INVITED PAPER

Cyber–Physical Control of Road Freight Transport

This paper reviews how modern information and communication technology supports a cyber–physical transportation system architecture. It also presents a CPS approach toward the control and coordination of a large-scale transportation system.

By Bart Besselink, Valerio Turri, Sebastian H. van de Hoef, Kuo-Yun Liang, Assad Alam, Jonas Mårtensson, and Karl H. Johansson, *Fellow IEEE*

ABSTRACT | Freight transportation is of outmost importance in our society and is continuously increasing. At the same time, transporting goods on roads accounts for about 26% of the total energy consumption and 18% of all greenhouse gas emissions in the European Union. Despite the influence the transportation system has on our energy consumption and the environment, road transportation is mainly done by individual long-haulage trucks with no real-time coordination or global optimization. In this paper, we review how modern information and communication technology supports a cyber–physical transportation system architecture with an integrated logistic system coordinating fleets of trucks traveling together in vehicle platoons. From the reduced air drag, platooning trucks traveling close together can save about 10% of their fuel consumption. Utilizing road grade information and vehicle-to-vehicle communication, a safe and fuel-optimized cooperative look-ahead control strategy is implemented on top of the existing cruise controller. By optimizing the interaction between vehicles and platoons of vehicles, it is shown that significant improvements can be achieved. An integrated transport planning and vehicle routing in the fleet management system allows both small and large fleet owners to benefit from the collaboration. A realistic case study with 200 heavy-duty vehicles performing transportation tasks in Sweden is described. Simulations show overall fuel savings at more than 5% thanks to coordinated platoon planning. It is also illustrated how well the proposed cooperative look-ahead controller for heavy-duty vehicle platoons manages to optimize the velocity profiles of the vehicles over a hilly segment of the considered road network.

KEYWORDS | Automotive engineering; automated highways; intelligent transportation systems; intelligent vehicles; networked control systems; vehicular communication

I. INTRODUCTION

The freight transportation sector is of great importance to our society and the demand for transportation is strongly linked to economic development. As a result of the growing world economy, the road freight transportation sector in the Organisation for Economic Co-operation and Development (OECD) in 2050 is projected to have grown by roughly 90% with respect to 2010 levels, according to a prediction of the International Transport Forum [1]. For developing countries, a significantly larger growth is expected. At the same time, the transportation sector is responsible for a large part of the world's energy consumption and (greenhouse gas) emissions. As an example, in 2012, the road transportation sector amounted for 26% of the total energy consumption and 18% of all greenhouse gas emissions in the European Union [2]. This impact on the environment provides a strong motivation for developing a more fuel-efficient freight transportation sector, which is further encouraged by the fact that about one third of the cost of operating a heavy-duty vehicle is associated to its fuel consumption [3].

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B. Besselink, **V. Turri**, **S. H. van de Hoef**, **J. Mårtensson**, and **K. H. Johansson** are with the ACCESS Linnaeus Centre and the Department of Automatic Control, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm 114 28, Sweden (e-mail: bart.besselink@ee.kth.se; turri@kth.se; shvdh@kth.se; jonas.martensson@ee.kth.se; kallej@kth.se).
K.-Y. Liang is with the ACCESS Linnaeus Centre and the Department of Automatic Control, School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm 114 28, Sweden, and also with Scania CV AB, Södertälje 151 38, Sweden (e-mail: kyliang@kth.se).
A. Alam is with Scania CV AB, Södertälje 151 38, Sweden (e-mail: assad.alam@scania.com).

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Modern information and communication technologies enable such development, as the use of vehicle-to-vehicle and vehicle-to-infrastructure communication and the availability of ubiquitous computing power allow for the real-time coordination and automatic control of large groups of vehicles. In particular, the formation of groups of closely spaced heavy-duty vehicles allows them to cooperatively reduce fuel consumption through a reduction in aerodynamic drag. Experiments have shown that these platoons can lead to fuel savings of about 10% [4], [5]. Consequently, a cooperative approach offers great potential for developing a more efficient road freight transportation sector, especially since road transportation is currently mainly done by individual long-haulage vehicles that do not exploit the benefits of platoon formation.

In this paper, we present a cyber–physical approach to the control and coordination of a large fleet of heavy-duty vehicles that exploits the benefits of platooning. In particular, the contributions of the paper are the following.

First, a freight transport system is developed that tightly integrates the logistics system with the control and coordination of a fleet of vehicles. By exploiting real-time information flow, this system allows for a significant reduction in fuel consumption through the dynamic formation of platoons of vehicles. To support the implementation of this integrated system, a hierarchical approach is presented that allows for a layering of tasks using a three-layer architecture. The bottom layer in this architecture deals with the automatic control of individual heavy-duty vehicles and is referred to as the vehicle layer. This vehicle control exploits vehicle-to-vehicle communications and advanced sensor technology to achieve a stable and safe platoon formation, leading to a reduction in fuel consumption through reduced aerodynamic drag. The middle layer, referred to as the cooperation layer, achieves additional fuel savings through the computation of fuel-optimal vehicle trajectories for the entire platoon. In addition, the formation of platoons is addressed in this layer through local decision making and the execution of merging maneuvers. Finally, the fleet layer (i.e., the top layer) is aimed at the coordination of a potentially large fleet of vehicles belonging to multiple fleet owners. Here, the minimization of the fuel consumption is pursued by updating the plans of individual vehicles in order to achieve the most suitable platoon configurations and tight integration with the logistics system.

As a second contribution, it is shown how recent developments in cyber–physical systems enable the proposed approach. Namely, the tight integration of system components through vehicle-to-vehicle and vehicle-to-infrastructure communications as well as advanced onboard computations linked to cloud computations makes the road freight transportation system an excellent example of how cyber–physical systems enable major progress for such infrastructure applications. Herein, the careful layering of the freight transport system architecture allows for significantly optimizing system performance while keeping the complexity at a manageable level.

The remainder of this paper is outlined as follows. Section II discusses the opportunities cyber–physical systems bring to freight transport and introduces the proposed freight transport architecture. The three layers are further discussed in the next sections, where Section III discusses the vehicle layer as well as the heavy-duty vehicle model. Sections IV and V present the cooperation layer and the fleet layer, respectively. Section VI presents an evaluation of the freight transportation system through a case study and is followed by the conclusions in Section VII.

II. CYBER–PHYSICAL SYSTEMS OPPORTUNITIES

A. Enabling Technologies

Tremendous advances in computing, communication, and sensor technologies have enabled the current rapid development of intelligent transport systems [6]. Today's high-end road vehicles are typically equipped with extensive computing capabilities, multiple radio interfaces, and radar, camera, and other sensor devices. Low-cost wireless local and wide area network transceivers facilitate vehicle-to-vehicle and vehicle-to-infrastructure communications [7], [8]. By integrating vehicular communication with existing sensor technologies, applications that enhance safety, efficiency, and driver comfort are being developed.

