenhouse gas emissions in the European Union. Road transport was responsible for 72% of the greenhouse gas emissions within all modes of transport, leading to an emission of about 900 million tonnes CO_2 equivalent [4]. In fact, the transportation sector is the only major sector in the European Union for which greenhouse gas emissions are still rising.

Besides environmental incentives for reducing fuel consumption of HDVs, there is a clear economic incentive as well. Namely, fuel costs are about 35% of the operating costs of an HDV for a European haulage company [7] and the price of oil is expected to rise by approximately 60% by 2050 with respect to 2010 [2]. Since transport is one of the cornerstones of society and the economy, these rising oil prices can have a significant negative impact.

Therefore, it is not surprising that vehicle manufacturers are developing methods to reduce fuel consumption. These efforts typically focus on the fuel economy through the development of more efficient combustion engines and drive trains, as well as fuel-efficient tires, weight reduction, or better aerodynamics. More fundamental approaches such as alternative fuels, including hybrid or electric vehicles, are pursued as well. A combination of these developments has the potential to reduce fuel consumption of HDVs by about 30%, even with today's technology. For an overview of such technologies, see, for example, [8] and [9].

Platooning

The approaches toward the reduction of fuel consumption mentioned above focus on the fuel efficiency of *single* vehicles. However, additional benefits can be obtained through *cooperation*. The formation of HDV platoons, operating at close intervehicular distances, reduces the overall aerodynamic drag and thus results in lower fuel consumption. An illustration of this effect is given in Figure 2, which shows the reduction in aerodynamic drag for buses in small platoons of two or three vehicles. Here, a vehicle driving at 80 km/h and following one preceding vehicle at 25 m benefits from a 30% reduction in aerodynamic drag. This reduction increases to 40% with two preceding vehicles.

Moreover, at short intervehicular distances, even the leading vehicle takes advantage of platooning, due to reduced adverse aerodynamic effects. The reduction in aerodynamic drag increases significantly when the intervehicular distances are reduced even further. Since up to one fourth of the fuel consumption for a typical HDV can be spent on overcoming the aerodynamic drag, it is clear that platooning has the potential to provide substantial economic benefits for individual haulage companies in addition to the clear environmental gains due to reduced greenhouse gas emissions.

Apart from reducing fuel consumption, platooning potentially offers other important gains. First, when vehicles are operated at close intervehicular distances, the existing road infrastructure can be exploited more effectively and capacity can be increased. For passenger cars, it is argued that a capacity increase of 200% can be achieved [13]. Even though it is expected that such an increase cannot be achieved for HDVs, platooning can still provide a major improvement in the utilization of existing road capacity. The importance of this can be illustrated by the fact that road congestion in the European Union is estimated to cost the equivalent of 1% of GDP and this cost is predicted to increase by 50% by 2050 if no changes in policy are made [6].

Because human drivers are generally not capable of safely maintaining the close intervehicular distances as required by platooning, it is clear that automated driving technologies are needed. The increased level of automation provides a second advantage of cooperative transport technologies since automation is generally believed to have a positive effect on road safety [13], [14]. Namely, automatic systems can usually react more quickly to dangerous situations and can exploit additional information resulting from the communication and cooperation between vehicles. Indeed, because most road accidents are the result of human errors, increased automation has a strong potential to mitigate this factor.

An overview of related work on platooning is given in "A Brief Review on Platooning."

Freight Transportation Management

It is reasonable to predict that the future freight transportation sector will be based on ever-increasing levels of automation. The widespread incorporation of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (see [15] for a review of vehicle networking) will allow for unprecedented cooperation and coordination, which will have a large impact on the road transportation sector and the integration of its subsystems. In particular, the following scenario, illustrated in Figure 3, can be envisioned. First, we expect haulage companies to exploit large-scale optimization techniques for the distribution of the required flow of goods over individual HDVs. As an example, goods that share an origin and destination can be combined into a single vehicle, also taking constraints such as deadlines into account. By effectively distributing the required flow of goods over the available HDVs, this transport optimization has the potential to increase the utilization of the vehicles. This increased utilization reduces the costs of goods transport and further reduces the fuel consumption of the total fleet. Cooperation between several haulage companies can further improve this utilization.

Second, it is envisioned that route planning for HDVs will be performed by explicitly taking fuel consumption into account. This is contrary to today's practice, where typically shortest paths or fastest routes are considered. Fuel-efficient route planning can directly benefit from V2I communication. Communication allows for considering the routing problem for a multitude of vehicles simultaneously, thereby including the fuel-reduction potential offered by platooning. Stated differently, future route planning will coordinate the routes and timing of individual HDVs to create common paths on which several vehicles can form platoons and collaboratively save fuel. Platooning will typically be limited to highways since the relatively simple environment of highway driving as well as the high speeds make them particularly suited for platooning. Besides taking into account the possibility of platooning, it is foreseen that such route calculation also makes use of real-time data of the state of traffic, infrastructure, and environment (for example, weather) to enable reliable fuel-efficient routing. The platoons exploit V2V communication, which also allows for creating platoons on an ad hoc basis (that is, not necessarily preplanned in the route calculation).

A system architecture for a future freight transport system supporting the scenario in Figure 3 is presented in the section "Freight Transport System Architecture." Many of the technologies required are already in existence today.

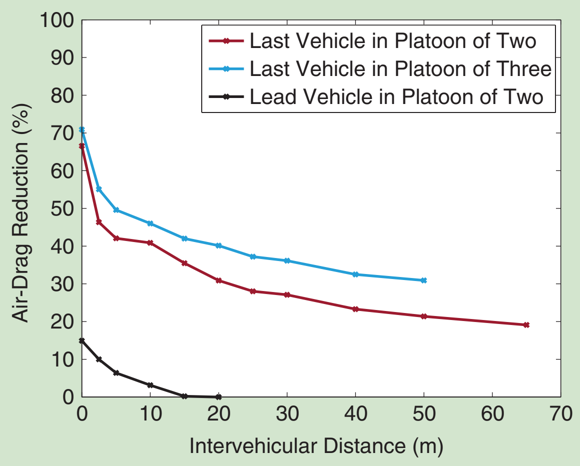


FIGURE 2 Air-drag reduction for buses in a platoon at 80 km/h. The figure is adapted from [10]. Similar results for heavy-duty vehicles can be found in [11] and [12].

A Brief Review on Platooning

Automated highway traffic is not a new idea. In fact, already at the 1939–1940 World's Fair in New York, General Motors presented a vision of automatically controlled vehicles on highways, aimed at guaranteeing safety for increased speed [S1]. Such automated highway systems, in which platooning plays an important role, have received considerable interest in California [13], [S2], [17]. Even before the automatic control of vehicles was considered, studies on the dynamics of a collection of vehicles following each other in a single lane (known as a string of vehicles) were performed as early as the 1950s. By assuming a simple model of driver behavior, [S3] and [S4] give early results on the dynamic response of follower vehicles to the behavior of the leading vehicle, where [S4] includes experiments using real vehicles. Strings of heavy vehicles (buses, in this case) are considered in [S5], where experiments of platoons of up to ten manually driven buses are discussed, considering traffic flow and the propagation of disturbances.

The design of automatic controllers for the longitudinal control of vehicles in a platoon was first considered in [S6] and [S7], where strings of infinite length were analyzed in the latter. However, both approaches construct a centralized controller, requiring knowledge of the states of all vehicles in the platoon and thereby limiting the practical implementation. Decentralized controllers, using only relative distance measurements with respect to nearest neighbors, were first given in [S8] and [S9]. Many results on decentralized controllers (sometimes including information obtained by communication with other vehicles or advanced sensors) have appeared since then (see, for example, [28], [S10], and [S11]), focusing on the effects of the intervehicular spacing policy [27] or the communication topology and available information [S12].

One important aspect of the performance and stability of platoons is given by the propagation of disturbances, as characterized through the notion of string stability [S13]. An increase in the tracking error of the intervehicular distance as disturbances propagate through the string of vehicles may lead to unstable behavior and has an adverse effect on traffic flow. An early definition of string stability is given in [S14] and used for controller design in [S9]. A formal definition is given in [S15], and an overview of string stability can be found in [S16].

Apart from theoretical developments, many experiments have shown that platooning is feasible in practice. One well-known successful demonstration was given by the PATH project in San Diego, California, in 1997, showing a platoon of eight passenger cars under combined longitudinal and lateral control [S17]. Within the same project, HDVs were considered as well [S18], [S19]. More experiments are given in [S20] for a platoon of six passenger cars under longitudinal control. For HDVs, experimental results for a platoon of four vehicles are given in [S21] within the scope of the Japanese Energy Intelligent Transportation System project [S22]. Similar European projects on HDV platooning were given by the Chauffeur [S23] and Konvoi [S24] projects. In the scope of the latter, experiments on a four-vehicle platoon on public German roads are reported in [S25]. At this point, it is recalled that, contrary to the work for passenger cars, platooning for HDVs is mainly aimed at reducing air drag and thereby fuel consumption. Consequently, many experimental studies focus on this aspect; see "Aerodynamics of Platooning" for a discussion on air-drag reduction. Finally, platooning under mixed traffic (that is, using both passenger cars and HDVs) has been shown in 2011 by the Grand Cooperative Driving Challenge [S26], where results are reported in the special issue

The concept of platooning does not need adaptations of the infrastructure and could be applied on the current highway network. As a result, the difficulties in the large-scale implementation of platooning are mainly related to legislation rather than technical aspects. In fact, in most countries it is currently prohibited to operate vehicles at the close intervehicular distances suggested for HDV platoons. Another important aspect is economics. Even though the benefits of platooning are clear, these benefits are not evenly distributed over all vehicles in a single platoon. Because, in a platoon, following vehicles typically save more fuel than the leading vehicle, it seems natural to introduce a pricing mechanism in which these benefits are equally shared over the vehicles. Note that platooning vehicles are potentially operated by different haulage companies. In a large system with many haulage companies having smaller or larger fleets of HDVs, the high-level decisions on who coordinates with whom will have economic impact and thus need to be organized with proper market models [16].

Since HDV platooning only requires partial automation, it might be a reality within the near future as well as provide a stepping stone toward higher levels of automation. Namely, platooning initially only automates the longitudinal control of all following vehicles in a platoon and can thus be seen as a natural extension of adaptive cruise control (ACC) systems. The lateral control (that is, steering) is performed by the driver, even though the automation of this aspect is a natural next step. Lateral control is particularly important for very short intervehicular distances because drivers have limited visibility in this case. On a longer time horizon, it is foreseen that a combination of measures will have to be taken to improve energy efficiency of road freight transportation, likely including the use of advanced drive trains on the basis of new more sustainable fuels or hybrid technologies as well as improved aerodynamics. However, it is expected that platooning will remain a part of this future road transportation system since it provides a relatively simple approach toward additional energy savings.

[S27]. The European project SARTRE [S28] has also focused on this aspect and results on mixed platoons are given in [S29].

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FREIGHT TRANSPORT SYSTEM ARCHITECTURE

A simplified system architecture for the future freight transport system is presented in this section. The system architecture provides a hierarchical decomposition of the overall transport problem into distinct layers. In particular, the three-layer architecture in Figure 4 is proposed, consisting of transport, platoon, and vehicle layers. Here, the transport layer is responsible for transport planning (that is, assigning goods to vehicles) and vehicle routing. The platoon layer translates the desired route into a specific trajectory for each vehicle, including platooning maneuvers such as the merging or splitting of platoons. Finally, the vehicle layer is aimed at tracking the desired trajectories from the platoon by real-time vehicle control. A detailed description of each of the three layers is given in the following sections. Other transport architectures for vehicle platooning have been proposed in [13] and [17], but they do not focus on freight transportation.

Transport Layer

The transport layer handles the transport planning problem by distributing the required flow of goods over the available HDVs and subsequently assigning their routes. Thus, the transport layer comprises two closely related tasks: transport planning and vehicle routing.

