A Predictive Framework for Dynamic Heavy-Duty Vehicle Platoon Coordination

SEBASTIAN VAN DE HOEF, JONAS MÅRTENSSON, DIMOS V. DIMAROGONAS, and KARL HENRIK JOHANSSON, KTH Royal Institute of Technology

This article describes a system to facilitate dynamic en route formation of heavy-duty vehicle platoons with the goal of reducing fuel consumption. Safe vehicle platooning is a maturing technology that leverages modern sensor, control, and communication technology to automatically regulate the inter-vehicle distances. Truck platooning has been shown to reduce fuel consumption through slipstreaming by up to 10% under realistic highway-driving conditions. To further benefit from this technology, a platoon coordinator is proposed, which interfaces with fleet management systems and suggests how platoons can be formed in a fuel-efficient manner over a large region. The coordinator frequently updates the plans to react to newly available information. This way, it requires a minimum of customization with respect to the logistic operations. We discuss the system architecture in detail and introduce important underlying methodological foundations. Plans are derived in computationally tractable stages optimizing fuel savings from platooning. The effectiveness of this approach is verified in a simulation study. It shows that the coordinated platooning system can improve over spontaneously occurring platooning even under the presence of disturbances. A real demonstrator has also been developed. We present data from an experiment in which three vehicles were coordinated to form a platoon on public highways under normal traffic conditions. It demonstrates the feasibility of coordinated en route platoon formation with current communication and on-board technology. Simulations and experiments support that the proposed system is technically feasible and a potential solution to the problem of using vehicle platooning in an operational context.

CCS Concepts: • **Applied computing** → **Transportation**; • **Information systems** → *Spatial-temporal systems*; • **Theory of computation** → Theory and algorithms for application domains; • **Computer systems organization** → *Embedded and cyber-physical systems*; • **Computing methodologies** → **Multi-agent planning**;

Additional Key Words and Phrases: Platooning, road freight transport, cooperative adaptive cruise control

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Authors' address: S. van de Hoef, J. Mårtensson, D. V. Dimarogonas, and K. H. Johansson, KTH Royal Institute of Technology, Malvinas väg 10, Stockholm, 100 44, Sweden; emails: {shvdh, jonas1, dimos, kallej}@kth.se.
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1 INTRODUCTION

Freight transport is important for the economy. Freight transport volumes are directly coupled to the gross domestic product [14, 38, 46], and thus economic growth goes hand in hand with an increase in transported goods. Road freight transport is an integral component in the freight transport system mainly due to its large flexibility, with the majority of destinations directly accessible by road [3].

To sustain current or increasing levels of road freight transport, major challenges have to be overcome. One challenge is that road infrastructure reaches its limits in many heavily populated areas, resulting in economic losses due to congestion [18, 48]. Building more infrastructure is costly and in many cases not feasible. Another major challenge is that road transport largely relies on fossil fuels, which results in problematic levels of emissions, most notably greenhouse gases. The transport sector accounts for 18% of all manmade CO_2 emissions globally, with levels growing quicker than other in sectors [18, 38].

1.1 Cyber-Physical Transport Systems

One promising way to address these challenges are intelligent transportation systems (ITS), which employ information and communication technology (ICT) to improve efficiency, safety, and reliability [20, 21, 37]. ITS are cyber-physical systems, as both the physical hardware and the cyber software components have to be considered simultaneously in the design [7]. A number of developments in the ICT area are drivers in ITS. One important aspect is that new cheap and small sensors such as radars, cameras, and global positioning systems become increasingly available. Growing computing power is another essential factor, both locally in the vehicles and in the roadside infrastructure, and globally through cloud computing. A third crucial component is communication technology [22]. The Internet, mobile data networks, and dedicated vehicle-to-vehicle and vehicle-to-infrastructure communication make the connection of vehicles, infrastructure components, individuals, traffic centers, and company ITS cheap and flexible [54]. The early development of ITS was focused on immediate use of new hardware components, whereas more recent developments are increasingly on software components such as decision support systems, system-level optimization, and automatic control [12, 23].

An emerging ITS technology is driver-assisted truck platooning (DATP). DATP allows heavy freight vehicles to drive in groups, so-called platoons, with small inter-vehicle distance enabled by automatic longitudinal control (Figure 1). DATP is made possible, by vehicle-to-vehicle communication, radar sensors, cameras, and global positioning systems, among others [4]. Truck platooning reduces fuel consumption through the slipstream effect, improves road utilization, and eases the automation of the trailing vehicles. It is seen as a key ITS technology to create a sustainable road freight transport system. Platooning technology is relatively well researched on the vehicle level [5, 49] and is currently under commercialization. First, demonstrations are conducted in which platooning is used as part of the regular transport operations.

1.2 Contribution

The contribution of this article is to present a platoon coordination system that solves the problem of integrating platooning technology into the day-to-day operation of commercial long-haulage vehicles as means of reducing fuel consumption. The proposed solution is to form platoons en route, facilitated by small adjustments of the vehicle speeds and departure times, as illustrated in Figure 2. This approach is supported by studies that investigate the potential of platooning technology based on fleet data and show that relatively small adaptations in the vehicles' itineraries would be sufficient to enable a large percentage of vehicles to platoon [5, 33, 49]. It can be

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Fig. 1. A three-vehicle platoon in the COMPANION project.

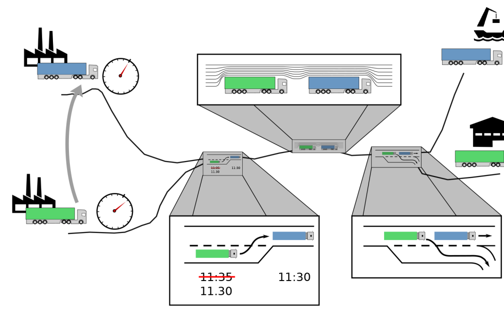

Fig. 2. Vehicles adapt their speed to meet and form platoons on common sections of their route.

contrasted with more invasive coordination approaches that operate on the logistic planning level, grouping vehicles with the same departure location or gathering vehicles at dedicated rendezvous points [8, 25], which is complex to generalize to the specific needs of different transport operators. Instead, our system adapts swiftly to changes both from the logistic operations and disturbances, facilitated by fast optimization algorithms and real-time position feedback from the vehicles. By adjusting vehicle speed and platoon configurations in real time, the system is resilient to disturbances and unplanned events. It has minimal impact on the operation of vehicles in their logistic context.