Another set of technologies that support cooperative transportation systems is given by cloud computing and service architectures [9]. They offer large computing and storage capabilities together with a seamless integration of a diverse group of third-party tools and services. For vehicular and transportation applications, new possibilities are emerging to build systems spanning over large geographic areas with close to real-time data gathering and decision making [10]. Vehicular position and velocity data are an important example of such data that are readily available through various sensing devices including mobile phones [11]. Such data have proven to be very useful in many contexts including the understanding of road usage patterns in urban areas [12]. For freight transportation it is shown in this paper how traffic, weather, and other public and private data can be utilized in a transport planning and logistics application implemented through cloud technologies. The overall functional architecture of such a system is described next.

B. Freight Transport System Architecture

The freight transportation system discussed in this paper integrates potentially thousands of heavy-duty vehicles into a large-scale planning, cooperation, and

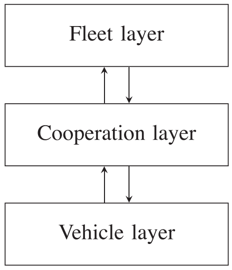

Fig. 1. ***Layered freight transport system architecture. The fleet layer and the cooperation layer are detailed in Figs. 4 and 6, respectively.***

real-time optimization and automation system. It is a complex and large-scale system built upon existing and emerging communication and computing infrastructures into a tightly coupled cyber–physical system. In order to manage the complexity of this large-scale coordination problem, the layered architecture in Fig. 1 is naturally adopted. Herein, the control of individual vehicles is addressed in the vehicle layer, whereas the cooperation layer targets the behavior and formation of platoons. The large-scale coordination of vehicle fleets is handled in the fleet layer.

Specifically, the vehicle layer builds upon existing vehicle control systems to achieve the desired longitudinal behavior as needed to safely and automatically operate vehicles and vehicle platoons. Hereto, a decentralized controller is synthesized that exploits vehicle-to-vehicle communication (e.g., WiFi) and advanced sensor information (e.g., radar) to guarantee the tracking of a specified intervehicular distance as well as the rejection of disturbances. The vehicle layer has a decentralized implementation and is embedded into the vehicles' onboard systems. We recall that the operation of vehicles in closely spaced platoons reduces fuel consumption.

The aim of the cooperation layer is twofold. First, it computes fuel-optimal velocity profiles for vehicle platoons taking road topography and traffic into account. For example, by exploiting look-ahead information about the road topography when driving over hilly terrain, braking can be avoided and additional fuel savings can be obtained. Second, the cooperation layer locally coordinates the behavior of vehicles or platoons with overlapping route segments by deciding whether neighboring vehicles should form a platoon. In addition to this decision-making process, the optimal control of merging maneuvers for platoon formation is handled in this layer. Vehicle-to-vehicle and vehicle-to-infrastructure communication are exploited for this coordination, which extend only to the relative vicinity of the vehicle and platoon. Specifically, the tasks in this layer are typically implemented on the onboard system of the platoon leader (i.e., the first vehicle in the platoon) and are therefore dynamically allocated as the platoon formation changes. Alternatively, an implementation on roadside units or a centralized implementation using cloud technology is possible.

The fleet layer targets the large-scale coordination over a significant geographic area for a large group of vehicles from potentially different fleet owners. By updating the routes and transport plans of individual vehicles, the formation of platoons can be encouraged and the total fuel consumption of the fleet can be minimized. In addition to this coordination, the fleet layer includes the task of transport planning to target a better utilization of the capacity of the freight transport system. Optimization criteria in this layer can incorporate not only costs directly associated with individual fleet owners, but can include societal aspects such as traffic congestion and environment impact. As a large number of vehicles is considered in this coordination and optimization problem, it relies on a centralized implementation. This can be achieved as a (third-party) service, e.g., exploiting cloud computing technology.

The layers in Fig. 1 are presented in some more detail in Sections III–V and the overall system is evaluated through a case study in Section VI.

C. Background on Vehicle Platooning

The freight transport architecture in Fig. 1 is motivated by the concept of an automated highway system [13], [14], in which cars are organized in platoons to increase traffic flow. Further examples of such systems are given in [15] and [16].

These architectures generally focus on improving traffic flow on highways and the layers in these architectures typically range from vehicles in the bottom layer to a road network in the top layer. The architecture presented in this paper does not target an improved traffic flow, but is aimed at optimizing the transportation of goods. Specifically, the fuel consumption of heavy-duty vehicles is minimized by exploiting platooning. Thereto, this architecture targets tasks ranging from goods distribution to the computation of fuel-efficient velocity profiles. We note that similar architectures are also used in many related engineering systems, such as air traffic management [17] and spacecraft formation [18].

The idea of highway automation and platooning has a long history, with first visions dating back at least to the 1930s [19]. Apart from early analysis of the dynamics of vehicle following [20], the first control strategies for vehicle platooning appeared in [21]–[23]. Many results have appeared since, focusing on topics ranging from analysis of spacing policies [24], [25] to experimental validation [26]. For heavy-duty vehicles, platooning is mainly motivated by a reduced fuel consumption and several experimental evaluations have focussed on this aspect [4], [27], [28].

III. VEHICLE LAYER

A. Vehicle Model

The heavy-duty vehicle control and cooperation algorithms are based on a dynamic model of the powertrain. Specifically, the longitudinal dynamics of a vehicle indexed i is modeled as

$$\begin{aligned} \dot{s}_i &= v_i \\ m\dot{v}_i &= -F_r(\alpha(s_i)) - F_g(\alpha(s_i)) - F_d(\tau_i, v_i) + F_{e,i} - F_{b,i}. \end{aligned} \tag{1}$$

Here, s_i and v_i denote its longitudinal position and velocity, respectively, which are collected in the state $x_i = (s_i, v_i)^T$. For ease of exposition, we let all vehicles have identical parameter values, but the results in the paper extend directly to heterogeneous vehicle groups. In (1), m represents the vehicle mass, whereas F_r and F_g denote the rolling resistance and the longitudinal component of gravity, respectively. The latter reads $F_g(\alpha(s_i)) = mg \sin \alpha(s_i)$, with $\alpha(s_i)$ the road gradient at position s_i and g the gravitational acceleration. The aerodynamic drag F_d satisfies

$$F_d(\tau_i, v_i) = \frac{1}{2} c_d(\tau_i) \rho A v_i^2 \tag{2}$$

where ρ is the air density and A denotes the frontal area of the vehicle. The air drag is dependent on the time gap τ_i between vehicle i and its predecessor, as captured through the air drag coefficient $c_d(\tau_i)$. Here, the time gap represents the time difference between two successive vehicle passing the same point on the road. The air drag coefficient is modeled as

$$c_d(\tau_i) = c_d^0 \left(1 - \frac{\alpha_1}{1 + \alpha_2 \tau_i} \right) \tag{3}$$

where c_d^0 represents the nominal air drag coefficient for a heavy-duty vehicle driving alone, and the parameters α_1 and α_2 characterize the air drag reduction as the time gap between vehicles decreases. Fig. 2 shows an illustration of $c_d(\tau_i)$ as estimated from experimental data. This air drag reduction obtained through smaller intervehicular distances offers a potential for saving fuel, which is extensively exploited throughout the paper.