The objective of the transport planning task is to maximize the capacity utilization of HDVs by grouping similar transport assignments into a single load. In this way, the number of vehicles used can be minimized. As an example, goods that need to be transported along the same route can be combined into a single vehicle. It is clear that constraints such as deadlines or physical attributes of the goods (weight, size, or even the need for refrigeration) have to be taken into account. By optimizing the assignment of goods to individual HDVs, the total number of vehicles or required trips (that is, the amount of vehicle-kilometers) could be reduced. Thus, the potential for fuel and cost reduction is already

Aerodynamics of Platooning

The reduction of fuel consumption obtained through platooning is the result of a reduced aerodynamic drag. This drag F_d can be modeled as

$$F_d = \tfrac{1}{2} c_D \rho A v^2, \tag{S1}$$

where c_D is the drag coefficient, ρ is the air density, A is the frontal area of the vehicle, and v is the relative velocity of the vehicle with respect to the air flow. Even though the air drag can be significantly reduced when the velocity v is decreased, this is typically not economically viable. The same holds for the use of smaller vehicles (with decreased frontal area). Consequently, the only feasible approach toward the reduction of air drag in commercial vehicles is through the reduction of the air-drag coefficient c_D, which is dependent on the detailed shape of the vehicle and its positioning with respect to other vehicles. Vehicle design choices needed for improved aerodynamics might conflict with the objective of maximizing the loading volume within current legislation. As a result, the most effective approach to reducing the air-drag coefficient is by the interaction with other vehicles. This approach forms the core idea behind the concept of platooning.

Platooning relies on taking advantage of the unrecovered flow behind each vehicle, a phenomenon referred to as drafting or slipstreaming. Following vehicles face a reduced air pressure [10], as can be observed in Figure S1. Specifically, this figure is the result of simulations using computational fluid dynamics software and shows the deviation from the nominal air pressure. The overall air drag is the result of a pressure difference between the front and rear of a vehicle, with skin friction also playing a role. Figure S1 shows that the pressure on the front of the follower vehicle is significantly reduced for short intervehicular distances, thus reducing its aerodynamic drag. Also, the first vehicle benefits from the close proximity of a follower vehicle, because the influence of the follower vehicle on the wake of the first vehicle leads to an increased pressure on the rear of the first vehicle.

Even though simulations using computational fluid dynamics software can give insight into the mechanisms leading to a reduction of aerodynamic drag, such simulations are sensitive to the exact geometry of the vehicle. As a result, it is difficult to obtain accurate quantitative results on air-drag reduction via simulation. Therefore, many experimental evaluations of the reduction of aerodynamics drag and the resulting fuel savings have been performed; see [S30], [11], [S31], and [S32]. The section "Experimental Evaluation" strengthens these results by an extensive experimental study, performed under realistic traffic conditions.

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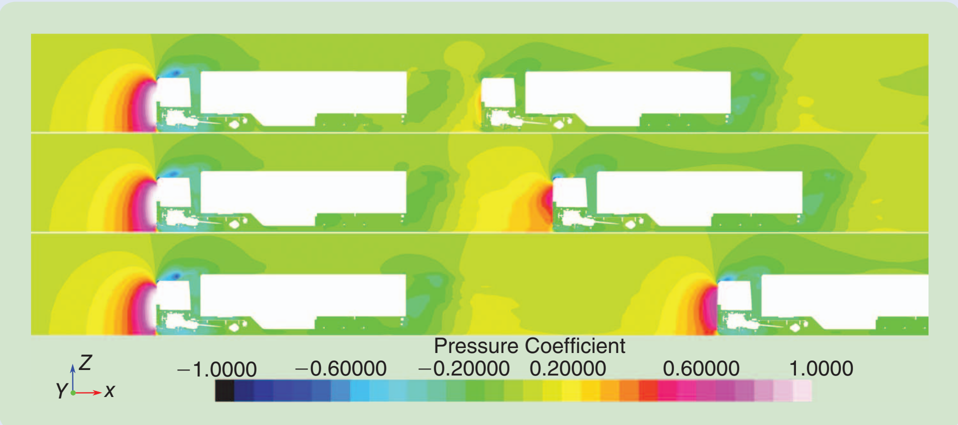

FIGURE S1 The pressure field for a two-vehicle platoon with a spacing of 5, 10, and 20 m. The pressure coefficient represents a scaled deviation from the nominal air pressure. (Reprinted with permission from [S33].)

apparent in this first aspect, particularly when noting that, in the European Union, HDVs are empty for about 20% of all driven kilometers [18].

The second task of the transport layer is the computation of routes for each vehicle, with the aim of finding the most fuel-efficient route. For example, a flat road through a valley might be more fuel efficient than a route through the mountains, even though the latter might be shorter. In this route calculation, the state of the traffic, infrastructure, and environmental conditions as well as drivers' resting times are taken into account to obtain reliable plans. One particularly important aspect of fuel-optimal routing is that routes are coordinated such that groups of vehicles can benefit from platooning on overlapping sections of their routes [19]. Consequently, a route for a single vehicle will not only contain the desired path but also the locations (and timing constraints) needed to rendezvous with other

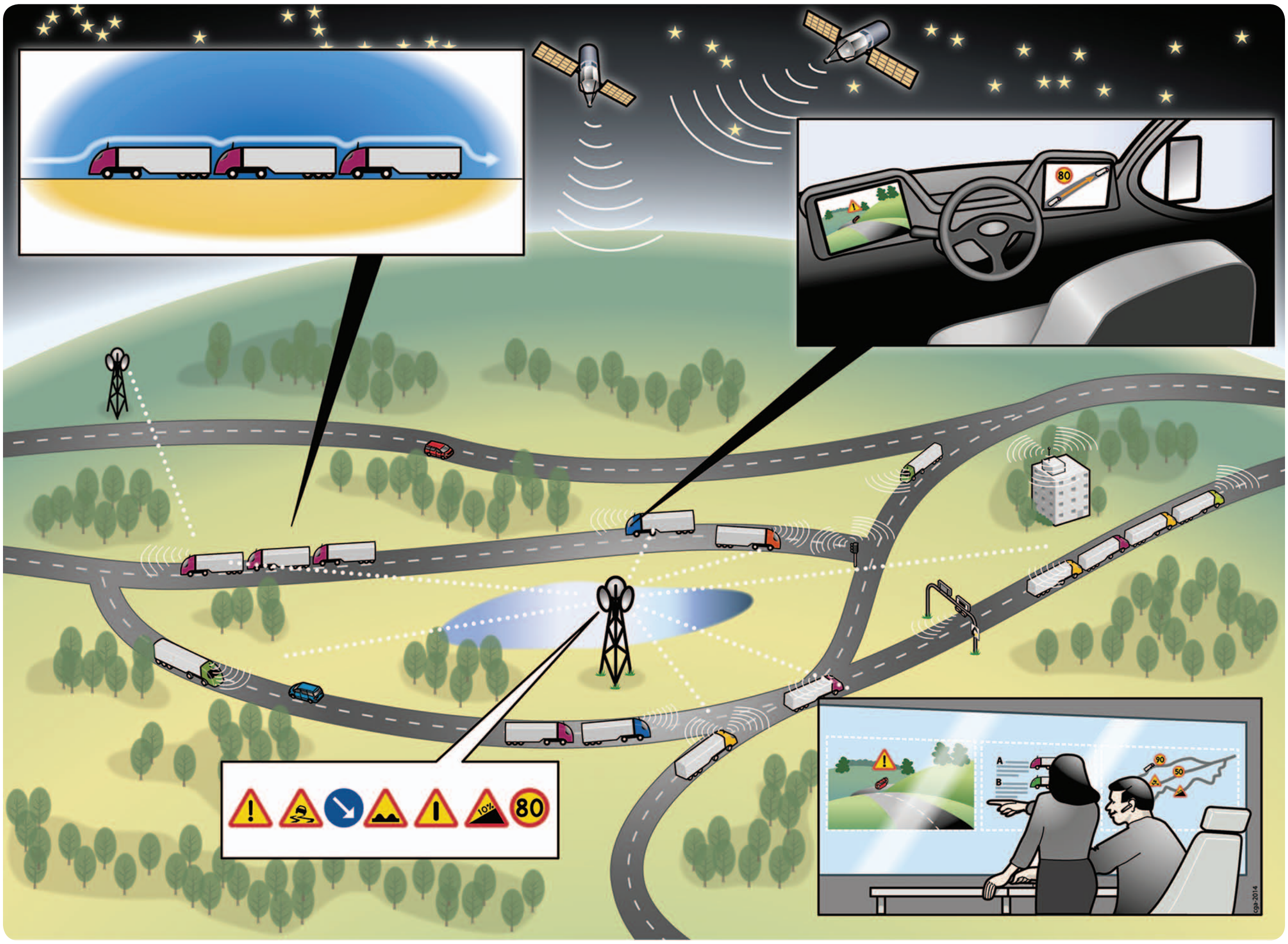

FIGURE 3 An illustration of a future freight transportation system. Each vehicle is able to serve as an information node through wireless communication, enabling a cooperative networked transportation system. Instructions, such as the possibility to platoon with vehicles further ahead and how to maneuver to an appropriate platoon position for fuel optimality, can be displayed on advanced human-to-machine interfaces inside the vehicles. Furthermore, the infrastructure aids vehicle platoons by providing information regarding, for example, road incidents, traffic conditions, road construction, and road tolls. A central office, such as a fleet management system, monitors each vehicle on the road and systematically coordinates scattered vehicles on the road network to form platoons to minimize fuel consumption under strict timing constraints.

vehicles to form platoons. This latter information will be referred to as a platooning schedule.

It is clear that the tasks of transport planning and routing are closely related and require large-scale optimization. In fact, the planning and routing tasks are equivalent to the vehicle routing problem (or traveling salesman problem). This vehicle routing problem has high computational complexity (specifically, it is NP-hard), but several heuristic approaches exist [20]. Note, however, that the scope for the tasks of transport planning and routing might be different. Namely, transport planning is typically performed within a haulage company, whereas the platooning-aware routing task might benefit from the inclusion of vehicles from a potentially large number of haulage companies. An implementation for the latter task might therefore be based on geographical regions. Finally, it is remarked that the optimization required in this layer will be continuously updated with the arrival of new transport assignments or

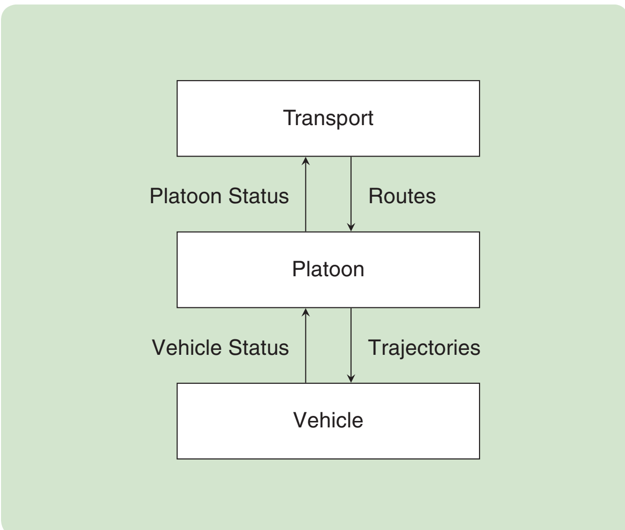

FIGURE 4 A layered freight transportation-system architecture.

vehicles deviating from earlier plans. To identify the latter, the transport layer monitors the status of the platoons.

Platoon Layer

The platoon layer takes the planned routes and platooning schedules, as computed by the transport layer, and assigns a reference velocity profile for each vehicle. This results in two distinct tasks: look-ahead trajectory planning and execution of platooning maneuvers.

Due to the large mass of HDVs, their fuel consumption is strongly dependent on the road grade (that is, the road slope in the direction of travel). However, when the topography of the road ahead is known, this information can be used to compute a velocity profile that minimizes the use of fuel. The need for braking on downhill road segments is reduced by lowering the velocity of the HDV before this segment. For single HDVs, experiments have shown that such an approach can result in a fuel reduction of about 3.5% for the same average velocity [21], whereas some first results on look-ahead trajectory planning for platoons giving additional savings can be found in [22].