A recent overview of work on fleet-level coordination of heavy-duty vehicle platooning can be found in Bhoopalam et al. [6]. Most existing works focus exclusively on the static planning problem [8, 31] without much consideration of the real-time integration into a dynamic transport system. They integrate platooning into the day-ahead planning of transport operators, which limits the size of the fleets that can be coordinated. This also motivates the formulation of rather complex optimization problems that take long time to solve and make adapting to real-time updates of the planning hard.

We introduce the architecture of this coordination system and how it integrates into current freight operations. Furthermore, some of the key algorithmic components for coordination, particularly for incorporating real-time feedback, are presented. The algorithmic framework allows the handling of large fleet sizes [6] close to real time while taking a high level of planning detail into account due to an hierarchical approach. The potential of this approach is demonstrated by simulation studies in a realistic setting and by a demonstrator implementing a complete platoon coordination system. This demonstrator was developed in the scope of the COMPANION project [15]. We present and analyze data collected during an experiment with this demonstrator on public motorways in Spain.

1.3 Related Work

Platooning technology on vehicle level is an important building block in our coordinated platooning system. It was first developed as a building block of automated highway systems [24, 45]. With increasing concerns for the emissions from road freight transport, vehicle platooning with the purpose of reducing fuel consumption came into the focus of research [50]. The reasons platooning technology is particularly applicable to commercial transport include higher level of predictability, existing integration with telematics systems, higher vehicle utilization, and higher pressure of economic operation. One of the first vehicle platooning systems developed and tested is reported in Fritz [19]. Kunze et al. [28] focus on testing platooning under realistic operation conditions. Mixed platoons with heavy-duty vehicles and passenger cars are reported in Chan [11]. A wide

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range of aspects and successful demonstration of four vehicle platoons can be found in Tsugawa [49]. The activities reported in Bevly et al. [5] investigate driver-assisted two-truck platooning for the U.S. American market with the goal of bringing the technology close to commercial implementation and have a strong focus on assessing the economic viability of this technology. In addition, McAuliffe et al. [35] aim at increasing the technology readiness of heavy-duty vehicle platooning. Controlling the inter-vehicle distance in a platoon is a challenging control problem, and many contributions have been made in developing string stable controllers for platoons [39, 40, 47, 53].

Several studies have been conducted (see Roberts et al. [41] for an overview) to assess the fuel-saving potential of heavy-duty vehicle platooning, which is the main economic driver behind DATP. Although it is nontrivial to quantify the exact reduction in fuel consumption due to the large number of influencing parameters, most studies agree that a reduction in the order of 10% can be established for the trailing vehicles in the platoon, the platoon followers, compared to driving alone. Apart from environmental considerations, DATP is also believed to be economically beneficial, mostly because relatively little additional hardware needs to be installed on the vehicles [26]. An additional driver for implementation is the increased safety, which can even result in economic benefits from reduced insurance fees.

The need to develop supportive systems for platooning is already recognized in Horowitz and Varaiya [24], where platooning is used as part of an automated highway system. This setup is quite different from the one considered here, as platooning is mostly seen as a way to organize the vehicle automation and to increase throughput. The contributions [29, 36] feature work to support driver-organized vehicle platooning, where suitable platoon partners are identified by means of data mining. These options are shown to the drivers, which are responsible for taking the decisions and executing the plans. This article proposes a higher degree of automation to maximize fuel savings and react to disturbances and unplanned events. In Larsson et al. [31], the authors formulate a combined routing and platoon coordination optimization problem and prove that it is hard to solve even under simplifying assumptions. A distributed framework to match vehicles approaching intersections is presented in Larson et al. [30]. Another distributed setup that allows vehicles to wait at intersections can be found in Elbert and Knigge [16]. We propose a solution with a central coordinator enabled by the available cellular communication infrastructure. Several contributions consider the formation process of platoons once the decision of which vehicle should be in the platoon has been made [17, 34, 43]. Related problems to the one considered in this article arise in other ITS, such as ride sharing [1], air traffic control [55], and inter-modal logistics [32]. In van de Hoef et al. [52], a method was developed to plan fuel-efficient platooning for batches of vehicles. We extend this planning algorithm to a building block of a predictive online framework, which can adapt to disturbances and changing planning information.

1.4 Outline

The remainder of the article is organized as follows. Section 2 introduces the architecture of the coordinated platooning system. In Section 3, the methodology to compute fuel-efficient plans is discussed. Section 4 presents results from a simulation evaluation of the proposed system. In Section 5, experimental results are given for a demonstrator that implements the coordination system featuring real-world test vehicles. Section 6 concludes the article and outlines open questions.

2 THE COORDINATED PLATOONING SYSTEM

In this section, we introduce the coordinated platooning system. The coordinated platooning system enables vehicles to effectively use platooning to reduce fuel consumption. The coordinated platooning system consists of platooning-enabled vehicles in a road network, fleet management

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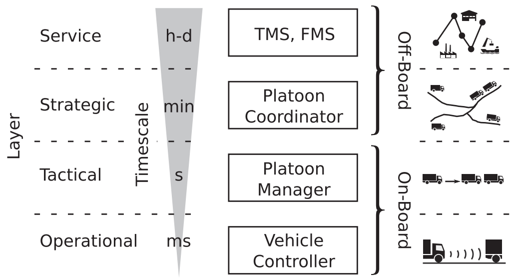

Fig. 3. A layered control system architecture for coordinated platooning.

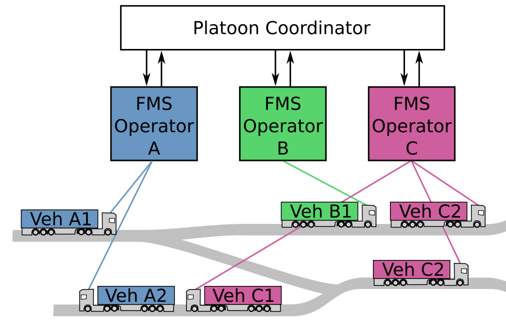

Fig. 4. The coordinator receives assignment data from the FMS of different transport operators and computes routes and speed profiles for the vehicles to form platoons en route.

systems (FMS), and a platoon coordination system. The platoon coordination system facilitates fuel-efficient platooning across multiple FMS.

Figure 3 shows a layered transport architecture inspired by the one proposed in Alam et al. [2]. The road transport system is structured in four layers with the highest abstraction at the top and increasing detail at the bottom. At the highest layer, the *service layer*, the existing logistic planning system resides in form of transport management systems (TMS) and FMS. On this layer, goods flows are matched to vehicles and drivers. Typical time scales on this layer are in the order of hours to days. A wide range of complexity levels can be encountered on this layer, ranging from manual planning to complex supply chain optimization.