Finally, the forces $F_{e,i}$ and $F_{b,i}$ in (1) denote the traction force at the wheels and the force exerted by the brakes, respectively. They are control inputs. The corresponding injected fuel flow φ_i depends on the instantaneous power $F_{e,i}v_i$, which is bounded as $P_{\min} \leq F_{e,i}v_i \leq P_{\max}$, and obtained through

$$\varphi_i = p_1 F_{e,i} v_i + p_0. \tag{4}$$

Here, the parameters p_0 and p_1 aggregate the effects of engine and gear box efficiency. Specifically, p_0 captures the fuel flow when the engine is idling. The remainder of this paper will be focused on systematically reducing the nominal fuel consumption by exploiting platooning.

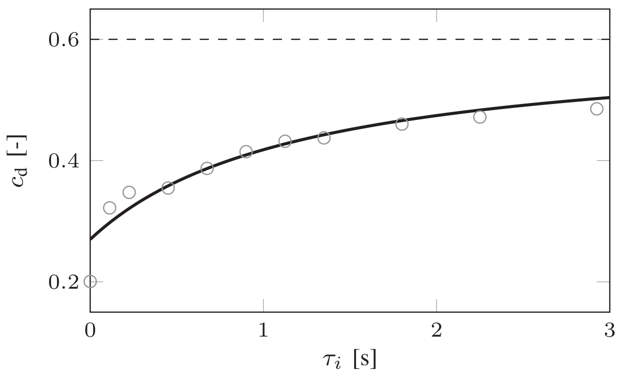

Fig. 2. *Air drag coefficient $c_d(\tau_i)$ as a function of time gap τ_i for $c_d^0 = 0.6$, $\alpha_1 = 0.53$, and $\alpha_2 = 0.81$. The function is estimated based on experimental data (circles) reported in [29].*

B. Vehicle Control Architecture

The vehicle control architecture for the powertrain is depicted in Fig. 3. A controller area network [30] inside the vehicle communicates radar and positioning data together with data from other vehicles through the wireless sensor unit to a data processing unit. The vehicle controller computes low-level commands and sends them to the engine management system, the brake management system, and the gear management system. These systems implement the desired longitudinal vehicle behavior.

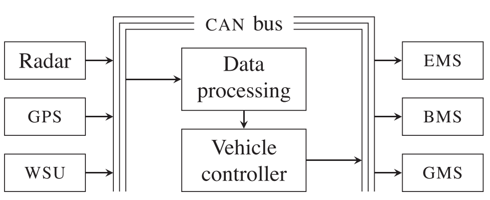

Fig. 3. *Controller area network enables the communication of sensor data to the vehicle controller, which computes control commands to be executed by the engine, braking, and gear management systems.*

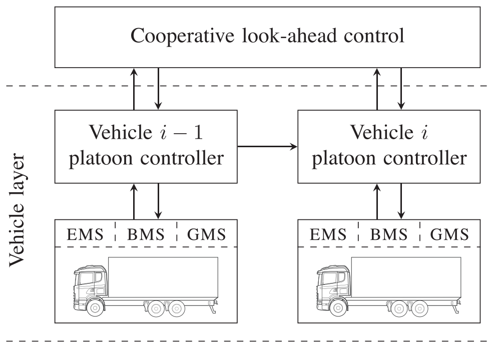

Fig. 4. ***Control architecture corresponding to the vehicle layer in Fig. 1.***

Automatic velocity control is often achieved by letting the vehicle controller execute (adaptive) cruise controller algorithms aimed at maintaining a constant reference velocity. In the next section, an alternative vehicle controller is presented that exploits additional information about the preceding vehicle obtained through wireless communication.

C. Vehicle Control for Platooning

This section presents a strategy for the longitudinal control of heavy-duty vehicle platoons. It is positioned in the vehicle layer of the freight transport architecture in Fig. 1 and is detailed in Fig. 4. The objective of the platoon controller is to achieve small intervehicular distances while tracking a varying reference velocity $v_{\text{ref}}(\cdot)$. The reference velocity, which is specified as a function of the position on the road, is the result of the cooperative look-ahead control strategy that is discussed in Section IV-A.

As is well-known that standard policies for specifying the inter-vehicular distance in a platoon are not compatible with tracking a spatially varying reference velocity profile [31], [32], we adopt the delay-based spacing policy

$$s_{\text{ref},i}(t) = s_{i-1}(t - \tau_{\text{ref}}) \tag{5}$$

where $s_{\text{ref},i}$ denotes the desired longitudinal position of vehicle i. It is convenient to express (5) in the spatial domain. To this end, let the spatial position s be the independent variable and denote $t_i(s)$ as the time instance at which vehicle i passes s. By introducing the time gap tracking errors

$$\Delta_i(s) = t_i(s) - t_{i-1}(s) - \tau_{\text{ref}} \tag{6}$$
$$\Delta_i^0(s) = t_i(s) - t_0(s) - i\tau_{\text{ref}} \tag{7}$$

the policy (5) is equivalent to $\Delta_i = 0$. Condition (7) represents the time gap tracking error with respect to the first vehicle in a platoon. Similarly, a velocity tracking error e_i can be defined for each vehicle, representing the deviation from the desired reference velocity profile $v_{\text{ref}}(s)$. Then, a weighted error signal can be introduced as

$$\delta_i(s) = (1 - h_0)\Delta_i(s) + h_0\Delta_i^0(s) + he_i(s) \tag{8}$$

in which the parameters $0 \leq h_0 < 1$ and $h > 0$ provide a measure of the influence of the lead vehicle and velocity tracking, respectively.

A distributed controller design can be achieved on the basis of the weighted error signal (8) and powertrain dynamics (1), hereby satisfying two objectives. First, the controller for vehicle i should guarantee the existence of a unique equilibrium point for which $\delta_i = 0$ and, second, it should asymptotically stabilize this equilibrium. Namely, any controller that achieves this ensures asymptotic stability of the desired spacing policy (5) throughout the platoon. A controller based on feedback linearization that achieves these objectives is given in [32]. It is stressed that, as each vehicle individually addresses the local goal of achieving $\delta_i \to 0$, the controller is distributed. Herein, vehicles exploit radar measurements as well as information from the preceding vehicle and (potentially) the lead vehicle obtained through wireless communication.