Besides look-ahead trajectory planning, the platoon layer enables platooning by coordinating platoon maneuvers. These maneuvers include the merging of platoons (or single vehicles) or the splitting or reordering of platoons. Maneuvers are taken into account in the computation of the optimal trajectories for every HDV. The trajectories computed by the platoon layer not only consist of the velocity reference for every vehicle but also include the desired (and potentially nonuniform) intervehicular distances for the vehicles in a platoon. Although platooning maneuvers can be scheduled by means of the platooning schedule, the platoon layer also enables ad hoc platooning. Ad hoc platooning refers to the formation of platoons with vehicles that are at close distances, but are not necessarily included in the high-level transport planner (and therefore not in the platooning schedule). This additional possibility of platoon formation has the potential to further increase the fuel savings, especially on busy highways [23].

Because the tasks of the platoon layer manage individual platoons, the implementation of the platoon layer can be decentralized. Within a platoon, the implementation can be done on a designated platoon leader. Conceptually, platoons consisting of a single vehicle are allowed. Moreover, since platoons are subject to change due to platooning maneuvers such as merging and splitting, the execution of the platoon layer is dynamically attributed to the most suitable HDV. Finally, the implementation of the platoon layer uses predictive control, implemented in a receding horizon fashion. This allows for the optimization of the vehicle trajectories subject to constraints while being robust to disturbances in the vehicle layer.

Vehicle Layer

The vehicle layer deals with the real-time control of individual vehicles, using the output from the platoon layer as a reference trajectory. In particular, the onboard vehicle controller ensures tracking of the desired velocities and intervehicular distances, exploiting V2V communication and (radar) measurements of the intervehicular distance. Moreover, this controller should ensure a proper rejection of local disturbances, in which the concept of string stability is important. In particular, the vehicle controllers are responsible for the safe operation of the platoon and should provide guarantees that the HDVs in a platoon do not collide (for example, when, in an emergency, a vehicle in the platoon suddenly applies maximum braking). Here, it is crucial that safe operation of the vehicle layer does not explicitly require correct operation of the transport layer and platoon layer, such that the vehicle layer guarantees a safe fallback scenario in case information from the transportation system and/or platoon layers is missing or incorrect. Since the control tasks of the vehicle layer target the behavior of single vehicles, the implementation of the vehicle layer can be distributed over each individual HDV, leading to a decentralized approach.

We note that most existing research on (HDV) platooning has focused on the real-time vehicle control as performed in this layer (see "A Brief Review on Platooning" for an overview) and the role of platooning in the broader setting of freight transport has not received much attention. In the remainder of this article, we focus on the vehicle layer by designing a specific vehicle controller and presenting a detailed experimental evaluation of the fuel-saving potential of HDV platooning.

FUEL-EFFICIENT PLATOON CONTROL

In this section, we present a controller synthesis approach for the control of HDVs in a platoon. This feedback controller can be regarded as a specific implementation of the vehicle layer in the system architecture of Figure 4. An experimental evaluation of the performance of this controller will be given in the section "Experimental Evaluation."

An overview of the proposed platoon control system is given in Figure 5. The cruise control (CC) and ACC are commercially available systems in most modern HDVs. Hence, to allow for a smooth integration into the already-existing controller architecture, we propose that the cooperative adaptive CC (CACC) for vehicle platooning should be integrated with the existing cruise controller architecture. This facilitates a fast introduction of platooning as a commercial system. The arrows in Figure 5 indicate the information flow. Vehicle information, which is used in feedback control, is obtained through onboard sensors. The arrow between a preceding vehicle and the ACC represents the information obtained from the radar. The arrows between each CACC and the wireless communication network show the two-way communication between the platooning vehicles. It includes the system state and vehicle parameter information. The driver can manually choose to engage the CC, ACC, or CACC. In case of system failure or unpredicted behavior, the driver is instructed to take full control of the vehicle. Sometimes CACC can then instead be downgraded to ACC and ACC to CC.

A conventional CC offers three advantages over manual driving: maintained vehicle speed, improved fuel economy, and driver comfort over long distances. It typically uses velocity feedback information and is implemented as a PI- or PID-controller to determine the required change in velocity, which is then sent as a reference input to the low-level engine management control system. HDVs typically accelerate over downhill segments due to their large mass and then can potentially exceed the road speed limit, even though no fuel is injected. Hence, the downhill speed control (DHSC) [24] has been developed as an extension of the CC functionality. It is an automatic brake system that comprises the various braking systems on an HDV (that is, engine brake, retarder, and service brakes) and prohibits the vehicle from exceeding a certain maximum velocity.

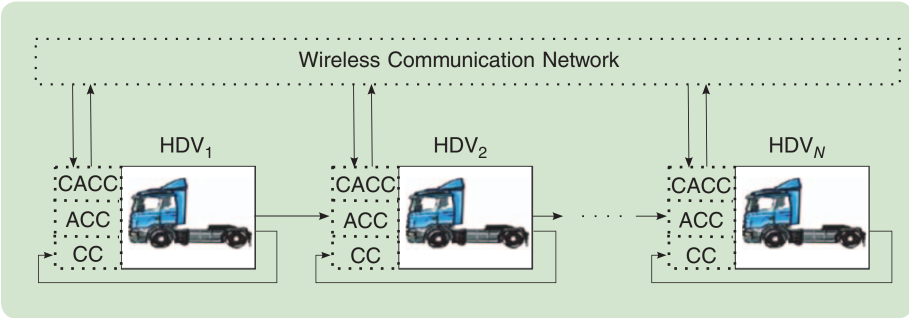

FIGURE 5 A platoon system architecture for an N heavy-duty vehicle (HDV) platoon. The lead vehicle, with index $i = 1$, is to the left and the last vehicle is to the right. The information flow over communication and sensor channels is illustrated by the arrows. The control options for vehicle speed control are shown in front of each vehicle. For platoon driving, the first vehicle will use either a cruise controller (CC) or adaptive cruise controller (ACC), whereas the follower vehicles will employ the cooperative adaptive cruise controller (CACC) when a wireless connection is established. The first vehicle might switch to the CACC controller when approaching another platoon.

A conventional ACC [25], [26] aims to maintain a desired spacing by using distance and relative velocity information based on the radar measurements to the preceding vehicle. A constant spacing [27], constant time headway [28], or a nonlinear spacing policy [29] can be used. The commercial ACC considered in this article uses a constant time-gap policy (or constant time headway policy) given by

$$d_{\text{ref}} = \tau v, \tag{1}$$

where d_{ref} is the desired intervehicular distance, v is the vehicle velocity, and τ is the desired time gap. The ACC aims to maintain the desired distance while also considering fuel efficiency and driver comfort. This is typically achieved by a controller that switches between various operating modes, for instance, to allow for a smaller intervehicular distance during downhill sections to avoid unnecessary braking. Safety constraints are incorporated since, as opposed to the CC, the ACC is allowed to actuate the brakes and can react faster than a driver.

The aim of the CACC is to maintain a suitable intervehicular distance to enhance fuel efficiency, provide robustness with respect to external disturbances, and ensure safety. The spacing policies can be similar to the ones for the ACC. However, as opposed to the ACC, the control inputs are coordinated among several vehicles, which allows for a cooperative and synchronous behavior. This allows the intervehicular distance to be reduced and thus the fuel consumption is lowered through reduced air drag. The CACC evaluated in the section "Experimental Evaluation" is a decentralized linear-quadratic regulator. Its cost function includes the behavior of the preceding vehicles, such that control actions are based on self-interest as well as the interests of other vehicles in the platoon. Specifically, the cost function captures the deviations from the desired intervehicular spacing and relative velocities as well as includes a cost on the control input. By choosing a suitable weighting, desirable behavior can be obtained [30]. The particular structure of the platoon system dynamics can be divided into subsystems. Each vehicle in the platoon computes its locally optimal controller and transmits control gains, vehicle parameters, and state information to the follower vehicles. Hence, the controllers are derived sequentially, which allows for a decentralized and scalable implementation. Note that each follower vehicle only considers the information of all preceding vehicles within radio range when deriving its feedback control law. As a result of subsequently deriving controllers based on local model information and interconnections, a global suboptimal decentralized feedback control law, $u(k) = -Lx(k)$, is produced, where $x(k)$ denotes the state vector containing information for all the preceding vehicles within radio range and where the state feedback gain matrix L has a lower block-diagonal form

$$L = \begin{bmatrix} L_{11} & 0 & 0 & \dots & 0 \\ L_{21} & L_{22} & 0 & \dots & 0 \\ L_{31} & L_{32} & L_{33} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ L_{N1} & L_{N2} & L_{N3} & \dots & L_{NN} \end{bmatrix}. \tag{2}$$

The matrix elements L_{ij}, $i = 1,\dots,N$, $j = 1,\dots,i$ denote the feedback gains for the ith vehicle in the platoon based on state and system-parameter information from all vehicles j. Note that the feedback gain matrix in (2) is given in a general form. However, it can have a lower band diagonal structure depending on the radio range. When the communication range is limited, the states for the first or other preceding vehicles outside the range cannot be considered and the corresponding matrix elements are then set to zero.

When basing the control on information from several preceding vehicles, the number of harsh accelerations and decelerations can be reduced, and the fuel efficiency can be improved significantly. A more detailed description is given in [12].

Several low-level vehicle control systems are involved in executing the control commands from the CC, ACC, or CACC. The low-level controllers in a commercial HDV consist of an engine management system (EMS), a brake management system (BMS), and a gear management system (or transmission management system, TMS). The EMS receives a velocity request as an input and adjusts the engine fueling to obtain the requested velocity. The EMS also assures that no oscillations arise in the drive train. It monitors the turbo pressure and limits the fueling in case the amount of air is insufficient for the combustion process. Hence, the achievable torque might be limited. There are several brake systems in a modern HDV, ranging from the weaker exhaust brake to the strong disc brakes. The BMS receives a deceleration request and typically blends the brake power over the different systems to assure that no system overheats. Therefore, the achieved braking force varies with respect to the current state of the system. The TMS is an automated gear-changing system that enables the driver to devote more attention to handling the vehicle and to traffic. Monitoring the engine speed and the drivetrain torque request, the TMS is designed to change gears quickly and comfortably in a fuel-efficient manner. Note, however, that a delay typically arises when disengaging and engaging a new gear. The low-level controllers inherently linearize the vehicle behavior to some extent, even though model uncertainties and nonlinearities are present when a large dynamic range of operation is considered. For example, step responses in velocity of the same magnitude might vary depending on the current gear, if the engine was idling or active, or if the BMS was active just before the step is requested. These nonlinearities must be taken into consideration by the high-level controller in the vehicle layer of Figure 4. It is not fuel efficient to brake since the energy produced through diesel combustion is wasted through heat loss produced by the frictional forces in the brake discs. However, braking may be required if, for example, a preceding vehicle decelerates or when traversing a steep downhill [22], [31]. Therefore, we propose a control system that switches between engine and brake control, as illustrated in Figure 6. Gear changes are handled automatically by the existing TMS.

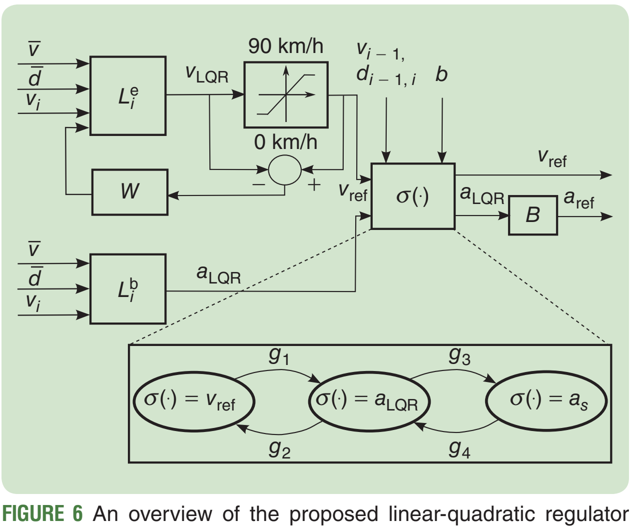

FIGURE 6 An overview of the proposed linear-quadratic regulator with bumpless transfer. The controller consists of two regulators L_i^{e} and L_i^{b} that obtain the desired behavior through controlling the engine and brake system, respectively. This leads to a reference velocity (v_{ref}) or acceleration (a_{ref}) command that will be handled by lower-level control systems. The regulators take velocity and intervehicular spacing data from all preceding vehicles denoted by $\bar{v}$ and $\bar{d}$, whereas v_j and d_j represent these data for a specific vehicle with index j. Note that i is the index of the vehicle under control. Finally, σ represents the switching logic, W an antiwindup filter, and B a low-pass filter that enables bumpless switching.