On the layer below, the *strategic layer*, the platoon coordinator is situated. The platoon coordinator is the central system provided by a platoon service provider. Platoon service providers have been postulated in the literature [25] as organizations that provide crucial platooning services shared between road transport providers, such as certification, insurance, and coordination. The coordination service, also known as match making, is discussed in this article. This service might be provided as a public service or through private enterprises.

At the *tactical layer*, the platoon manager resides. The platoon manager controls the formation, splitting, reorganization, and operation of the platoons according to the platoon plans. It is implemented in a distributed way. The platoon management sets reference speeds and reference inter-vehicle distances for the vehicle in a platoon, which are then tracked by the vehicle controller on the operational layer. The tactical information is also communicated to the driver in each vehicle. The driver takes a supervising role and might override the decisions of the platoon management.

At the *operational layer*, the vehicle controller tracks the speed and distance references from the tactical layer. It commands the engine actuators, the brake systems, and the gearbox. It abstracts the complex vehicle-specific dynamics and presents a standardized interface to the tactical layer.

From bottom to top, the level of abstraction, the geographic scale and dispersion, and the timescale increase. Fast dynamics are handled locally where communication delays are small, whereas the slow dynamics that require information from the entire system are handled globally. This is a proven design pattern for automatic control systems. The effect of the update frequency on the strategic layer is further discussed in Sections 4 and 5. In general, selecting update frequencies is a tradeoff between performance and system requirements in terms of computation power and communication delays/throughput and needs to be performed through experimentation.

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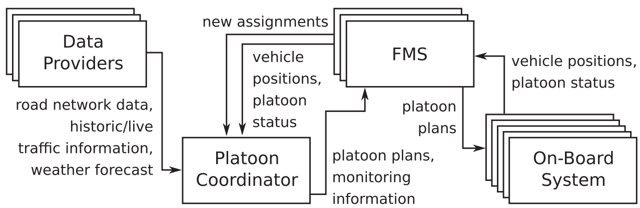

Fig. 5. Chart detailing the dataflow between the components of the coordinated platooning system.

Remark 1. The service layer introduced here is sometimes divided into a strategic, tactical, and operational layer [13], which should not be confused with the layer structure introduced in this article.

The platoon coordinator interfaces with the FMS of the transport operators as illustrated in Figure 4. Each FMS controls the vehicles that belong to its transport operator. The platoon coordinator receives assignments from the FMS as shown in Figure 5. An assignment $\mathcal{A} = (\mathcal{P}^{\mathrm{S}}, \mathcal{P}^{\mathrm{D}}, t^{\mathrm{S}}, t^{\mathrm{D}}, \mathcal{D})$ consists of a start location $\mathcal{P}^{\mathrm{S}}$ at which the vehicle will start its trip at start time t^{S} and a destination $\mathcal{P}^{\mathrm{D}}$ at which the vehicle is supposed to end the trip before deadline t^{D}. Additional data $\mathcal{D}$ can be associated with the assignment, such as the type of vehicle and constraints on the route. Each assignment is associated with one vehicle.

Remark 2. Complex transport missions with multiple stops are broken down into multiple assignments by the FMS. Start location and destination do not have to match the position at which the vehicle starts driving but can be, for instance, the points where the vehicle enters and leaves the highway network.

For each assignment, the platoon coordinator computes a platoon plan using information provided by the FMS and data providers. A platoon plan $\pi = (\mathbf{e}, \mathbf{t}, \mathbf{p})$ consists of a route $\mathbf{e}$, a time profile $\mathbf{t}$, and a platoon configuration profile $\mathbf{p}$. The route $\mathbf{e}$ connects the start location $\mathcal{P}^{\mathrm{S}}$ of the corresponding assignment with the destination $\mathcal{P}^{\mathrm{D}}$ in the road network. The time profile $\mathbf{t}$ is defined along the route and encodes when the vehicle should be at a location. The platoon configuration profile $\mathbf{p}$ encodes in which platoon configurations the vehicle travels along the route. The platoon plans predict a desirable evolution of the coordinated vehicles. They are updated on a timescale of minutes to adapt to new assignments, new planning information, and deviation from the platoon plans.

Remark 3. The platoon coordinator cannot interface directly with the vehicles' on-board systems as the layered architecture in Figure 3 might suggest. This is because the mapping between vehicles and transport assignments is only known by the respective FMS. Furthermore, the transport operator might want to check the generated platoon plans for its vehicles and potentially update or cancel the assignment when errors are detected. Note that each FMS only receives the platoon plans corresponding to the vehicles it manages.

3 COMPUTING VEHICLE PLATOON PLANS

In this section, we discuss methodology used in the computing steps to compute fuel-efficient platoon plans $\pi = (\mathbf{e}, \mathbf{t}, \mathbf{p})$ based on assignments $\mathcal{A} = (\mathcal{P}^{\mathrm{S}}, \mathcal{P}^{\mathrm{D}}, t^{\mathrm{S}}, t^{\mathrm{D}}, \mathcal{D})$. The challenge with computing platoon plans is the high degree of combinatorial complexity [31]. To have a significant impact on the overall fuel efficiency of the road freight transport system, the coordinated platooning system has to be able to handle a significant number of vehicles. Furthermore, the plan computation needs to be fast enough to accommodate new assignments and react to disturbances. Therefore,

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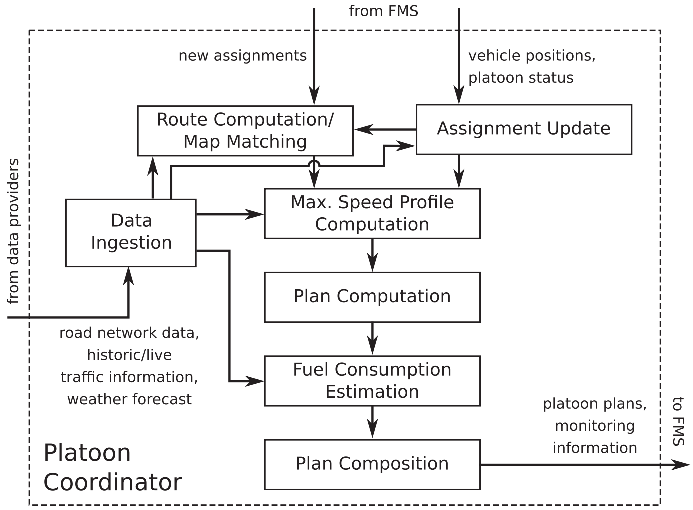

Fig. 6. Flow chart illustrating components of the platoon coordinator and the data exchanged.

we concentrate on finding heuristic solutions that allow computation of vehicle platoon plans for a large number of vehicles quickly. We build on the approach introduced in van de Hoef et al. [52].