For any controller that asymptotically stabilizes the equilibrium corresponding to $\delta_i = 0$, it can be shown that the velocity tracking errors of two successive vehicles satisfy

$$\int_0^s |e_i(\sigma)|^2 d\sigma \leq \int_0^s |e_{i-1}(\sigma)|^2 d\sigma \tag{9}$$

which indicates that any perturbations do not grow as they propagate through the platoon. The inequality is strict when information of the lead vehicle is included, i.e., $h_0 > 0$, which also ensures robustness with respect to external disturbances acting on the vehicles; see [32] and related work in [33]. Condition (9) is an example of string stability, which provides stability notions for vehicle platoons. An early notion of string stability can be found in [34], whereas a formal definition is given in [35]. For an overview and examples of alternative definitions, see [36]–[38]. A discussion on safety aspects in vehicle control for platooning can be found in [39] and [40].

IV. COOPERATION LAYER

A. Cooperative Look-Ahead Control

The aim of the cooperative look-ahead control strategy is to compute a velocity profile $v_{\text{ref}}(\cdot)$ that is feasible for each individual heavy-duty vehicle in the platoon and fuel optimal for the overall platoon. The speed profile is communicated to the vehicle layer, as described in Fig. 4, where each vehicle controller tracks $v_{\text{ref}}(\cdot)$ while guaranteeing stability and safety. The computation of the speed profile is accomplished by solving a receding horizon control problem that includes the dynamics and corresponding constraints of each vehicle and minimizes a cost function depending on the fuel consumption of the whole platoon. To this end, the vehicle model (1) is expressed in the spatial domain, as all vehicles in the platoon track the same velocity profile

$$v_i(s) = v_{\text{ref}}(s), \qquad i = 1, \ldots, N \tag{10}$$

where N is the number of vehicles in the platoon. Note that the delay-based spacing policy (5) also requires equal velocity profiles in the spatial domain, which therefore corresponds to the constraint (10). Moreover, as the road altitude is dependent on the position, this policy is well suited for platooning over road segments with varying topography [40].

The cost function for the cooperative look-ahead controller is given by the total fuel consumption

$$J_{\text{CLAC}} = \frac{1}{NH}\sum_{i=1}^{N}\int_{s^0}^{s^0+H} \varphi_i(s)\frac{1}{v_{\text{ref}}(s)}ds \tag{11}$$

where φ_i is the injected fuel flow (4) (expressed in the spatial domain), s_0 the current position of the leading vehicle [i.e., $s_1(t)$], and H the horizon length. The average speed request for a given road segment as imposed by the fleet management layer is denoted by $\bar{v}$ and is enforced through the constraint

$$\frac{1}{H}\int_{s^0}^{s^0+H}\frac{1}{v_{\text{ref}}(s)}ds = \frac{1}{\bar{v}}. \tag{12}$$

The cooperative look-ahead controller is implemented with a receding horizon and can be summarized as follows:

$$\begin{aligned} \min \quad & \text{platoon fuel consumption (11)} \\ \text{subject to} \quad & \text{vehicle dynamics (1)} \\ & \text{constraints on state and input} \\ & \text{constraint on the average velocity (12)} \\ & \text{common platoon velocity (10).} \end{aligned}$$

Here, the constraints on state and input refer to the speed limits as well as the bounds on engine power and braking force. The receding horizon problem can be solved using dynamic programming [41]; see [40] for details. In the special case that the platoon consists of only $N = 1$ vehicle, the proposed platoon controller corresponds to the single-vehicle look-ahead controller [42].

Altitude variations have a significant impact on the behavior of heavy-duty vehicles. Due to their inertia and limited engine power, they are typically not able to maintain a constant velocity while driving over steep up-slopes and down-slopes. This effect is critical when a group of vehicles that can significantly differ in mass and powertrain characteristic need to maintain the short intervehicular distances required by platooning. Experimental results have, for instance, shown how follower vehicles in a platoon driving downhill need to brake in order to compensate their different inertia and experienced air drag force [28]. Therefore, the particular structure of the cooperative look-ahead controller proposed here with common velocity profiles (10) seems to have several advantages [40]. Earlier work on look-ahead control for the fuel-efficient traversal of hilly road segments has focussed on single vehicles only, with early work considering simple road profiles and exploiting analytical solutions [43], [44]. Algorithms based on dynamic programming suitable for more generic road profiles have also been proposed [42], [45], [46].

B. Optimal Control of Merging Maneuvers

Let us now focus on the formation of platoons through the merging of individual vehicles or platoons that approach a common point after a highway intersection or an on-ramp. This maneuver is essential for platoon formation and it enables the high-level coordination of platoons (see Section IV-C).

Consider the simple merging problem for two vehicles $i = 1, 2$, illustrated in Fig. 5. Here, s^m denotes the location of an intersection and s_1^s, s_2^s the positions on two road segments from which the merging maneuver is initiated. The times t_1^s and t_2^s at which the vehicles arrive at these positions are taken as the starting times for the merging maneuver, for which the initial states

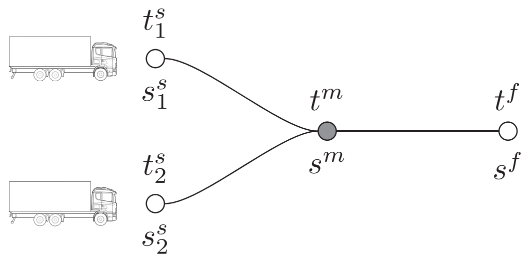

Fig. 5. *Schematic illustration of a two-vehicle optimal merging problem.*

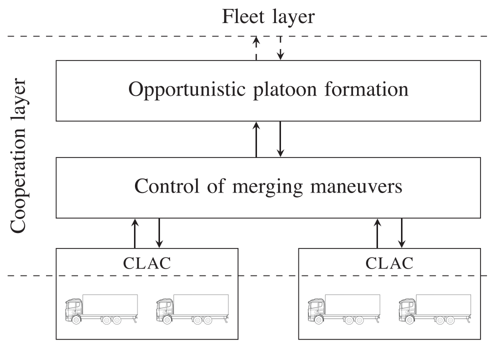

Fig. 6. *Platoon coordination architecture according to the cooperation layer in Fig. 1. The lower blocks correspond to the cooperative look-ahead control of the platoons linked to the vehicle layer in Fig. 4.*