The feedback gain matrices, L_i^{e} when actuating through the EMS and L_i^{b} when actuating through the BMS, for the controller in Figure 6 are established sequentially by considering the previous vehicles as outlined above. The speed demand sent to the EMS will never exceed the legal speed limits of the road, which might saturate the control demand produced by the L_i^{e}. Hence, an antiwindup filter W is implemented.

The switching guards, g_i in Figure 6, between the three modes of operation are defined as

g_1: $(d_{i-1,i} < \beta\tau v_i$ and $v_{i-1} < v_i)$ or $(b = 1$ and $d_{i-1,i} < \tau v_i)$

g_2: $d_{i-1,i} \geq \tau v_i$ and $v_{i-1} \geq v_i$ and $b = 0$ and $d_s < d_{i-1,i}$

g_3: $[v_i, d_{i-1,i}, v_r]^T \in \partial\mathcal{S}$

g_4: $[v_i, d_{i-1,i}, v_r]^T \in \mathrm{int}(\mathcal{S})$

where $d_{i-1,i}$ denotes the spacing between the ith vehicle and its preceding vehicle, v_i denotes the velocity for the ith vehicle, $b \in \{0,1\}$ is a binary signal that indicates whether a preceding vehicle brakes, d_s is a minimum allowed safety distance, and $\beta \in [0,1]$ is a design parameter that determines how much the intervehicular distance is allowed to decrease from the reference distance before the brakes should be applied. The safe set $\mathcal{S}$, derived through a game theoretical formulation for guaranteeing safety [32], is given as $\mathcal{S} = [0, v_i^{\max}] \times [d_{i-1,i}^{\min}, \infty) \times [v_r^{\min}, v_r^{\max}]$, where v_r is the relative velocity with respect to the preceding vehicle. A collision can always be avoided despite the worst-case behavior of the preceding vehicle if the vehicle states are inside the safe set; otherwise, a collision can occur. Hence, if a vehicle reaches the boundary of the safe set, denoted as $\partial\mathcal{S}$, a collision avoidance brake request a_s is sent to the BMS to guarantee safety. The collision avoidance is aborted, and the control is resumed once the vehicle reaches sufficiently inside the safe set. The controller output v_{ref} is directly fed through if the vehicle operates within the allowed intervehicular distance. If the spacing decreases below the allowed limit and the preceding vehicle has not started to increase its velocity, or if any of the preceding vehicles brakes, the controller output a_{LQR} is fed through until the preceding vehicles cease braking and the required distance is resumed. If the spacing to the preceding vehicles decreases slightly, a reduced reference velocity is initially provided and the engine torque will drop to zero. A large jerk might occur when switching to braking since the spacing is shorter than the reference. To facilitate a bumpless transfer when the controller switches to a_{ref}, a lowpass filter $B(z)$ is implemented after the switch.

EXPERIMENTAL EVALUATION

This section evaluates the fuel-saving potential of platooning, which provides a motivation for the development of a road freight system architecture as presented in the section "Freight Transport System Architecture." The experiments use the decentralized CACC controller as designed in the previous section and, rather than focusing on fuel savings alone, also address the performance of this decentralized feedback controller. Realistic environmental conditions are obtained by performing the experiments on Swedish public highways. In this section, we first present the experimental setup and methodology. Then we investigate the experimental results, focusing on controller behavior and the fuel-savings obtained by platooning on various road topographies. In particular, it will be shown that platooning offers a significant reduction in fuel consumption when road segments with moderate road grade are considered. For these road segments, a fuel consumption reduction of up to 6.5% is obtained under varying environmental conditions. Furthermore, it will be shown that these fuel savings are not obtained for roads with large road grades and that more-advanced predictive control strategies are required to unlock the fuel-saving potential of platooning on such roads.

Experiment Setup and Methodology

Three standard Scania tractor-trailer HDVs, denoted $\mathrm{HDV_A}$, $\mathrm{HDV_B}$, and $\mathrm{HDV_C}$, were used in the experiments. The vehicles are equipped with additional control and communication hardware, as illustrated in Figure 7. The CACC, outlined in the section "Fuel-Efficient Platoon Control," is implemented in an electronic control unit (ECU). All tractors have two axles, of which the rear axle is driven by the engine, and the trailers have three axles. The total length of each vehicle configuration is 18 m. $\mathrm{HDV_C}$ is not as tall as the other vehicles and therefore has a larger wind deflector. Nevertheless, the total frontal area, in combination with the attached trailer, is 10.2 m^2 for all three vehicles. The masses (of the fully fueled vehicles) were measured to be 37.5 t for $\mathrm{HDV_A}$, 38.4 t for $\mathrm{HDV_B}$, and 39.4 t for $\mathrm{HDV_C}$. Since 40 t is the legal limit in many European countries, the experiments performed with these vehicles give a realistic assessment of the fuel-saving potential offered by platooning. Note that this potential is expected to increase for lighter vehicles since other resistive forces such as rolling resistance or the effect or road grade decrease with decreased vehicle weight. For lighter vehicles, the relative fuel savings can thus be expected to increase. All vehicles are equipped with slightly different, but automatic, gearboxes and a 480-hp engine. The vehicles have a standard Doppler radar, which sends the relative distance with a 40-ms measurement interval to the central coordinating ECU. The final gear ratios are slightly different for each vehicle. A smaller final gear ratio implies that the vehicle will run faster for a fixed engine speed and a larger gear ratio implies that the vehicle can output a larger torque. Standard global positioning systems (GPSs) and ECUs are used for positioning and to execute the proposed control. A wireless sensor unit (WSU) with the standard wireless communication protocol IEEE 802.11p is mounted in each vehicle. The WSU is directly connected to the vehicle's internal controller area network (CAN), and messages are broadcast on demand. Thus, the internal CAN signals such as velocity, acceleration, system model parameters, and control inputs are available to all vehicles within communication range.

The experiments were conducted on highway E20 between the Swedish cities Mariefred and Eskilstuna, west of Stockholm, as shown in the map of Figure 8. Part (a) shows the elevation profile, and parts (b) and (c) depict the corresponding road grade profile. Data were collected when the vehicles start at the cross (×) and head westbound until they

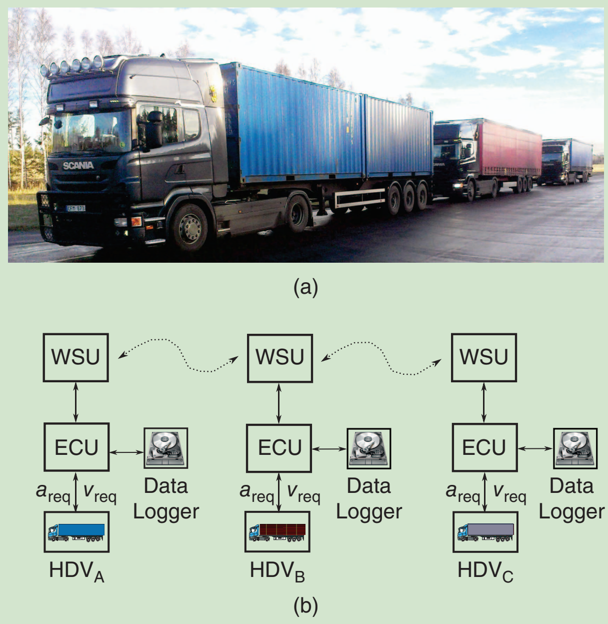

FIGURE 7 A schematic overlay of the experimental setup. Part (a) shows the heavy-duty vehicles (HDVs) used in the experiments, where the left vehicle is the lead vehicle. The wireless sensor unit (WSU), electronic control unit (ECU), and data logger communicate through a vehicle's internal controller area network [see (b)]. A velocity request v_{req} and acceleration request a_{req} are generated by the high-level controllers and executed by low-level controllers in the vehicles. As soon as new local information is obtained in a vehicle, it is broadcast to the other vehicles through the wireless communication network. (Image courtesy of Scania CV AB.)

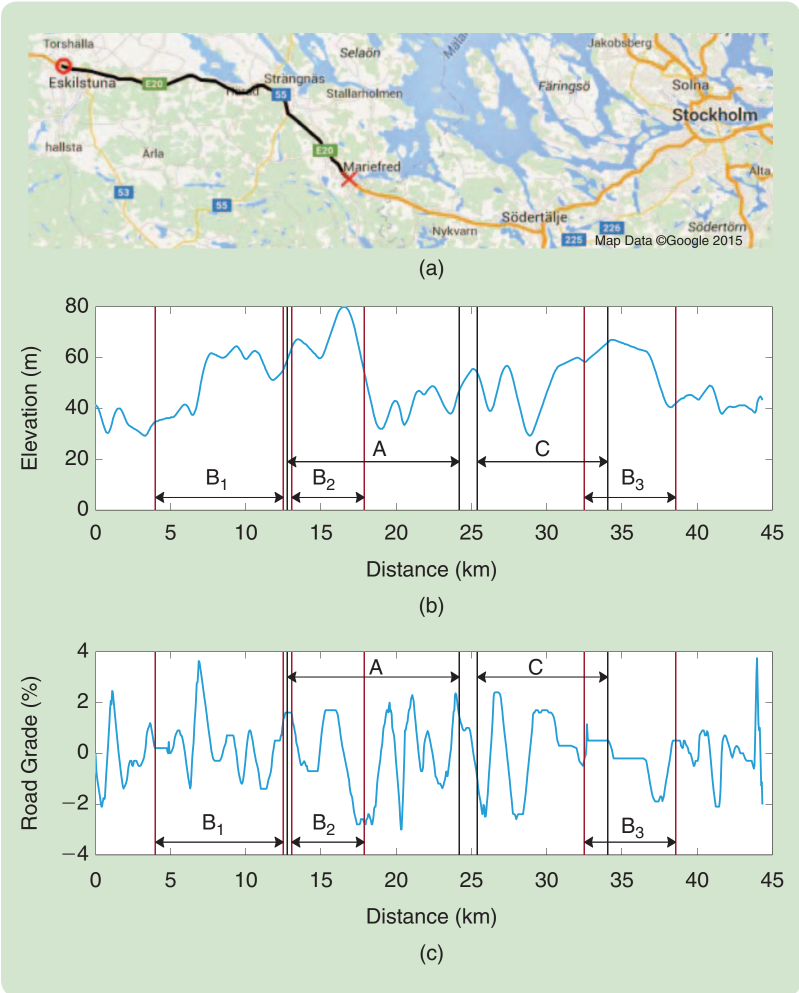

FIGURE 8 Road data for the Swedish highway E20 between Mariefred and Eskilstuna that was used for the experiments. The elevation and road-grade profiles correspond to the westbound part, where the vehicles start at the × and finish at the ○ on the map. The road segments denoted by A, B_1, B_2, B_3, and C are discussed in the sections "Evaluation of Controller Performance" and "Evaluation of Fuel Savings."