Figure 6 shows a flow chart detailing the computational steps and the dataflow of the platoon coordinator shown in Figure 5. In the following sections, we discuss the key steps in computing platoon plans from assignments; vehicle positions; platoon status; and external data such as road network data, historic/live traffic information, and weather forecasts. There are several possible error scenarios, such as an arrival time that is infeasible or that no route for the vehicle can be found. These are not detailed here to keep the presentation concise.

3.1 Route Computation and Map Matching

The route computation and map matching stage computes the assignment's route. The route encodes the way the vehicles travel in the road network from start to destination. A route $\mathbf{e}$ is represented as a sequence of consecutive road segment identifiers $\mathbf{e} = (\mathbf{e}[1], \mathbf{e}[2], \ldots, \mathbf{e}[N^{\mathrm{A}}])$, where N^{A} is a notational convenience with the purpose of referring to the last segment in the route. The start position is the beginning of the first road segment represented by $\mathbf{e}[1] = \mathcal{P}^{\mathrm{S}}$ and the destination the end of the last road segment represented by $\mathbf{e}[N^{\mathrm{A}}] = \mathcal{P}^{\mathrm{D}}$. The route segments identifiers are the basis on which all other data in the platoon plan are represented. They come from a road network graph with edge set $\mathcal{E}_{\mathrm{r}}$, where nodes correspond to geographic locations and edges to road segments connecting those locations. A graph is a standard representation of a road network that commonly is used in route planning. Normally, road segments are chosen in way that map attributes, such as the legal speed limit, are constant on a segment. If some road segments are too long for planning time profiles, they can easily be subdivided into smaller segments.

We deliberately exclude the possibility of rerouting the vehicles for the sake of platooning, due to the large combinatorial complexity limiting the ability to quickly react to new assignments and updated information. Algorithms to compute routes in road networks are well developed. Such algorithms typically compute a shortest path according to a cost function such as travel time, distance, or fuel consumption. In addition to a static cost, they can also handle time-dependent cost functions based on traffic predictions and weather data [44]. In many cases, the FMS compute routes as part of the assignment generation process and require the vehicles to follow these routes.

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In such a case, the routes have to be matched to the internal representation $\mathcal{E}_\mathrm{r}$ of the platoon coordinator, using geographic coordinates as intermediate encoding. A variety of map matching algorithms can be employed for that purpose [9]. The other planning stages work solely with the time profile $\mathbf{t}$ and the platoon profile $\mathbf{p}$ and leave the route unchanged.

3.2 Maximum Speed Profile Computation

The time profile $\mathbf{t} = (\mathbf{t}[1], \mathbf{t}[2], \ldots, \mathbf{t}[N^\mathrm{A} + 1])$ according to which the vehicle is supposed to travel along the route is represented by a list of segment start times. For $i \in \{1, \ldots, N^\mathrm{A}\}$, $\mathbf{t}[i]$ is the reference time when the vehicle should start traversing the road segment identified by $\mathbf{e}[i]$. The first element $\mathbf{t}[1]$ is the start time of the vehicle, and $\mathbf{t}[N^\mathrm{A} + 1]$ is the arrival time of the vehicle.

The time profile can be converted into a speed profile $\mathbf{v}$ approximating the speed on a road segment as constant. The length of a road segment is denoted $L : \mathcal{E}_\mathrm{r} \to \mathbb{R}^+$. It is the distance a vehicle travels from the beginning to the end of the road segment. The speed profile is defined as

$$\mathbf{v}[i] = \frac{L(\mathbf{e}[i])}{\mathbf{t}[i+1] - \mathbf{t}[i]}, \quad i \in \{1, \ldots, N^\mathrm{A}\}.$$

The speed profile $\mathbf{v}$ combined with the start time $\mathbf{t}[1]$ can be used to compute the corresponding time profile $\mathbf{t}$ as

$$\mathbf{t}[i] = \mathbf{t}[1] + \sum_{j=1}^{i-1} \frac{L(\mathbf{e}[j])}{\mathbf{v}[j]}, \quad i \in \{2, \ldots, N^\mathrm{A} + 1\}. \tag{1}$$

Constraints on the time profile are more conveniently expressed in the speed profile representation. For vehicles to platoon, they have to be at the same location at the same time, which is easier to express in terms of the time profile. Hence, we work with both representations and (implicitly) convert from one representation to the other whenever necessary.

We derive time profiles based on a maximum speed profile $\bar{\mathbf{v}}$. The maximum speed profile corresponds to a vehicle that at any point drives as close to the maximum legal speed $\mathbf{v}^{\max}$ as possible (i.e., that accelerates whenever possible and decelerates only as much needed). The maximum speed profile $\bar{\mathbf{v}}$ is defined for a speed limit $\mathbf{v}^{\max}$, maximum speed change $\Delta\mathbf{v}^{\max}$, and minimum speed change $\Delta\mathbf{v}^{\min}$ as

$$\bar{\mathbf{v}}[i] = \min(\mathbf{v}^{\mathrm{fwd}}[i], \mathbf{v}^{\mathrm{bwd}}[i]),$$

where $\mathbf{v}^{\mathrm{fwd}}[i]$ and $\mathbf{v}^{\mathrm{bwd}}[i]$ are recursively defined as

$$\begin{aligned}
\mathbf{v}^{\mathrm{fwd}}[i+1] &= \min(\mathbf{v}^{\mathrm{fwd}}[i] + \Delta\mathbf{v}^{\max}[i], \mathbf{v}^{\max}[i+1]), \quad \mathbf{v}^{\mathrm{fwd}}[1] = \mathbf{v}^{\max}[1] \\
\mathbf{v}^{\mathrm{bwd}}[i-1] &= \min(\mathbf{v}^{\mathrm{bwd}}[i] - \Delta\mathbf{v}^{\min}[i-1], \mathbf{v}^{\max}[i-1]), \quad \mathbf{v}^{\mathrm{bwd}}[N^\mathrm{A}] = \mathbf{v}^{\max}[N^\mathrm{A}].
\end{aligned}$$

The speed limit $\mathbf{v}^{\max}$ covers legal restrictions that depend on the vehicle, road segment, and the limiting effect of surrounding traffic. Legal restrictions are mostly straightforward to retrieve from databases. Predicting the effect of traffic is more involved and is based both on historic and real-time measurements in combination with advanced prediction models. The maximum speed change $\Delta\mathbf{v}^{\max}$ between consecutive segments takes into account the limited power-to-weight ratio of heavy vehicles. This becomes particularly important on hilly roads where maximum engine power is not sufficient to keep the legal speed. The minimum speed change $\Delta\mathbf{v}^{\min}[i] \leq 0$ from segment i to segment $i + 1$ is limited by safety and comfort considerations, as the maximum braking performance is sufficient to be reserved for emergency situations.