$x_i^s = (s_i^s, v_i^s)^T$, $i = 1, 2$, hold for some velocity v_i^s. A common final state $x^f = (s^f, v^f)^T$ and time t^f is chosen after the intersection to obtain the desired average velocity over the road segment. Suppose the vehicles merge to form a platoon at s^m at time t^m, so that approximately

$$x_1(t) = x_2(t) \qquad \forall\, t \in [t^m, t^f]. \tag{13}$$

The merging time t^m is not fixed *a priori*, but is the result of an optimization. Due to a reduced aerodynamic drag, the vehicle dynamics and the total fuel cost is obviously different after the merging point compared to before. Therefore, the total fuel consumption for the overall operation can be expressed as

$$\sum_{i=1}^{2} \int_{t_i^s}^{t^m} \varphi_i(t)dt + \int_{t^m}^{t^f} \sum_{i=1}^{2} \varphi_i(t)dt. \tag{14}$$

This cost function can be minimized subject to the dynamics (1) using a two-step hybrid optimal control approach [47], [48], as detailed in [49]. In the first step, after selecting a fixed merging time t^m, the problem reduces to the fuel-optimal traversal of a given road segment. The partitioning of the total cost in (14) corresponds exactly to these road segments. For the last road segment traversed as a platoon, the platoon dynamics satisfy the constraint (13). In the second step, an optimization of the merging time t^m is performed. When this process is repeated iteratively, the optimality of the overall problem can be guaranteed through the hybrid maximum principle [47], which is an extension of the Pontryagin maximum principle. The two-vehicle merging problem discussed here is easily extended to cases in which the optimization includes more vehicles, constraints on the desired velocity at the merging instant, and successive merging maneuvers. Moreover, a receding horizon implementation of the optimal merging procedure can be used to guarantee robustness with respect to disturbances such as the influence of surrounding traffic. These extensions can be found in [49].

C. Opportunistic Platoon Formation

In the previous discussion on the optimal control of merging maneuvers, the decision on forming a platoon had already been made. Next we discuss how such a decision-making process can take place and how an opportunistic platoon formation fits into the cooperation layer according to Fig. 6. The aim of the opportunistic platoon formation is to decide whether it is fuel efficient to form a platoon with a nearby heavy-duty vehicle and, if so, determine where the merge should take place to maximize the fuel savings.

A pairwise platoon formation strategy is proposed. Let s_1^0, s_2^0 denote the initial positions of a pair of vehicles and s^f their common destination, which is the last point at which their routes overlap. Note that this information is available as the routes are precomputed and can be shared amongst vehicles using wireless communication. The decision on whether to form a platoon will be based on the computation of the optimal merging point s^m. Contrary to the detailed merging maneuver in the previous section, the current platoon formation scenario is performed over a potentially large geographical region and large distances. As a result, vehicle dynamics can be neglected and constant vehicle velocities $\bar{v}_i$ and platoon velocity $\bar{v}^p$ are assumed. This assumption additionally implies that no detailed road topography information is needed for this decision making. Recall that the cooperative look-ahead controller can guarantee the required average velocities even over roads with varying topography, whereas the merging controller will execute the actual merging maneuvers when the vehicles are close.

The optimal fuel cost of forming a platoon will be compared to the fuel consumption of the two vehicles driving to their destination independently. As a result, only the effect of aerodynamic drag has to be considered and the average fuel flows follow from (2) and (4) as

$$\bar{\varphi}_i = \frac{1}{2} p_1 c_d^0 \rho A \bar{v}_i^3 + p_0, \qquad i \in \{1, 2\} \tag{15}$$

$$\bar{\varphi}^p = \frac{1}{2} p_1 \left(c_d^0 + c_d(\tau_{\mathrm{ref}}) \right) \rho A (\bar{v}^p)^3 + 2p_0. \tag{16}$$

Here, $\bar{\varphi}_i$ gives the fuel flow of a vehicle without a predecessor as captured through the nominal air drag coefficient c_d^0, while $\bar{\varphi}^p$ is the fuel flow of the two-vehicle platoon. Obviously, $\bar{\varphi}^p < \bar{\varphi}_1 + \bar{\varphi}_2$. The corresponding fuel cost now reads

$$\bar{J}_{\mathrm{OPF}} = \sum_{i=1}^{2} \bar{\varphi}_i \frac{s^m - s_i^0}{\bar{v}_i} + \bar{\varphi}^p \frac{s^f - s^m}{\bar{v}^p} \tag{17}$$

in which the merging point s^m can be expressed as

$$s^m = \frac{\bar{v}_2 s_1^0 - \bar{v}_1 s_2^0}{\bar{v}_2 - \bar{v}_1}. \tag{18}$$

Then, the fuel-optimal platoon formation problem is stated as

$$\begin{aligned} \min \quad & \text{total average fuel consumption (17)} \\ \text{subject to} \quad & \text{constraint on the merging point (18)} \\ & \text{constraints on the average velocity} \end{aligned}$$

in which the constraints on the average velocity are such that the platoon formation does not lead to a delayed arrival at the final destination s^f nor that road speed limits are violated. If $\bar{J}^*_{\mathrm{OPF}}$ denotes the optimal solution, then a platoon is formed between the considered two vehicles if this total fuel cost is less than that of the two vehicles driving independently, i.e.,

$$\bar{J}^*_{\mathrm{OPF}} < \sum_{i=1}^{2} \bar{\varphi}_i \frac{s^f - s_i^0}{\bar{v}_{\mathrm{nom},i}} \tag{19}$$

with $\bar{v}_{\mathrm{nom},i}$ the nominal average velocity of vehicle i. Details on this opportunistic platoon formation can be found in [50], whereas an alternative heuristic approach is given in [51].

V. FLEET MANAGEMENT LAYER

A. Fleet Management Architecture

The fleet management layer handles transport planning, routing, and coordination. Transport planning amounts to distributing the flow of goods over the available vehicles in the fleet. This is a logistics problem in which the available resources are managed to meet customer requirements. The assignment of goods to vehicles is optimized by combining similar assignments to the same vehicle. Size, weight, and type of cargo must be considered. The availability of drivers and the drivers' legal resting times should be regarded as well.

Routing is the process of finding the most suitable path from the origin to the destination. In our setting the aim is to find the most fuel-efficient route. The topography of the road has a large influence on the fuel consumption, for heavy-duty vehicles. The traffic conditions, estimated from historic and real-time data, and current and predicted weather should also be taken into account. Equally important is the reliability of the plan, as accurate predictions of the time of arrival and the corresponding fuel consumption are essential.

The following section describes a procedure for coordinated platoon planning to adjust the velocity profiles in order to form fuel-efficient platoons.