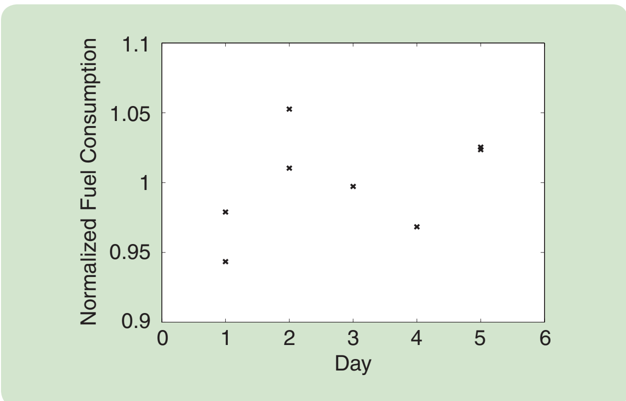

FIGURE 9 Normalized fuel consumption for a heavy-duty vehicle (HDV_C) driving alone for each day. The fuel consumption results are normalized with respect to the average fuel consumption for all the days. To isolate the effect of platooning, the data for one of the test runs on day 3 and day 4 are discarded since those runs were interrupted by traffic cutting in the platoon.

reach the circle (○). The vehicles then turn, and data are recorded starting from the circle, heading eastbound, and finishing at the cross. We refer to one such round trip as a test run. The total road length between the markers is 45 km, and, therefore, one test run is 90 km. As shown by the road grade profile, the road under consideration contains several hills and the road grade varies between −3 and 3%. Six test runs were conducted every day for five days. Consequently, the experiments are conducted and data are collected over a total of 2700 km per vehicle. Two of the daily test runs are conducted when the vehicles operate alone to determine the average fuel consumption over the road stretch without any air-drag reduction from platooning. Two test runs are conducted when the vehicles are operated as a platoon to investigate the change in fuel consumption over the same stretch and in similar weather conditions. In the final two test runs of the day, the positions of the two follower vehicles are interchanged to determine whether fuel-saving results are consistent with respect to these vehicles. HDV_A is always in the first platoon position to maintain the platoon-leader behavior, whereas HDV_B and HDV_C are follower vehicles. To obtain normal vehicle operating temperature, the vehicles are driven 35 km before starting the test runs, since a large amount of energy is initially spent on heating various components, such as the lubrication oil and the cabin. The total fuel consumption over each test run is obtained by integrating the instantaneous fuel consumption, which is recorded over the CAN. The vehicle speed sensor in a commercial vehicle can have a slight offset. Therefore, the speed for each vehicle is calibrated with respect to the common GPS speed information before the experiment trials. The maximum allowed road speed in Sweden for HDVs with the configuration at hand is 80 km/h. However, the nominal operating speed for all vehicles was set to 75 km/h to reduce the traffic interference as much as possible, with a DHSC offset of 10 km/h. By operating the vehicles at a lower-than-allowed speed, it is expected that surrounding vehicles pass the platoon and do not change the operating conditions of a test run by cutting in between. The CACCs of the follower vehicles are set to maintain a time gap of $\tau = 1$ s. Operating at closer distances is currently not allowed by Swedish legislation.

Weather conditions change over time, which affects the instantaneous fuel consumption for an HDV and can create a variation in fuel consumption from day to day. For example, the wind speed adds to the vehicle velocity and has a quadratic influence on the air-drag force. The temperature and precipitation influence fuel consumption since the air density changes with variation in temperature or humidity and the road friction changes when wet. In fact, during the five-day period in which the test runs were conducted, the temperature fluctuated between −1 and 8 °C and the road was wet due to rain on some days. Hence, the fuel consumption when traveling alone varied ±6% between experiments, as illustrated in Figure 9. The markers represent the fuel consumption over a single test run when traveling alone, where the results are normalized with respect to the average fuel consumption over all the days. As the results in Figure 9 indicate, the fuel-saving potential due to platooning cannot be evaluated by considering the absolute fuel consumption. Instead, normalized fuel consumption is reported in this article. For each vehicle and each test run, the fuel consumption is compared to the amount of fuel the same vehicle consumed when driving alone on the same day. Thus, the influence of environmental conditions is reduced and reproducible and reliable results are obtained.

Evaluation of Controller Performance

To assess the performance of the proposed controller, the results for one test run over the westbound part are shown in Figure 10. Starting from the top, (a) shows the elevation profile of the third vehicle in the platoon, and (b) shows the velocity profiles for the three-vehicle platoon. HDV_A is the lead vehicle, HDV_B the second vehicle, and HDV_C the third. Part (c) shows the relative distance between the vehicles, where d_{AB} denotes the distance between the first and the

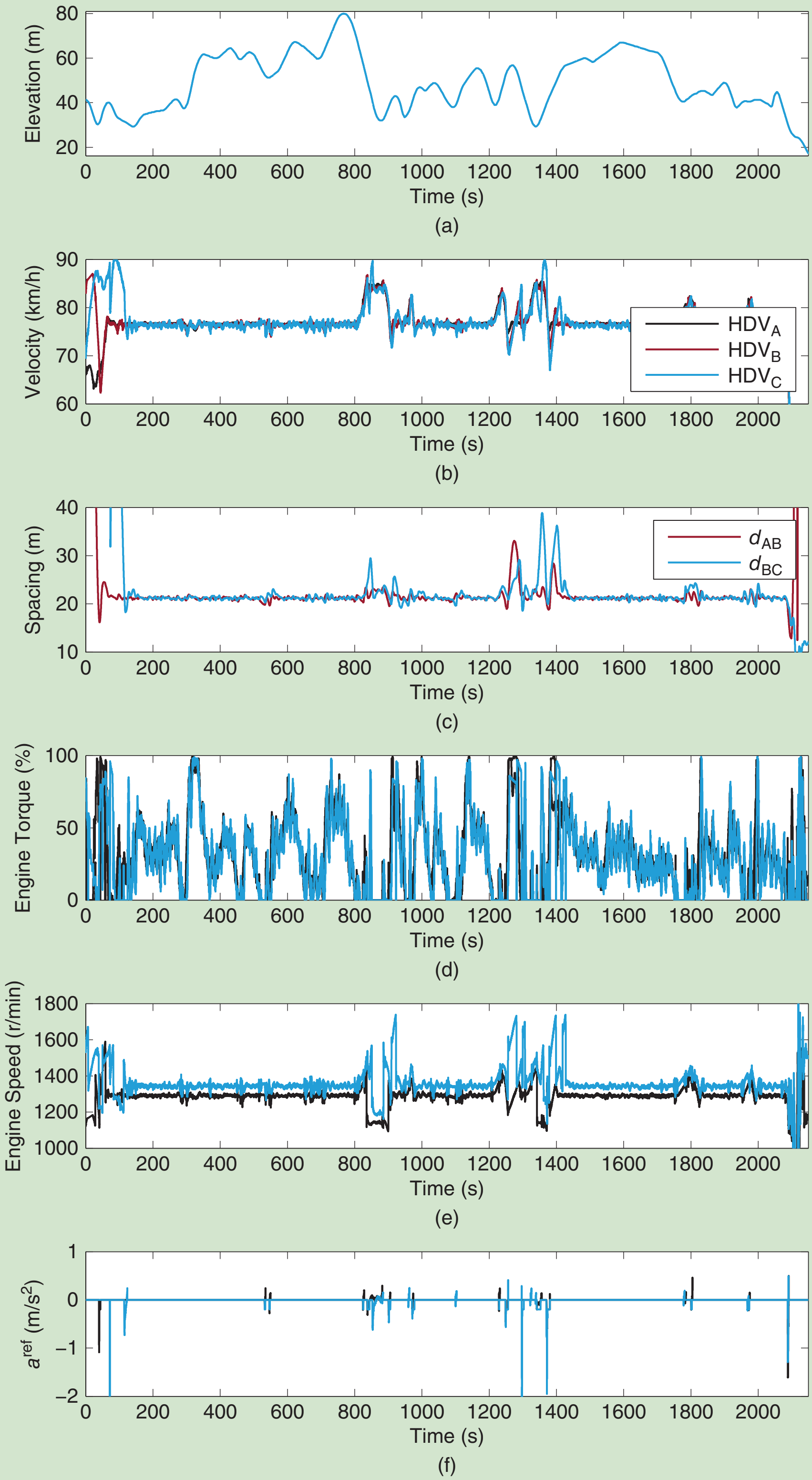

FIGURE 10 Experimental results obtained for the three-vehicle platoon traveling west over the E20 near Stockholm, Sweden. The results were obtained with HDV_A as the lead vehicle, HDV_B as the second vehicle, and HDV_C as the third. In all plots, except in (a), the black lines are the profiles for the first vehicle in the platoon, the red lines are the profiles for the second vehicle, and the blue lines are the profiles for the third vehicle.

Weather conditions change over time, which affects the instantaneous fuel consumption for a heavy-duty vehicle.

second vehicle and d_{BC} gives the distance between the second and the third vehicle. Part (d) shows the normalized engine torque for all vehicles. Part (e) shows the engine speed for the second and third vehicle, where the sudden jumps in engine speed, for example between the 800 and 900 s time markers, signify gear changes. Finally, part (f) shows the corresponding brake requests. Note that a small braking force might be needed to maintain the relative distance to a lighter preceding vehicle when coasting over a downhill segment. The positive braking requests in part (f) are due to the fact that braking is required to limit the (positive) acceleration in steep downhills.

The test runs are initialized by letting the vehicles travel at a large intervehicular spacing followed by a merging action, as illustrated between the 0 and 200 s time markers in Figure 10. The lead vehicle is governed by its CC, set at the nominal operating speed of 75 km/h. The follower vehicles are governed by the CACC, which acts as a CC if no preceding vehicle is detected. To catch up with the lead vehicle, the set speed for the follower is higher than the nominal operating speed. When a wireless connection is established and relevant information is obtained, the CACC reduces the speed reference to join a platoon with the vehicle ahead.

It can be observed in Figure 10 that the CACC is able to maintain the desired intervehicular spacing (that is, given through the time gap of 1 s) over most parts of the road. The velocity and relative distance between the vehicles do not vary significantly over segments with small road grade. For example, the unbiased sample standard deviations over the segment denoted by B_3 in Figure 8 for the velocity are $\sigma_{\mathrm{A}}^{\mathrm{v}} = 0.3\ \mathrm{km/h}$, $\sigma_{\mathrm{B}}^{\mathrm{v}} = 0.4\ \mathrm{km/h}$, and $\sigma_{\mathrm{C}}^{\mathrm{v}} = 0.4\ \mathrm{km/h}$ for the first, second, and third vehicle, respectively. The unbiased sample standard deviation is defined here as $\sigma_i^{\mathrm{v}} = \sqrt{(1/(n-1))\sum_{k=1}^{n}(v_i(k) - \bar{v}_i)^2}$, where n is the number of samples, $v_i(k)$ is the velocity at sample k for vehicle $i \in \{\mathrm{A,B,C}\}$, and $\bar{v}_i = (1/n)\sum_{k=1}^{n} v_i(k)$. Small disturbances produced by the varying road grade create a variation in velocity for the follower vehicles. This is also confirmed by the sample standard deviation for the intervehicular spacing, given by $\sigma_{\mathrm{AB}}^{\mathrm{d}} = 0.3\ \mathrm{m}$ and $\sigma_{\mathrm{BC}}^{\mathrm{d}} = 0.3\ \mathrm{m}$. Thus, it can be inferred that the CACC performs well when the deviations from steady-state operations are small (for a discussion of safety aspects related to large deviations, see [30]). Moreover, as indicated by the brake requests, the follower vehicles brake over steep downhill segments. Braking is required in these cases since the follower vehicles are heavier than the lead vehicle. Thus, they coast with a higher acceleration over the downhill segments and inherently would slide in to the preceding vehicle if braking is not performed. The trajectories for the engine speed show that a braking is often followed by a gear change. Hence, a jump occurs in the engine speed, as can be seen between the 800–1000 s time markers in plot (e).

Unwanted braking actions can occur over steep downhill segments with the CACC. Figure 11 zooms in to the interval 600–1150 s of Figure 10, which corresponds to segment A in Figure 8. Note that a high variation in relative velocity arises over the downhill segment between 750 and 950 s. Here, the first vehicle starts to coast when entering the downhill segment by cutting off the fuel injection and thereby reducing the engine torque to zero, as shown in plot (d). However, due to its large vehicle mass, the first vehicle continues to accelerate until the DHSC constraint is reached at 830 s. The second vehicle initially increases the torque to maintain the relative distance and then reduces it to zero when entering the downhill segment. The second vehicle, being heavier, then obtains a higher velocity over the downhill segment and is forced to apply the brakes to not collide with the preceding vehicle. The same behavior can be observed for the third vehicle, which is heaviest. However, in this case an excessive braking action increases the spacing more than desired and inherently increases the variation in velocity. Hence, additional fuel consumption is necessary to close the gap, as shown by the increase in engine torque for the third vehicle around the 850-s time marker. Thus, unmodeled dynamics in the braking system can induce a behavior that increases the fuel consumption. The fuel consumption under these circumstances is discussed in the next section. Furthermore, the varying topography seems to induce large changes in engine torque. In Figure 11, part (d) shows that the engine torque for the second vehicle varies more than it does for the first vehicle. This is due to the additional transient control actions that are necessary for maintaining the spacing when disturbances are imposed on the system. The variation in engine torque is marginally higher for the third vehicle since it has a higher mass and lower final gear ratio compared to the second vehicle.