3.3 Plan Computation

At this stage, speed profiles are computed, which are combined in the plan composition stage. To this end, for each assignment, a default speed profile is computed. Furthermore, all combinations

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of two assignments are considered, the ones that can platoon are identified, and time profiles that facilitate that vehicles platoon are computed.

The default speed profile is the speed profile used when the vehicle travels alone. It is a scaled version of the maximum speed profile $\bar{\mathbf{v}}$ that is computed in the previous stage.

Definition 1. The default speed profile is defined as $\mathbf{v}^{\mathrm{d}}[i] = \sigma\bar{\mathbf{v}}[i]$, where $\sigma = \max(\sigma_{\mathrm{d}}, (\underline{t}^{\mathrm{A}} - t^{\mathrm{S}})/(t^{\mathrm{D}} - t^{\mathrm{S}}))$, with $\underline{t}^{\mathrm{A}} = \underline{\mathbf{t}}[N^{\mathrm{A}} + 1] \leq t^{\mathrm{D}}$ being the arrival time according to the maximum speed profile and $0 < \sigma_{\mathrm{d}} \leq 1$. The time profile corresponding to $\mathbf{v}^{\mathrm{d}}$ according to (1) is denoted $\mathbf{t}^{\mathrm{d}}$ with $\mathbf{t}^{\mathrm{d}}[1] = t^{\mathrm{S}}$.

Remark 4. If $\underline{t}^{\mathrm{A}} > t^{\mathrm{D}}$, the vehicle cannot meet its deadline, which means that the assignment is ill-posed and the vehicle travels as fast as possible to its destination. The factor σ_{d} determines how much slower a vehicle travels compared to the maximum speed profile when the deadline permits it. The benefit of letting the vehicle travel slower is more room for the low-level controller that tracks the time profile to account for small disturbances and to allow other vehicles to catch up to the platoon. We consider σ_{d} being a choice of the transport operator.

The next step is to consider all pairs of assignments and to determine for which it is possible to compute a speed profile so that the two vehicles platoon during part of their journey. The first requirement for vehicles to platoon is to have a common part in their routes. Consider two assignments n and m. We denote the index of the first segment of the route that vehicle n has in common with vehicle m as $\underline{N}^{\mathrm{M}}_{n,m}$ and the last as $\overline{N}^{\mathrm{Sp}}_{n,m}$. This means that

$$\mathbf{e}_n\left[\underline{N}^{\mathrm{M}}_{n,m} + i\right] = \mathbf{e}_m\left[\underline{N}^{\mathrm{M}}_{m,n} + i\right], \quad i \in \left\{0, \ldots, \overline{N}^{\mathrm{Sp}}_{n,m} - \underline{N}^{\mathrm{M}}_{n,m} - 1\right\}.$$

Note that $\overline{N}^{\mathrm{Sp}}_{n,m} - \underline{N}^{\mathrm{M}}_{n,m} = \overline{N}^{\mathrm{Sp}}_{m,n} - \underline{N}^{\mathrm{M}}_{m,n}$. If two vehicles do not have a common part in their routes, they cannot platoon with each other. In case there is more than one intersection between the two routes, one of them is selected by a heuristic rule, for instance, selecting the longer intersection. Filtering techniques can be employed to efficiently rule out pairs with no intersection [51].

In case two assignments have a part of their routes in common, the adapted speed profile is computed. This is done in a way that the vehicle with the adapted speed profile meets the vehicle with the default speed profile on the common part of their routes to platoon until the two routes split as shown in Figure 7. For notational convenience, we introduce the offset in the route segment index on the common part of the route $\Delta N_{n,m} = \underline{N}^{\mathrm{M}}_{m,n} - \underline{N}^{\mathrm{M}}_{n,m}$.

Definition 2. The adapted speed profile of n adapted to the default speed profile $\mathbf{v}^{\mathrm{d}}_m$ of assignment m is denoted as $\mathbf{v}^{\mathrm{a}}_{n,m}$ and the corresponding time profile denoted $\mathbf{t}^{\mathrm{a}}_{n,m}$ are such that

$$\mathbf{v}^{\mathrm{a}}_{n,m}[i] = \begin{cases} \sigma_{\mathrm{M}}\bar{\mathbf{v}}_n[i] & \text{for } i \in \{1, \ldots, N^{\mathrm{M}}_{n,m} - 1\} \\ \mathbf{v}^{\mathrm{d}}_m[i + \Delta N_{n,m}] & \text{for } i \in \{N^{\mathrm{M}}_{n,m}, \ldots, N^{\mathrm{Sp}}_{n,m}\} \\ \sigma_{\mathrm{Sp}}\bar{\mathbf{v}}_n[i] & \text{for } i \in \{N^{\mathrm{Sp}}_{n,m} + 1, \ldots, N^{\mathrm{A}}_n\}, \end{cases}$$

with $\underline{\sigma} \leq \sigma_{\mathrm{M}} \leq 1$ and $\sigma_{\mathrm{d}} \leq \sigma_{\mathrm{Sp}}$, and with $\mathbf{e}_n[i] = \mathbf{e}_m[i + \Delta N_{n,m}]$ for $i \in \{N^{\mathrm{M}}_{n,m}, N^{\mathrm{Sp}}_{n,m}\}$, and $\mathbf{t}^{\mathrm{a}}_{n,m}[N^{\mathrm{A}}_n + 1] \leq t^{\mathrm{D}}_n$, and $\mathbf{t}^{\mathrm{a}}_{n,m}[N^{\mathrm{M}}_{n,m}] = \mathbf{t}^{\mathrm{d}}_m[N^{\mathrm{M}}_{n,m} + \Delta N_{n,m}]$.

To check whether or not an adapted speed profile that fulfills the preceding definition exists and computing one if it exists is straightforward as such but entails many steps and is thus omitted here. If the vehicle is parked at the beginning of its trip, the start time $\mathbf{t}^{\mathrm{a}}_{n,m}[1] \geq t^{\mathrm{S}}$ can be adjusted to minimize $|\sigma_{\mathrm{d}} - \sigma|$—that is, the deviation from the default speed profile during the first part of the adapted speed profile. We call the vehicle that adapts a coordination follower and the vehicle that is adapted to the coordination leader. In the later stages, this structure of the plans is exploited.