B. Coordinated Platoon Planning

The modern communication infrastructure allows for the fusion of real-time position, velocity, and assignment information of heavy-duty vehicles together with external influences such as traffic data and thus enables the centralized coordination of a large number of vehicles over a large geographical area. In this section, one such coordination method is described, aimed at achieving fuel savings through the formation of platoons. This approach can be regarded as an extension of the opportunistic platoon formation approach of Section IV-C, where the latter is inherently local in nature.

In order to efficiently obtain platoon configurations and the corresponding average velocities for each vehicle, a three-step approach is taken. The first step comprises finding the most suitable route for each vehicle, taking factors such as road topography and traffic information into account.

In the second step, two vehicles are considered at the time. For the first vehicle, the fuel-optimal velocity trajectory is computed, hereby taking into account starting time and arrival deadline as well as constraints such as driver resting times. Note that this trajectory is independent from the second vehicle. Instead, if this second vehicle has a partially overlapping route, the pairwise analysis of Section IV-C is used to determine how beneficial it is to adapt the second vehicle's velocity profile to form a platoon with the first vehicle. Note that the availability of the routes of all vehicles allows for identifying the overlapping part on which a platoon can be formed. Moreover, the arrival deadline of the second vehicle is taken into account in this step. If the second vehicle adapts its velocity profile to form a platoon, it is referred to as a coordination follower, whereas the corresponding first vehicle is called coordination leader. By combining this analysis for any pair of vehicles, multiple coordination followers can be assigned to a single coordination leader, where it is recalled that the latter does not adapt its velocity profile.

The selection of the most suitable coordination leaders is crucial in obtaining significant fuel savings. This selection forms the third step. Repeating the pairwise analysis for every potential coordination leader leads to a data set that can be conveniently represented as a graph. In this graph, the nodes represent the vehicles and their incoming edges denote the fuel savings obtained when this vehicle is selected as a coordination leader. From clustering algorithms [52], an algorithm can be derived to compute a suitable set of coordination leaders. Specifically, a greedy algorithm that incrementally adds or removes individual vehicles from the set of coordination leaders provides a computationally efficient and scalable approach [53]. Instead of coordination of vehicles through adaptation of their velocity profiles, vehicle sorting for platooning has been considered [54], as well as techniques from data mining [55].

C. Incentives for Cooperation

There are many incentives for individual owners of truck fleets to optimize their long-haulage transportation tasks. By coordinating timing and routing of vehicles, the fleet owner can utilize their available resources (fuel, vehicles, drivers, etc.) as efficiently as possible. Through vehicle platooning, the tasks can be further optimized and fuel consumption decreased, as discussed in this paper. The long-haulage transport and logistics industry consists of a large and diverse set of fleet owners, however, and it is for obvious reasons hard for many of them to cooperate without financial guarantees and trust. To be able to capitalize on vehicle cooperation, we need to have as big pool as possible of heavy-duty vehicles that travel on the same (or similar) route and at the same time. It is rarely the case for small fleet owners to have so many similar tasks to satisfy this criterion. One solution to this problem is instead to create a fleet management service for the owners and their vehicles. In such a service, the fleet owners can privately provide their routes and timetables so that the service provider can pair the vehicles for cooperation. For participating in this service, the fleet owners may need to pay a subscription fee in addition to invest in devices to facilitate cooperation. The case of cooperative heavy-vehicle platooning is discussed next.

A fleet management service for heavy-duty vehicle cooperation focusing on platooning can be evaluated considering existing patterns of long-haulage goods delivery. Based on position data from thousands of heavy-duty vehicles, it has been shown that many vehicles have other vehicles in their vicinity, even when only a single vehicle brand is considered [56]. Hence, it is possible with minimum effort to form a vehicle platoon, as was described in Section IV. It is also clear from these data that quite a few vehicles are actually driving in spontaneous platoons already today. To automate a platooning service, it is essential to present transparent information on benefits and costs to individual fleet owners and drivers. By utilizing economic theory on technology adoption [57] and data from actual transportation tasks [56], it is possible to reason how a market for such a service can be established [58]. One example is centralized cooperation, in which fleet owners pay to subscribe to a third-party service provider and then can cooperate with any other fleet owner who is part of the system. The pricing strategy needs to be carefully developed for such a service, as the marginal benefit for joining such a system for a large fleet owner might be smaller than for a fleet owner with few vehicles. In addition, it needs to be assured that benefits are shared amongst the lead vehicle and follower vehicles in a platoon, e.g., by micropayments.

VI. CASE STUDY

A. Scenario

The platoon control and coordination algorithms presented in this paper are demonstrated by means of a simulation scenario representing a part of the highway network of Sweden; see Fig. 7. On this network, 200 heavy-duty vehicles originating from six locations in the Stockholm area in the east travel to five destinations in the west. The origin–destination pair for each vehicle is chosen randomly within these locations. The starting times for these vehicles are taken from a two-hour interval, whereas the parameter values for each vehicle are given in Table 1. The coordinated platoon planning for this scenario is evaluated in Section VI-B before focusing on the cooperative look-ahead control for one specific platoon in Section VI-C.

B. Coordinated Platoon Planning Evaluation

The methodology for coordinated platoon planning in Section V-B is used to select suitable coordination leaders and their respective followers. Herein, pairwise plans are considered in which the coordination followers catch up with their leaders and platoon until either of their routes end or their routes split up. For this scenario, the coordination algorithm selects 54 coordination leaders and 139 coordination followers, which adjust their velocity profiles to catch up with the coordination leaders in order to form platoons. The maximum number