Evaluation of Fuel Savings

The achieved fuel savings for the three-vehicle platooning experiments are discussed next. To obtain reliable results, only the relative fuel consumption is considered for each vehicle. It is obtained by measuring the fuel consumption when a vehicle is operating in a platoon and normalizing it with respect to the average fuel consumption when driving alone on the same day, as given in Figure 9. The same gear is used when driving over road segments with small grade to obtain comparable results for the fuel consumption. Namely, the selection of a higher gear over the same road stretch would imply a lower fuel consumption. To ensure that gear changes do not occur on segments with small road grades, the automatic gear box was operated in a mode that allows for higher engine revolutions per minute (RPM) and thereby reduces the number of gear shifts. Because the engine fuel–torque and torque–RPM mappings are nonlinear, the fuel consumption might vary considerably if, for example, the RPM is slightly different between test runs. To eliminate the effects of detailed engine characteristics on the fuel consumption, a measure of the engine output is considered as well. This propulsion energy is defined as $E = \int T_e \omega_e \, dt$, where T_e is the net engine torque and ω_e the angular velocity of the engine. It can be regarded as the net energy needed to drive the vehicle (without considering engine characteristics) and will therefore be referred to as energy consumption. In the remainder of this section, the fuel and energy consumption over the segments indicated in Figure 8 are discussed. First, the fuel consumption over road segments with a small road grade is presented, whereas the consumption over road segments with a steep grade is discussed next.

Fuel Consumption Over Road Segments with Small Grade

The normalized fuel and energy consumptions for test runs over road segments with small grade corresponding to the segments B1, B2, B3 in Figure 8 are given in Figure 12. By road segments with small grade, we mean segments where the vehicles do not have to brake when coasting

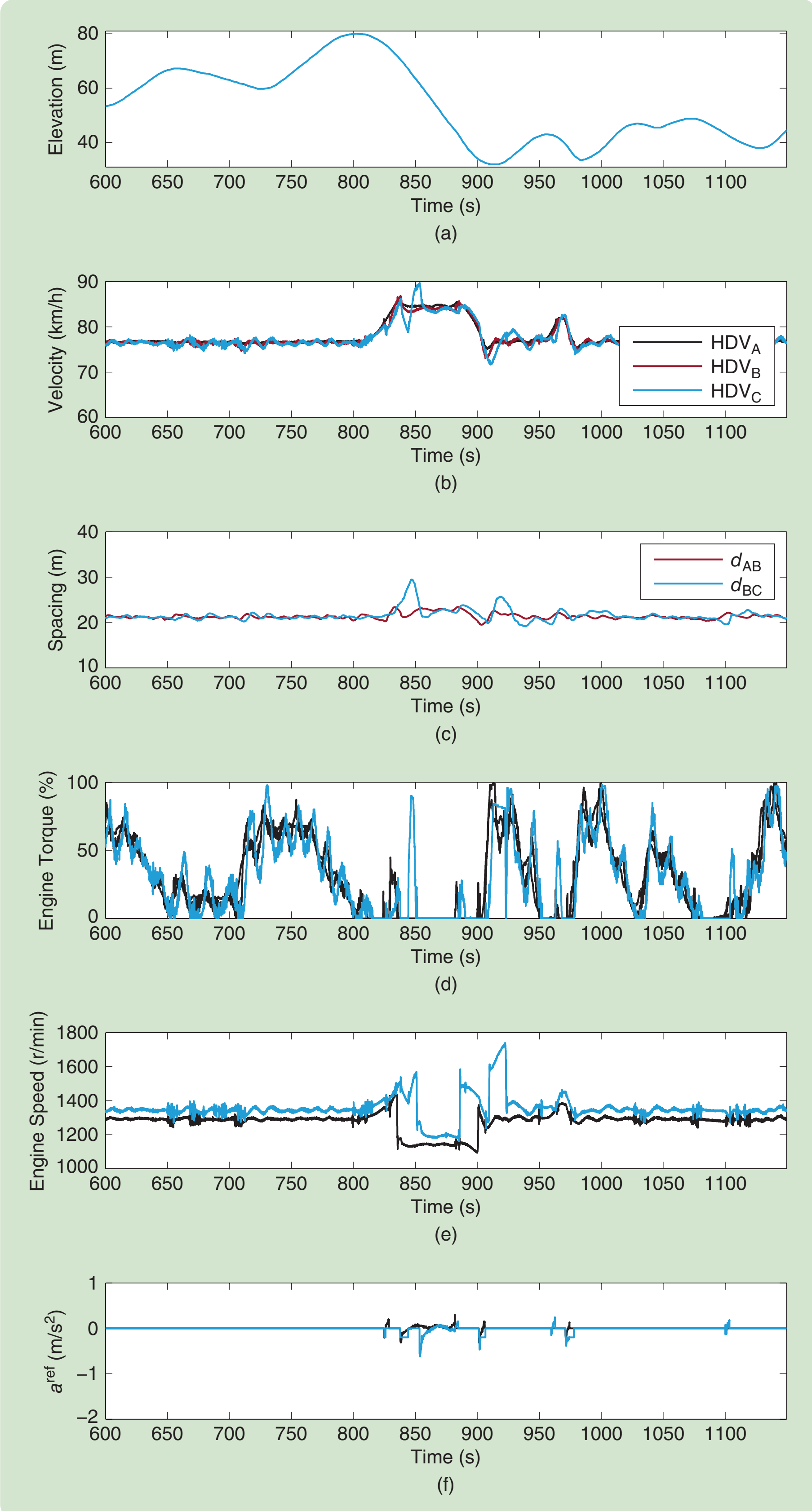

FIGURE 11 Experimental results obtained for the three-vehicle platoon when traveling over road segment A in Figure 8, which corresponds to the road segment between 600 and 1150 s in Figure 10.

Weather conditions change over time, which affects the instantaneous fuel consumption for a heavy-duty vehicle.

over a downhill section or change the gear for maintaining the speed in uphill climbs. A little less than half of the considered road stretch falls under this classification. In Figure 12, (a) and (c) show the results for HDV_B and (b) and (d) show the results for HDV_C. Plots (a) and (b) show the normalized fuel consumption, and (c) and (d) show the corresponding normalized energy consumption for each vehicle. Recall that the fuel consumption and energy consumption over a single test run are normalized with respect to the average fuel and energy consumption, respectively, when driving alone on the same day. Data are given for the follower vehicles when they travel alone, in second, and third position. The markers $\times, \diamond, \circ, \cdot$, and $*$ denote the measured normalized fuel consumption over a single test run. The red squares with black borders denote the average fuel consumption over all the test runs in the corresponding platoon position. The correlation between the fuel consumption for the follower vehicles is illustrated by the marker type and color. For example, a black $\Diamond$ indicates one experiment when HDV_C is traveling in the second platoon position and HDV_B

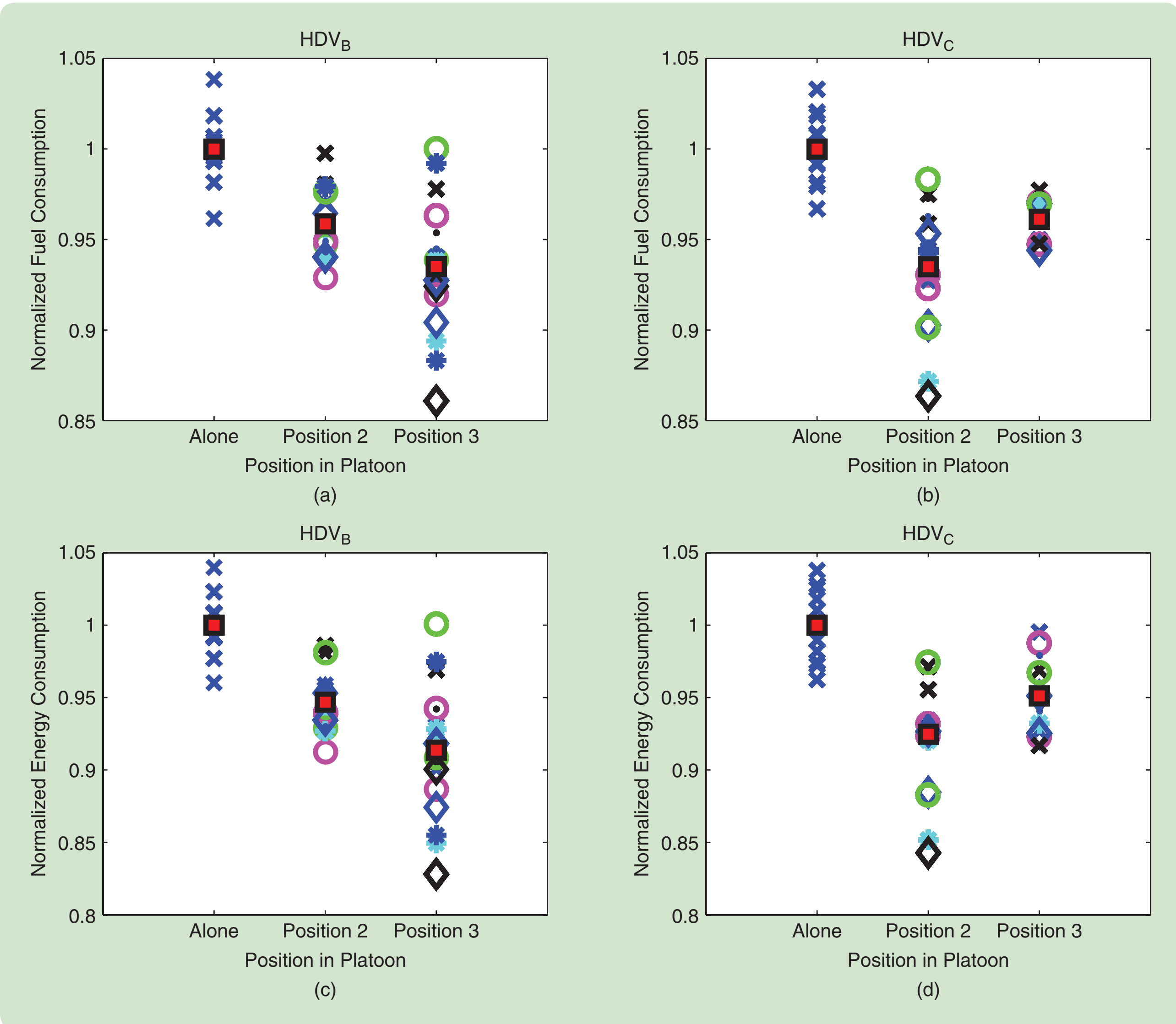

FIGURE 12 Normalized fuel and energy consumption over the road segments B_i, $i = 1, 2, 3$, in Figure 8. Plots (a) and (c) show the results for HDV_B, and plots (b) and (d) show the results for HDV_C. Plots (a) and (b) show the normalized fuel consumption, and plots (c) and (d) show the corresponding normalized energy consumption.

The experiments were conducted on highway E20 between the Swedish cities Mariefred and Eskilstuna, west of Stockholm.

in the third platoon position. For this particular experiment, it is noted that both HDV_B and HDV_C have relatively low fuel and energy consumptions.

The results in Figure 12 show that a significant fuel saving can be obtained when traveling in a platoon. The fuel consumption is reduced on average by 4.1% for HDV_B, when traveling in the second platoon position. It is reduced further when traveling in the third position, where the fuel consumption is reduced on average by 6.5%. The corresponding energy reduction is 5.3 and 8.6% when traveling in second and third position, respectively. The saving in propulsion energy from the engine is higher than the fuel savings, since the internal engine losses depend on the operating point. HDV_C achieves an average fuel reduction of 6.5 or 3.9% and an average energy reduction of 7.5 or 4.9%, when traveling in the second or third platoon position, respectively. As opposed to HDV_B, the fuel saving is less when operating in the third position. The average fuel consumption of HDV_C is larger in the third platoon position than the second position since the control effort is increased, which can be inferred by studying the variation in vehicle velocity for all the vehicles. The velocity sample standard deviation for the two follower vehicles, given in Table 1, indicates that a larger overall control effort is required for HDV_C in position three. The CACC in HDV_B produces a higher variation in velocity, compared to HDV_C, when traveling as the second vehicle in the platoon. Hence, HDV_B experiences a lower variance in velocity from both preceding vehicles and inherently produces a lower control effort when it is traveling in third position, compared to HDV_C. It can thus be concluded that the behavior of the preceding vehicle has a notable effect on the fuel savings of the follower vehicle. Note that some markers in Figure 12 for one HDV do not have a corresponding marker for the other vehicle because the surrounding traffic occasionally interrupted a test run by cutting in between the platooning vehicles. In those cases, the vehicles automatically increased the intervehicular distance. Hence, the fuel consumption increased due to additional control actions for handling the traffic disturbance and the air-drag reduction was lost during that period. Thus, the data for those instances were discarded.