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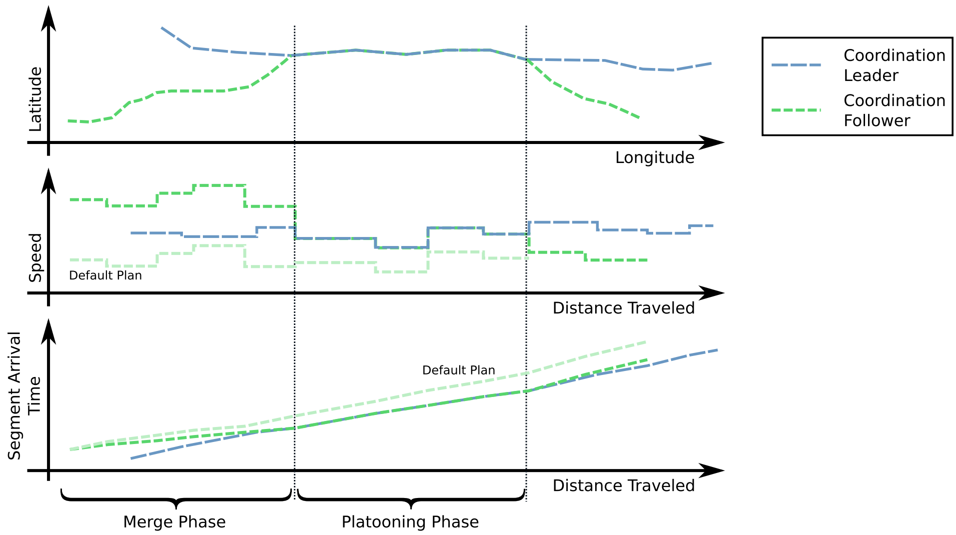

Fig. 7. A coordination follower scales the default speed profile to platoon with the a coordination leader on the common part of their routes.

Remark 5. We neglect the small time gap between the vehicles in the platoon for the sake of planning as they are small compared to disturbances from traffic, road grade, and so forth. Once a platoon is formed, the low-level platoon controller ensures cohesion of the platoon. The objective of the coordinator is to get vehicles close enough so that platoons can be formed and small deviations from the time profiles are expected and dealt with by lower layers of control.

3.4 Fuel Consumption Estimation

To guide the selection of adapted plans, the resulting fuel consumption needs to be estimated. Hereby, when considering an adapted plan of vehicle n, its fuel consumption is compared to the fuel consumption of its default plan and not platooning. The two factors that change the fuel consumption of the adapted plan compared to the default plan is the speed profile and that the two vehicles platoon for some distance.

Speed influences the fuel consumption in multiple ways as shown in Figure 8. When traveling with low speeds, smaller gears have to be selected, causing increased friction losses per distance traveled and the correlation between speed and fuel consumption is negative. At high speeds, the quadratic increase of air drag leads to a positive correlation between vehicle speed and fuel consumption.

The reduction of fuel consumption due to platooning is caused by a reduction in air drag due to the small inter-vehicle distances. The dominant effect is a drag reduction for the trailing vehicle called *slipstreaming*. At very small distances, a smaller effect on the lead vehicle can also be observed. These effects have been reported in a large number of studies using computational fluid dynamics, wind tunnel experiments, and experiments with real vehicles. The results consistently show a reduction of fuel consumption for the trailing vehicles in the order of 10% [41].

To get a tractable solution to the planning problem, we estimate the fuel consumption reduction resulting from an adapted plan of vehicle n adapted to the default plan of vehicle m denoted $\Delta F(n, m)$ individually. Since the coordination leader's speed profile is not changed due to the adaptation, fuel consumption due to speed is only changed for the coordination follower. Furthermore, we assume that the effect of fuel saved during platooning due to the coordination follower is

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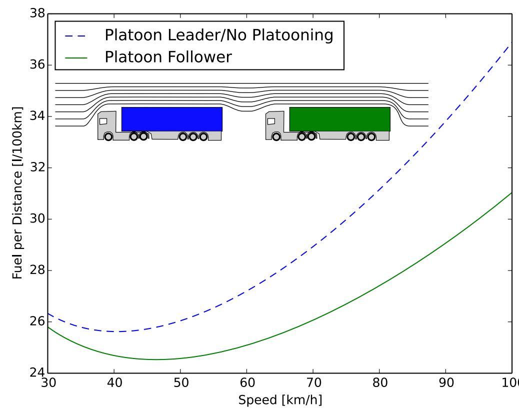

Fig. 8. The fuel consumption per distance traveled as a function of speed with and without the slipstream effect that lowers fuel consumption when platooning.

independent of the other vehicles in the platoon. Both physical models and data-driven models, or combinations of the two, can be used.

Remark 6. It also possible to consider other aspects than fuel in the cost function, such as the trip duration or the risk of being delayed. It is also possible to add a fixed cost to join a platoon to a model a merge phase.

3.5 Plan Composition

We use the default and adapted speed profiles as building blocks for platoon plans with more than two vehicles in the platoon. The approach is to select a subset $\mathcal{N}_\mathrm{l} \subset \mathcal{N}_\mathrm{c}$ of all vehicles $\mathcal{N}_\mathrm{c}$ to take the role of coordination leaders that implement their default speed profile. The remaining vehicles take the role of coordination followers and implement the adapted speed profile, adapted to its best coordination leader in terms of fuel consumption. The objective is then to find the set of coordination leaders that maximizes the total fuel savings. To this end, we compute the coordination graph, which represents all adapted plans with positive fuel savings. It is defined as follows.

Definition 3 (Coordination Graph). The coordination graph is a weighted directed graph $\mathcal{G}_\mathrm{c} = (\mathcal{N}_\mathrm{c}, \mathcal{E}_\mathrm{c}, \Delta F)$. The elements of $\mathcal{N}_\mathrm{c}$ represent the vehicles. The edge set is denoted $\mathcal{E}_\mathrm{c} \subseteq \mathcal{N}_\mathrm{c} \times \mathcal{N}_\mathrm{c}$, and $\Delta F : \mathcal{E}_\mathrm{c} \to \mathbb{R}^+$ are edge weights, such that there is an edge $(n, m) \in \mathcal{E}_\mathrm{c}$, if the adapted plan of n to m saves fuel compared to n's default plan—that is, $\mathcal{E}_\mathrm{c} = \{(n, m) \in \mathcal{N}_\mathrm{c} \times \mathcal{N}_\mathrm{c} : \Delta F(n, m) > 0, n \neq m\}$.