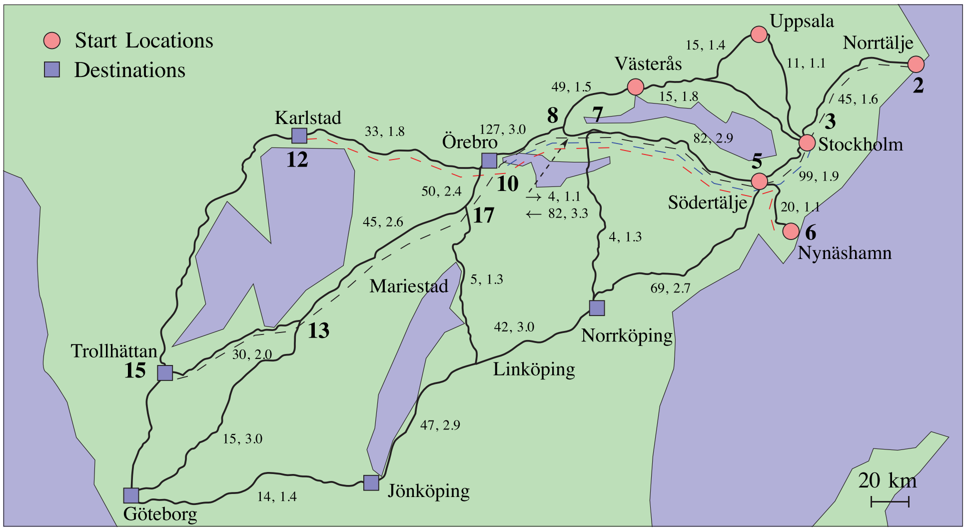

Fig. 7. ***The Swedish road network used in the case study. Starting locations and destinations are indicated by red circles and blue squares, respectively, and the boldface numbers represent intersections. The two numbers next to the road segments indicate the number of vehicles that traverse this segment and the average platoon size on this segment, respectively, as a result of the applied coordination algorithm. The road segment between nodes 7 and 8 is traversed in both directions and the statistics for vehicles traveling in either direction are indicated separately. Three routes, indicated by dashed lines, are highlighted as an example for a group comprising a coordination leader (black) and two coordination followers (blue and red).***

of coordination followers per coordination leader is 8, whereas the median is 2. The remaining seven vehicles do not platoon but traverse their routes individually. The coordinated platoon planning amounts to a fuel saving of 5.7%, when compared to all vehicles driving independently. Considering that the maximum fuel saving is assumed to be 12.0% when vehicles platoon, the coordination layer is fairly efficient in this scenario. Recall that the velocity adjustments necessary for coordination lead to an increased fuel consumption. The total fuel savings amount to 1045 L of diesel fuel and a reduction of CO_2 emissions of 2770 kg.

The routes of one particular coordination leader and its two coordination followers are highlighted in Fig. 7. The corresponding trajectories are presented in Fig. 8, where the time gaps with respect to the coordination leader as a function of the position on the road are shown. Note that the first coordination follower (blue) shares the first part of its route with the coordination leader (black), but as it starts 1.25 h later it catches up at maximum speed, indicated by a decreasing gap to the leader in Fig. 8. It then meets the platoon consisting of the coordination leader and the other coordination follower (red) between nodes 5 and 7, in which it stays until its destination at node 10 is reached. The route of the second coordination follower intersects with the route of the coordination leader at node 5 and the coordination follower's start time is such that it catches up to the coordination leader at a velocity that is lower

Table 1 Model Parameters Used in the Experimental Evaluation

m	40 000	kg	p_0	$5.36 \cdot 10^{-4}$	kg s^{-1}
A	10	m^2	p_1	$5.15 \cdot 10^{-8}$	kg s^{-1} W^{-1}
c_d^0	0.6		ρ	1.29	kg m^{-3}
α_1	0.53		P_min	-9	kW
α_2	0.81	s^{-1}	P_max	300	kW

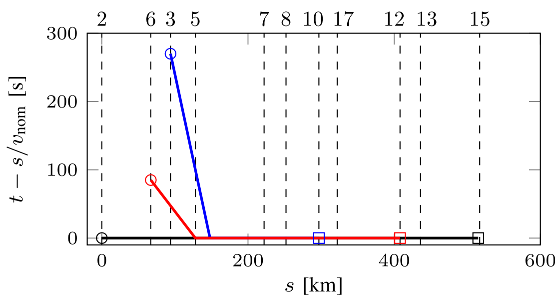

Fig. 8. ***Platoon plans for a coordination leader (black) and two coordination followers (blue and red) that catch up with the coordination leader to form a platoon. The graph shows the time gap to the platoon leader as a function of the position on the road, where this position is taken along the routes of the individual vehicles. The dashed lines denote the position of the nodes representing road intersections in Fig. 7, with the top labels denoting the node number. As an example, note that the coordination leader starts from Norrtälje (node 2) and drives to Trollhättan (node 15). When the time gap is zero and the routes of the vehicles overlap (between nodes 5 and 10), the vehicles operate in a platoon.***

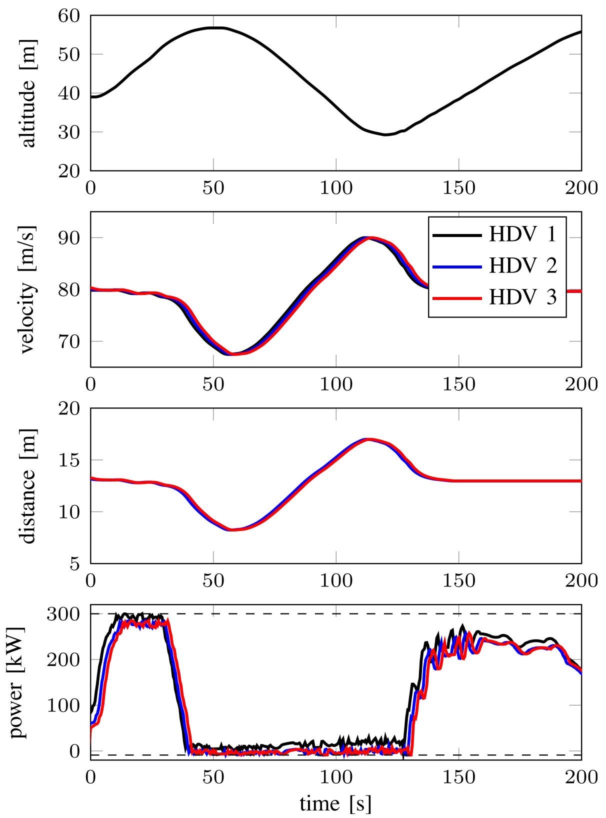

Fig. 9. ***Cooperative look-ahead control local behavior of the three-vehicle platoon depicted in Fig. 8. The plots show the road topography experienced by the leading vehicle, the vehicle speeds, the intervehicle distances, and the generated power, respectively. The generated power is the sum of the engine power and the power dissipated by the braking system. The dashed lines represent the minimum and maximum engine powers.***

than the maximum speed. The coordination follower and the coordination leader form a platoon at node 5 and platoon until node 10 where their routes split up.

C. Cooperative Look-Ahead Control Evaluation

The cooperative look-ahead control and the vehicle layer govern the local behavior of each platoon by explicitly taking into account topography information. Fig. 9 illustrates the effective behavior of the three-vehicle platoon discussed in the previous section when driving along a 4-km road stretch in the latter part of the segment between node 5 and node 7. It can be observed that the three vehicles follow approximately the same velocity profile, albeit shifted in time as required by their cooperative look-ahead control strategy. Consequently, the vehicles follow approximately the same velocity profile in the spatial domain and, due to the dependence of the slope on position, this results in similar power profiles.