TABLE 1 The average velocity sample standard deviations σ_i^v over all test runs for the follower vehicles HDV_B and HDV_C.

	Alone	Position 2	Position 3
HDV_B	0.11	0.51	0.48
HDV_C	0.11	0.26	0.63

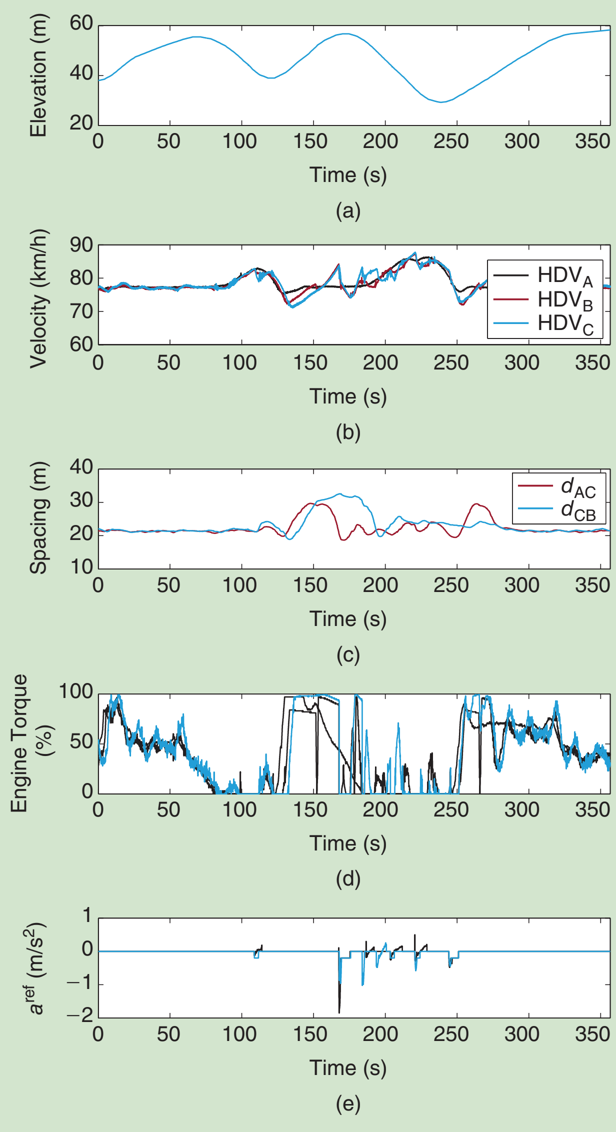

FIGURE 13 Experimental results when traversing road segment C in Figure 8. HDV_A is the lead vehicle, followed by HDV_B and HDV_C in the second and third position, respectively.

Fuel Consumption Over Road Segments with Steep Grade

As shown in the previous section, the platoon controller can obtain a significant fuel saving over road segments with small grade. However, steep road grades create undesirable behavior due to unmodeled system dynamics. A representative case is illustrated in Figure 13, corresponding to road segment C in Figure 8. All vehicles initially travel at the

A vision of a future freight transportation system is given, in which cooperation and platooning play an important role.

same velocity and with a constant intervehicular spacing. When entering the first downhill segment, at the 70 s time marker, the vehicles start to coast by cutting off the fuel injection and thereby reducing the engine torque to zero. As the velocity increases, the intervehicular spacing remains constant. For the implemented time-gap policy, however, the desired relative distance increases with the velocity. Thus, the follower vehicles eventually have to apply their brakes, as can be seen right after the 100-s time marker in Figure 13(e). Hence, the spacing is increased and the engine turbo pressure remains low for both follower vehicles. The lead vehicle drops slightly in velocity when it enters the following uphill segment but increases the engine torque as soon as possible to maintain the set velocity. The follower vehicles observe that the lead vehicle is initially slowing down, and the CACC thus defers the increase in velocity until the desired relative distance is resumed. In addition, a delay arises in building up the turbo pressure and, inherently, the engine torque when entering the uphill segment. Furthermore, the acceleration is constrained due to large vehicle masses and engine torque limitations. Thus, the relative velocity to the preceding vehicle increases and the relative distance grows over the uphill segment. Moreover, HDV_B changes gear in the middle of the uphill segment, as indicated by the sudden short drop in velocity, which further increases the relative distance. To regain the desired relative distance after the uphill climb, fuel is injected to increase the velocity. However, since a downhill segment follows, the velocity is increased too much and the follower vehicles must brake in the downhill to maintain the desired relative distance. Finally, additional fuel is injected in the downhill road segment because a higher deceleration than desired was initially produced by the unmodeled dynamics in the braking system.

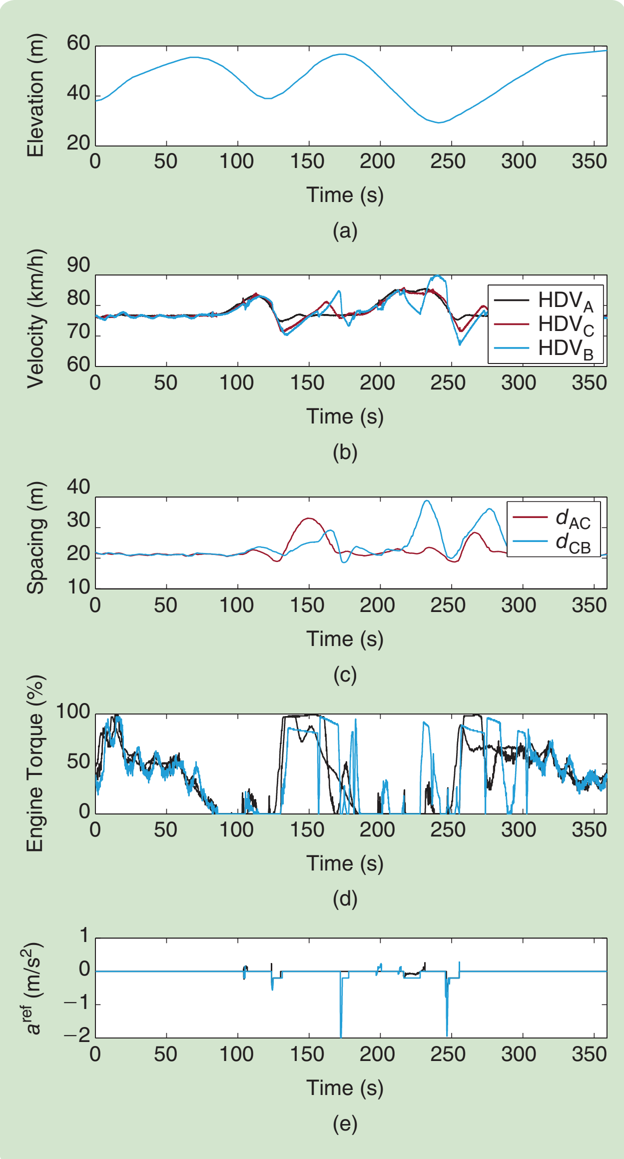

FIGURE 14 Experimental results when traversing road segment C in Figure 8. HDV_A is the lead vehicle, followed by HDV_C and HDV_B in the second and third position, respectively. This experiment is the same as in Figure 13, but with the order of the follower vehicles switched. Note that the colors indicate platoon position rather than vehicle index.

Performing a similar analysis to what was presented in Figure 12, we find that the fuel consumption is actually increased on average by 4% for HDV_B compared to driving alone. However, for HDV_C and when traveling in the second platoon position over the entire road segment shown in Figure 14, the fuel consumption is unchanged with respect to driving alone. The unaffected fuel consumption for HDV_C can be explained by Figure 14, which illustrates the behavior over the same road stretch when the order of the follower vehicles is changed, such that HDV_C is in the second platoon position and HDV_B in the third. A similar behavior as before can be observed for this vehicle ordering. The intervehicular spacing increases over the uphill segment starting at the 120-s time marker. However, a gear change does not occur for HDV_C when it is in the second platoon position, which produces a smoother behavior when catching up with the lead vehicle. The braking over the following downhill

To obtain the full fuel-saving potential of platooning, this article presented a three-layer freight transport architecture aimed at the coordination of HDVs.

section is also reduced. HDV_B, on the other hand, performs a gear change over the uphill climb, which even for this case causes it to brake over the following downhill segment when it is catching up. A smoother overall behavior and significantly less braking is achieved over the entire road stretch with HDV_C in the second platoon position, instead of HDV_B. Thus, the fuel consumption is unchanged for HDV_C in this case. Recall that HDV_C is the heaviest vehicle in the platoon. Hence, it has difficulties in maintaining the intervehicular spacing over uphill sections and has to brake slightly over the downhill sections to avoid coasting into the lead vehicle, when traveling in the second platoon position. The unfavorable gear change performed by HDV_B in Figure 14 over the uphill segment increases the intervehicular spacing and creates additional braking. The fuel consumption is increased by 12 and 9% in the third platoon position for HDV_B and HDV_C, respectively. Thus, due to unmodeled road topography and engine dynamics, the fuel-saving potential due to air-drag reduction in platooning can be lost over hilly road segments such as the ones presented in Figure 13.

Look-Ahead Control for Platooning

The fuel economy over segments with steep road grades can be improved by exploiting preview information on the road topography. To illustrate this, the results in Figures 13 and 14 are reproduced by simulations of a two-vehicle platoon. In these simulations, a model of the longitudinal dynamics of an HDV is exploited. In addition, simple but realistic heuristics for the CC of the lead vehicle are used, in which a constant set speed of 79 km/h is maintained as long as the maximum available engine torque is not exceeded. Braking is avoided until a maximum set speed of 90 km/h is reached. The follower vehicles are assumed to perfectly track the desired intervehicular distance. Even though these simulations do not include the unmodeled gear changes and engine dynamics, the simulation results in Figure 15 show similar characteristics as the experiments in Figures 13 and 14. Namely, the speed of the vehicles increases during the first downhill section and a constant velocity cannot be maintained in the first part of the following uphill despite the use of maximum engine power. More importantly, it can be observed in the downhill section around the 100- and 200-s time markers that the follower vehicle needs to brake more than the lead vehicle to maintain the desired vehicle spacing. This is particularly clear around the 90- and 180-s time markers, where the lead vehicle does not apply its brakes.

Figure 16 depicts the same scenario but now exploits the use of preview information of the road topography in determining the optimal velocity profile for the lead vehicle using an approach introduced in [31] and [22]. The follower vehicle tracks a time-delayed version of the trajectory of the lead

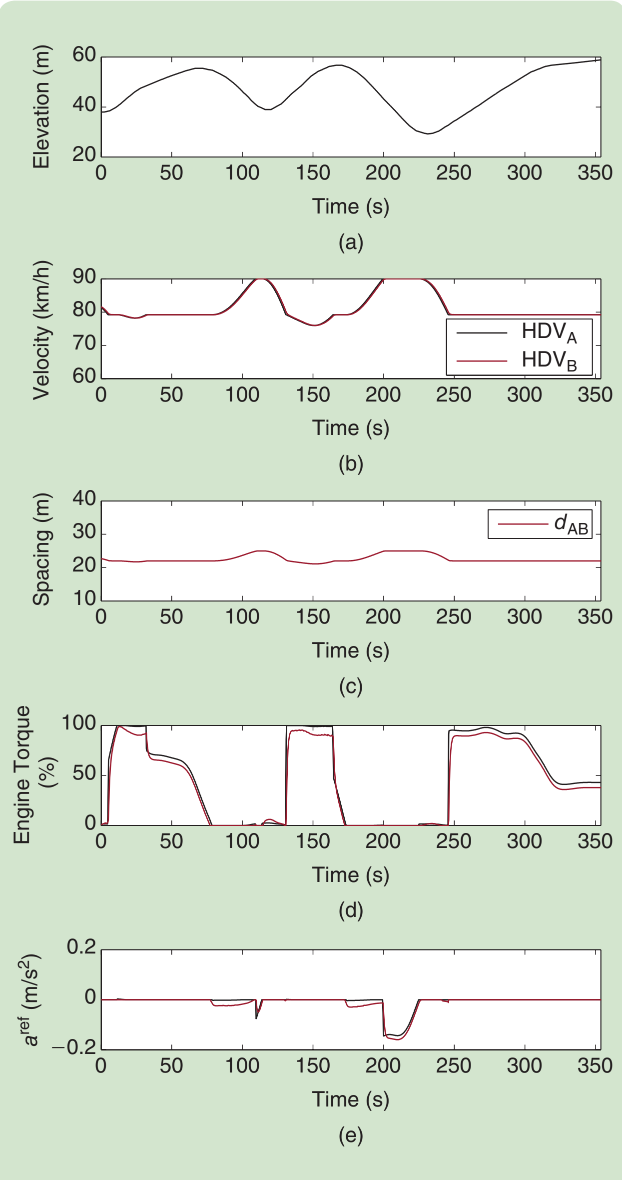

FIGURE 15 Simulation results for road segment C in Figure 8 with the lead vehicle HDV_A using a cruise control system and HDV_B following using the constant time-gap policy (1).