Furthermore, we introduce the set of in-neighbors of a node $n \in \mathcal{N}_\mathrm{c}$ as $\mathcal{N}_n^\mathrm{i} = \{m \in \mathcal{N}_\mathrm{c} : (m, n) \in \mathcal{E}_\mathrm{c}\}$ and the set of out-neighbors of n as $\mathcal{N}_n^\mathrm{o} = \{m \in \mathcal{N}_\mathrm{c} : (n, m) \in \mathcal{E}_\mathrm{c}\}$. We define the maximum over an empty set to be zero—that is, $\max_{i \in \emptyset}(\cdot) = 0$. With these definitions, we are ready to formulate the problem of finding a fuel optimal set of coordination leaders $\mathcal{N}_\mathrm{l}$.

Problem 1. *Given a coordination graph $\mathcal{G}_\mathrm{c} = (\mathcal{N}_\mathrm{c}, \mathcal{E}_\mathrm{c}, \Delta F)$, find a subset $\mathcal{N}_\mathrm{l} \subset \mathcal{N}_\mathrm{c}$ of nodes that maximizes $f_\mathrm{ce}(\mathcal{N}_\mathrm{l})$, where $f_\mathrm{ce}(\mathcal{N}_\mathrm{l})$ is defined as*

$$f_\mathrm{ce}(\mathcal{N}_\mathrm{l}) = \sum_{n \in \mathcal{N}_\mathrm{c} \setminus \mathcal{N}_\mathrm{l}} \max_{m \in \mathcal{N}_n^\mathrm{o} \cap \mathcal{N}_\mathrm{l}} \Delta F(n, m).$$

A coordination follower n implements the adapted plan to the best coordination leader—that is, to $\arg\max_{m \in \mathcal{N}_n^\mathrm{o} \cap \mathcal{N}_\mathrm{l}} \Delta F(n, m)$. If there is no coordination leader for a coordination follower, then

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$\mathcal{N}_n^o \cap \mathcal{N}_l = \emptyset$ and $\max_{m \in \mathcal{N}_n^o \cap \mathcal{N}_l} \Delta F(n,m) = \max_{m \in \emptyset} \Delta F(n,m) = 0$. In this case, the coordination follower does not platoon and implements its default speed profile. One coordination leader can have multiple coordination followers leading to platoons with more than two vehicles. The exact order of the platoon is left to the on-board systems to coordinate locally.

Remark 7. Realistically, there is a limit on the size of a platoon. This can be either handled by splitting up large platoons into several platoons or by putting an additional constraint on the number of a coordination followers of a coordination leader. Note, however, that the platoon size can be smaller than the number of coordination followers of a coordination leader since different coordination followers can follow the same coordination leader at different parts of its route.

The problem of finding the optimal set of coordination leaders is an NP-hard combinatorial optimization problem [52]. Therefore, we resort to heuristic algorithms to find good solutions with reasonable computational effort. We consider two heuristic solutions to Problem 1. The first approach is presented in Buchbinder et al. [10] and guarantees a (1/3)-approximation in case the problem is submodular, meaning that for every $\mathcal{N}_1 \subseteq \mathcal{N}_2 \subset \mathcal{N}_c$ and $n \in \mathcal{N}_c \setminus \mathcal{N}_2$, we have that $f_{ce}(\mathcal{N}_1 \cup n) - f_{ce}(\mathcal{N}_1) \geq f_{ce}(\mathcal{N}_2 \cup n) - f_{ce}(\mathcal{N}_2)$.

The proof that Problem 1 is submodular is omitted due to space constraints. The algorithm is shown in Algorithm 1 as pseudocode. Buchbinder et al. [10] also present a randomized version of the algorithm that is a (1/2)-approximation in expectation. Note also that $f_{ce}(\underline{\mathcal{N}}_l \cup n) - f_{ce}(\underline{\mathcal{N}}_l)$ and $f_{ce}(\overline{\mathcal{N}}_l \setminus n) - f_{ce}(\overline{\mathcal{N}}_l)$ can be computed based on the subgraph induced by the two-hop out-neighbors of n without computing f_{ce} explicitly, which can significantly improve performance.

ALGORITHM 1: One-Pass Algorithm

Input: $\mathcal{G}_c$
Output: $\underline{\mathcal{N}}_l$

```
N̲_l ← ∅, N̄_l ← N_c
for n ∈ N_c do
    a ← f_ce(N̲_l ∪ n) − f_ce(N̲_l), b ← f_ce(N̄_l \ n) − f_ce(N̄_l)
    if a ≥ b then
        N̲_l ← N̲_l ∪ n
    else
        N̄_l ← N̄_l \ n
    end if
end for
```

The second approach is a greedy algorithm, presented in pseudocode in Algorithm 2, where

$$\Delta u(n^*, \mathcal{N}_l) = \begin{cases} f_{ce}(\mathcal{N}_l \setminus \{n^*\}) - f_{ce}(\mathcal{N}_l) & \text{if } n^* \in \mathcal{N}_l \\ f_{ce}(\mathcal{N}_l \cup \{n^*\}) - f_{ce}(\mathcal{N}_l) & \text{otherwise.} \end{cases}$$

The submodular property suggests that the greedy algorithm typically works well, as the largest gains in the objective f_{ce} can be made when the set of coordination leaders $\mathcal{N}_l$ is empty. However, no guarantee on the performance can be given. Each iteration of Algorithm 2 is of comparable complexity as the iteration of Algorithm 1. Algorithm 1 deterministically executes $|\mathcal{N}_c|$ iterations, whereas Algorithm 2 can theoretically execute $2^{|\mathcal{N}_c|} - 2$ iterations. Practically, it terminates after a much smaller number of iterations. Furthermore, it is an anytime algorithm, that can be terminated after any iteration with a suboptimal solution to Problem 1. It is also possible to initialize Algorithm 2 with $\mathcal{N}_c \neq \emptyset$, coming, for instance, from a previously computed solution or a solution computed by another algorithm such as Algorithm 1.