In order to respond to the fuel-optimality criterion, the cooperative look-ahead control requires the vehicles to follow a particular speed profile depending on the road topography. Specifically, it requires the vehicles to keep a constant speed of 80 km/h during the uphill segment and to drop the speed down to 68 km/h at the top of the hill. This allows the vehicles to gain speed during the downhill without reaching the speed limit of 90 km/h. In particular, the required downhill speed profile is such that the lead vehicle fuels slightly, whereas the follower vehicles coast (i.e., they do not fuel). Hereby, the desired intervehicular distances are maintained even though the follower vehicles experience a reduced aerodynamic drag. Hence, the proposed cooperative controller avoids braking and exploits the combined potential of both platooning and look-ahead control. As a result, it achieves larger fuel savings than for each of the methods independently. For the hilly stretch shown in Fig. 9, it allows to save approximately 10% of energy compared to the vehicles driving alone using look-ahead control and 7% compared to the vehicles platooning without cooperating and exploiting topography information.

VII. CONCLUSION

A cyber–physical systems approach toward the control and coordination of a large-scale transportation system was presented in this paper. The approach relies on modern vehicle-to-vehicle and vehicle-to-infrastructure communication and is supported by ubiquitous computation power as offered through cloud services and onboard computers. The coordination of heavy-duty vehicles is aimed at the reduction of fuel consumption and a layered freight transport system architecture was developed that achieved this reduction through exploiting the formation of closely spaced groups of vehicles, which leads to a reduced aerodynamic drag. The distributed control of platooning vehicles was handled in the low-level vehicle layer of the system architecture, whereas the middle-level cooperation layer employed look-ahead control to further reduce fuel consumption. The formation of platoons was also handled in this cooperation layer. Finally, the fleet layer on top performed the large-scale coordination of the platoons with integrated routing and transport planning. A case study involving 200 vehicles confirmed the feasibility of this cyber–physical approach to freight transport.

Extensive real-world experimental evaluation of the approach developed in the paper is the scope of ongoing (see [59]) and future work. Such evaluation should include both small- and large-scale tests. Experiments with vehicles on public roads are obviously needed to study many practical implications. Such experiments build on earlier experiences of individual platoon experiments on Swedish roads [5], [28]. ■

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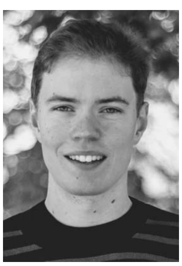
ABOUT THE AUTHORS

Bart Besselink received the M.Sc. degree in mechanical engineering (*cum laude*) and the Ph.D. degree in mechanical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 2008 and 2012, respectively.

He is a Postdoctoral Researcher with the ACCESS Linnaeus Centre and the Department of Automatic Control, Royal Institute of Technology (KTH), Stockholm, Sweden. He was a short-term visiting researcher at the Tokyo Institute of Technology, Tokyo, Japan, in 2012. His main research interest includes systems theory and model reduction for nonlinear dynamical systems and large-scale interconnected systems with applications in the field of intelligent transportation systems.

Valerio Turri received the M.Sc. double degree in control engineering (*cum laude*) from Politecnico di Milano, Milan, Italy and Politecnico di Torino, Turin, Italy, in 2011. Currently, he is working toward the Ph.D. degree in electrical engineering at the ACCESS Linnaeus Centre and the Department of Automatic Control, Royal Institute of Technology (KTH), Stockholm, Sweden.

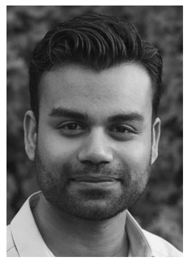
He was a Research Engineer at the Model Predictive Control Lab, Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA, USA, in 2012. His research interests include model predictive control and its application to advanced automotive control.



Sebastian H. van de Hoef received the B.Sc. degree in mechatronics from the Technische Universität Darmstadt, Darmstadt, Germany, in 2011 and the M.Sc. degree in systems, control, and robotics from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2013, where he is currently working toward the Ph.D. degree in electrical engineering at the ACCESS Linnaeus Centre and the Department of Automatic Control.

His research interests include dynamic coordination of distributed cyber-physical systems with a focus on coordination of truck platooning.

Kuo-Yun Liang received the M.Sc. degree in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2011, where he is currently working toward the industrial Ph.D. degree at the Department of Automatic Control and the ACCESS Linnaeus Centre, School of Electrical Engineering, and the Research and Development Department, Scania CV AB, Södertälje, Sweden.



Assad Alam received the M.Sc. degree in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2008 and the industrial Ph.D. degree from the Department of Automatic Control and the ACCESS Linnaeus Centre, School of Electrical Engineering, KTH, and the Research and Development Department, Scania CV AB, Södertälje, Sweden, in 2014.

He is a full-time Senior Engineer at the Driver Assistance Controls Department, Scania CV AB, Södertälje, Sweden. His research interests include fuel-efficient control of heavy-duty vehicle platooning.

Jonas Mårtensson received the M.Sc. degree in vehicle engineering and the Ph.D. degree in automatic control from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2002 and 2007, respectively. The topic of his Ph.D. dissertation was geometric analysis of stochastic model errors in system identification.

He holds a tenure-track position as an Assistant Professor with the Department of Automatic Control, KTH. He is also engaged as a program leader in the Integrated Transport Research Lab and he is thematic leader for the area Transport in the Information Age within the KTH Transport Platform. Between 2008 and 2012, he worked on 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 in several collaboration projects with Scania CV AB, Södertälje, Sweden, dealing with collaborative adaptive cruise control, look-ahead platooning, route optimization and coordination for platooning, path planning and predictive control of autonomous heavy vehicles, and related topics.

Karl H. Johansson (Fellow, IEEE) received the M.Sc. degree in electrical engineering and the Ph.D. degree in automatic control from Lund University, Lund, Sweden.

He is Director of the ACCESS Linnaeus Centre and Professor at the School of Electrical Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden. He is a Wallenberg Scholar and has held a Senior Researcher Position with the Swedish Research Council. He also heads the Stockholm Strategic Research Area ICT The Next Generation. He has held visiting positions at the University of California Berkeley, California Institute of Technology (CalTech), Nanyang Technological University (NTU), and Hong Kong University of Science and Technology (HKUST). His research interests are in networked control systems, cyber-physical systems, and applications in transportation, energy, and autonomous systems.

Dr. Johansson is a member of the IEEE Control Systems Society Board of Governors and past Chair of the International Federation of Automatic Control (IFAC) Technical Committee on Networked Systems. He has been on the Editorial Boards of many journals, such as *Automatica* and the IEEE Transactions on Automatic Control. He has received several awards, including the Young Author Prize from IFAC, Future Research Leader from the Swedish Foundation for Strategic Research, and Wallenberg Scholar from Knut and Alice Wallenberg Foundation.