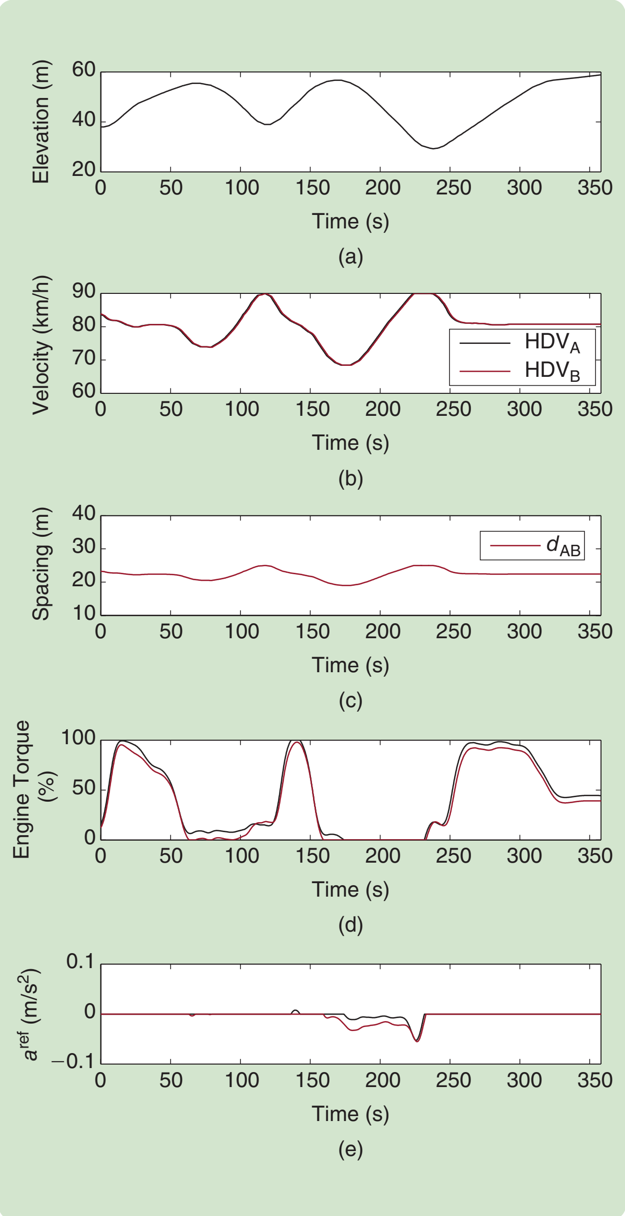

FIGURE 16 Simulation results for road segment C in Figure 8 with the lead vehicle HDV$_A$ using a cooperative look-ahead control system and HDV$_B$ following using a delay-based spacing policy. Compared to Figure 15, braking is significantly reduced.

TABLE 2 The average fuel and energy savings for the follower vehicles HDV$_B$ and HDV$_C$ in a platoon over the road segments B_1, B_2, and B_3 in Figure 8, which have a small road grade.

	Fuel Savings		Energy Savings	
	Position 2	Position 3	Position 2	Position 3
HDV$_B$	4.1%	6.5%	5.3%	8.6%
HDV$_C$	6.5%	3.9%	7.5%	4.9%

vehicle. This delay-based spacing policy guarantees that both vehicles achieve the same velocity profile in the spatial domain. It is apparent from Figure 16 that the velocity profile varies constantly in anticipation of the road topography. In particular, it can be observed that the velocity is decreased before entering a downhill section, which reduces the need for braking when driving downhill. In fact, no braking is required in the first downhill section around the 100-s time marker, whereas the braking action is significantly reduced with respect to the situation in Figure 15 in the second downhill section around the 200-s time marker. Also, it is noted that the velocity profile is optimized such that the second vehicle also avoids braking, even though it experiences a reduced aerodynamic drag due to platooning. This can be observed in the first downhill section and around the 90-s time marker, where the lead vehicle applies limited engine power to eliminate the need for braking of the follower vehicle. Such behavior cannot be achieved by look-ahead control strategies for single vehicles as in [21] and thus motivates the need for the development of dedicated (and cooperative) predictive control strategies for HDV platoons as in [31] and [22]. Over segment C in Figure 8, the cooperative look-ahead control approach in Figure 16 achieves a reduction in energy consumption of 8.6 and 9.3% for the lead and follower vehicle, respectively, when compared to the approach in Figure 15. These large savings are explained by noting that segment C has particularly large road grades. Finally, it is remarked that, because information about all vehicles in the platoon is required for the computation of fuel-optimal velocity profiles, such predictive control requires a freight transport system architecture as in Figure 4, where look-ahead control is performed in the platoon layer. Besides leading to a decreased fuel consumption, this approach thus also further motivates the adoption of the proposed system architecture.

Even though such a CACC with look-ahead information has the potential to significantly enhance platoon behavior and reduce fuel consumption, some improvements to the current CACC controller can also be made without including map data on road topography. The intervehicular communication can be exploited by sharing the reference velocity for the lead vehicle and information on the road topography that the lead vehicle experiences. On the basis of this information, follower vehicles know whether a change in velocity of the preceding vehicle is due to the road grade or a reference velocity change and can adapt their strategies accordingly by using feedforward in their controllers. For example, turbo pressure can be built up before entering a climb, and braking can be avoided by relaxing the spacing policy when needed. Such information could therefore reduce some of the undesired effects observed in the experiments in Figures 13 and 14.

CONCLUSIONS

Improving the efficiency of the current freight transportation system is a challenging and complex problem. In this article, experimental results were given that indicate the

The second objective of this article is to present an experimental evaluation of the fuel-saving potential as offered by platooning under realistic conditions.

fuel-saving potential of HDV platooning as a (partial) solution to this problem. An architecture for such a freight transportation system was presented, which exploits platooning at its core and aims to increase the level of cooperation between vehicles.

The experimental results are summarized in Table 2, which lists the average fuel and energy savings for a three-vehicle platoon traveling over road segments with small road grade. These results, which were obtained under varying environmental conditions, indicate the potential of HDV platooning by a significant decrease in fuel and energy consumption, also leading to reduced (greenhouse gas) emissions and reduced operating costs. However, it was also shown that such significant fuel savings are not generally obtained for routes with large road grades. Instead, more advanced control techniques are required to effectively platoon over such terrain, providing a clear motivation for future research on predictive control. Some first results toward predictive control have been presented.

Even though several control policies currently exist for control of vehicle platoons and research projects exist worldwide to evaluate various performance criteria for HDV platoons in practice, most policies are only applicable for ad hoc platooning. Stated differently, existing policies typically assume that a platoon has already been formed. However, to obtain the full fuel-saving potential of platooning, this article presented a three-layer freight transport architecture aimed at the coordination of HDVs. This architecture includes the tasks of transport planning and routing as well as the computation of fuel-optimal platooning strategies. Such large-scale coordination not only aims at maximizing the benefits obtained by platooning, but also allows for an increase in the available transport capacity by better utilization of vehicles.

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AUTHOR INFORMATION

Assad Alam received the M.Sc. degree in electrical engineering from KTH Royal Institute of Technology, Stockholm, Sweden, in 2008. In 2014, he received an industrial Ph.D. degree from the Automatic Control Laboratory and the ACCESS Linnaeus Centre, School of Electrical Engineering, KTH, and the Research and Development Department, Scania CV, Södertälje, Sweden. He is now working as a full-time senior engineer at the Driver Assistance Controls Department at Scania CV. His research interests include the fuel-efficient control of heavy-duty vehicle platooning.

Bart Besselink (bart.besselink@ee.kth.se) is a postdoctoral researcher with the ACCESS Linnaeus Centre and Department of Automatic Control at KTH Royal Institute of Technology, Stockholm, Sweden. He received the M.Sc. degree (cum laude) in mechanical engineering in 2008 and the Ph.D. degree in 2012, both from Eindhoven University of Technology, The Netherlands. He was a short-term visiting researcher at the Tokyo Institute of Technology, Japan, in 2012. His main research interests include systems theory and model reduction for nonlinear dynamical systems and large-scale interconnected systems. In addition, he is working on applications in the field of intelligent transportation systems with a particular focus on the control and coordination of heavy-duty vehicle platoons. He can be contacted at the Department of Automatic Control, School of Electrical Engineering, KTH Royal Institute of Technology, Osquldas väg 10, 10044 Stockholm, Sweden.

Valerio Turri received the M.Sc. double degree (cum laude) in control engineering from Politecnico di Milano and Politecnico di Torino in 2011. He was a research engineer at the Model Predictive Control Lab of the Department of Mechanical Engineering, University of California, Berkeley, in 2012. Since September 2012, he has been a doctoral student at the ACCESS Linnaeus Centre and Department of Automatic Control, KTH Royal Institute of Technology, Stockholm, Sweden. His research interests include model predictive control and its application to advanced automotive control.

Jonas Mårtensson holds a tenure-track position as assistant professor with the Department of Automatic Control at KTH Royal Institute of Technology, Stockholm, Sweden. He is also engaged as a program leader in the Integrated Transport Research Lab and is thematic leader for the area transport in the information age within the KTH transport platform. He received the M.Sc. degree in

vehicle engineering in 2002 and the Ph.D. degree in automatic control 2007, both from KTH. Between 2008 and 2012, he worked on the modeling, control, and optimization of the transient torque response in combustion engines, utilizing variable-geometry turbines and variable valve timings. Since 2011, his main research has been in cooperative and autonomous transport systems, in particular, related to heavy-duty vehicle platooning. He is involved with several collaboration projects with Scania CV in Södertälje 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.

Karl H. Johansson is director of the ACCESS Linnaeus Centre and Professor at the School of Electrical Engineering, KTH Royal Institute of Technology, Sweden. He also heads the Stockholm Strategic Research Area ICT The Next Generation. He received M.Sc. and Ph.D. degrees from Lund University. He has held visiting positions at the University of California, Berkeley, and Caltech. He has been the chair of the IFAC Technical Committee on Networked Systems. He is or has been on the editorial boards of *Automatica*, *IEEE Transactions on Automatic Control*, *IEEE Transactions on Control of Network Systems*, and *European Journal of Control*. He received the Best Paper Award at the IEEE International Conference on Mobile, Ad-hoc, and Sensor Systems in 2009 and the Best Theory Paper Award at the World Congress on Intelligent Control and Automation in 2014. In 2009, he was named a Wallenberg Scholar, as one of the first ten scholars from all sciences, by the Knut and Alice Wallenberg Foundation. He was awarded Future Research Leader from the Swedish Foundation for Strategic Research and a senior researcher position with the Swedish Research Council, both in 2005. He received the triennial Young Author Prize from IFAC in 1996, the Peccei Award from the International Institute of System Analysis 1993, and Young Researcher Awards from Scania in 1996 and Ericsson in 1998 and 1999. He is a Fellow of the IEEE.

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