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ALGORITHM 2: Greedy Algorithm

Input: $\mathcal{G}_c$
Output: $\mathcal{N}_l$
  $\mathcal{N}_l \leftarrow \emptyset$
  while $\{n \in \mathcal{N}_c : \Delta u(n, \mathcal{N}_l) > 0\} \neq \emptyset$ **do**
    $n^* \leftarrow \arg\max_{\{n \in \mathcal{N}_c\}} \Delta u(n, \mathcal{N}_l)$
    if $n^* \in \mathcal{N}_l$ **then**
      $\mathcal{N}_l \leftarrow \mathcal{N}_l \setminus \{n^*\}$
    else
      $\mathcal{N}_l \leftarrow \mathcal{N}_l \cup \{n^*\}$
    end if
  end while

A set of coordination leaders $\mathcal{N}_l$ directly corresponds to a platoon plan $\pi = (\mathbf{e}, \mathbf{t}, \mathbf{p})$ for each vehicle. The route is computed at the route computation and map matching stage. A coordination leader implements the default speed profile, a coordination follower the adapted speed profile to $n_l = \arg\max_{m \in \mathcal{N}_n^o \cap \mathcal{N}_l} \Delta F(n, m)$ if $\mathcal{N}_n^o \cap \mathcal{N}_l \neq \emptyset$ and the default speed profile otherwise. The platoon profile of a coordination leader $n_l \in \mathcal{N}_l$ is accordingly $\mathbf{p}_{n_l}[i] = \{n \in \mathcal{N}_{n_l}^i : n_l = \arg\max_{m \in \mathcal{N}_n^o \cap \mathcal{N}_l} \Delta F(n, m) \wedge i \in \{N_{n,n_l}^M + \Delta N_{n,n_l}, \ldots, N_{n,n_l}^{Sp} + \Delta N_{n,n_l}\}\}$. The platoon profile $\mathbf{p}$ for a coordination follower n is $\{n\}$ for $i \notin \{N_{n,m}^M, \ldots, N_{n,m}^{Sp}\}$—that is, it does not platoon, and $\mathbf{p}_{n_l}[i + \Delta N_{n,n_l}]$ for $i \in \{N_{n,m}^M, \ldots, N_{n,m}^{Sp}\}$. At this point, the platoon plans are communicated back to the respective FMS and from there to the vehicles' on-board systems. The on-board systems track the time profile using a local controller that sets reference speeds to an adaptive cruise controller.

3.6 Assignment Update

The platoon plans are repeatedly updated while the vehicle is driving. A vehicle that follows a time profile is subject to disturbances. Those disturbances are hard to predict and to compensate for on vehicle level. They originate primarily from surrounding traffic but also from toll gates, incorrect estimation of the vehicle's acceleration capabilities, weather conditions, and so forth. Furthermore, the information used to compute the maximum speed profile $\bar{\mathbf{v}}$ can change while the system is running, for instance, as new real-time traffic data become available. New assignments are added to the system, and assignments are updated or even canceled.

This is handled by updating active assignments on a regular basis based on their current geographic position measured primarily though a satellite-based positioning system such as GPS or GLONASS. This position is matched to the vehicle's route $\mathbf{e}$, which is computed when the assignment is registered at the platoon coordinator. In case the vehicle deviates from the route or the route is no longer feasible, for instance, due to a traffic incident, a new route is computed; otherwise, the old one is kept. Based on the current speed profile, the arrival time at the beginning of the next edge is computed and taken as the new start time t^S of the assignment as illustrated in Figure 9. The next edge becomes the new start position $\mathcal{P}^S$ of the assignment. All other data in the assignment $\mathcal{A} = (\mathcal{P}^S, \mathcal{P}^D, t^S, t^D, \mathcal{D})$ remain the same. Like this, the updated assignment can be handled by the other modules in almost the same way as new assignments. What changes is that the start time $\mathbf{t}[1]$ can no longer be adjusted and the current platoon status can be taken into account when computing adapted plans in the sense that no merge penalty for vehicles in the current platoon is used when computing the fuel saved ΔF.

Remark 8. Although updated assignments can be handled in the same way as new assignments are handled, it is computationally more efficient to cache some of the information. For instance,

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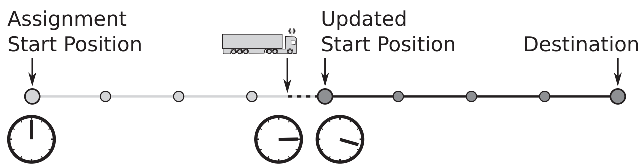

Fig. 9. At an update of plans, the beginning of the next road segment in the vehicle's route becomes the new start position and the predicted arrival time at that segment the new start time.

the information that assignments have a common part in their routes changes only when new routes are computed and the greedy algorithm (Algorithm 2) can be initialized with the set of coordination leaders $\mathcal{N}_l$ computed in the previous update minus the vehicles that have reached their destinations.

4 SIMULATION STUDY

This section presents simulation results with more than 3,000 active vehicles in the German road network. The influence of several design parameters and disturbances on the proposed coordinated platooning system is tested. The simulations focus on the behavior on a strategic level.

4.1 Scenario Description

Different scenarios are created to test the coordinated platooning system. A scenario consists of assignments, design parameters, and disturbances. To generate assignments, pairs of start and goal locations are sampled randomly from a population density map in the geographic area of Germany shown in Figure 10. For each pair, a route is computed based on Openstreetmap data for the German road network as a way to mimic the characteristics of real-world traffic patterns. Only roads labeled "motorway," "trunk," "primary," and "secondary," as well as the corresponding links, are used, with a strong speed penalty on roads classified as secondary. Part of the route at the beginning and the end consisting of road segments labeled as primary and secondary are removed. This is to take into account that platooning is likely to be limited to such roads. Assignments with less than 80 km traveled distance are rejected, and a random subroute of 360 km is selected for assignments longer than 360 km. This models that a driver has to rest after 4.5 hours of driving. The continuation of such a trip after a rest period would be registered by the FMS as a new assignment. The start of the subroute is then used as the start location $\mathcal{P}^{\mathrm{S}}$ and the end as the destination $\mathcal{P}^{\mathrm{D}}$. Start times t^{S} are sampled uniformly over an interval of 20 hours to study the steady state behavior of the system. Deadlines t^{D} are computed assuming a fixed speed of 80 km/h.

We consider that the maximum speed profile is $\bar{v} \equiv 90\,\mathrm{km/h}$. Default plans are computed according to Definition 1 with $\sigma_{\mathrm{d}} = 8/9$ (i.e., the default speed is 80 km/h). Adapted speed profiles are computed according to Definition 1 and in a way that the platooning distance is maximized, with $\underline{\sigma} = 7/9$ (i.e., the minimum speed during the merge phase is 70 km/h). These are typical speeds of heavy vehicles on European overland routes. No adaptation of the start time is considered. Platoon plans are updated at a regular interval of T_{upd}. The first time an assignment is considered in the planning process is at $t^{\mathrm{S}} - T_{\mathrm{hor}}$, where t^{S} is the assignments start time and T_{hor} is a design parameter that we refer to as the preview horizon. Should no plan be computed before the vehicle starts, the vehicle follows the default plan until the next update. The model for the fuel consumption estimation is a nonlinear analytical fuel model used in Besselink et al. [4]. It is plotted in Figure 8. It gives a fuel consumption reduction of 12% at 80 km/h for each trailing vehicle in the platoon compared to traveling alone, assuming a 33% air-drag reduction for a fully loaded trailing

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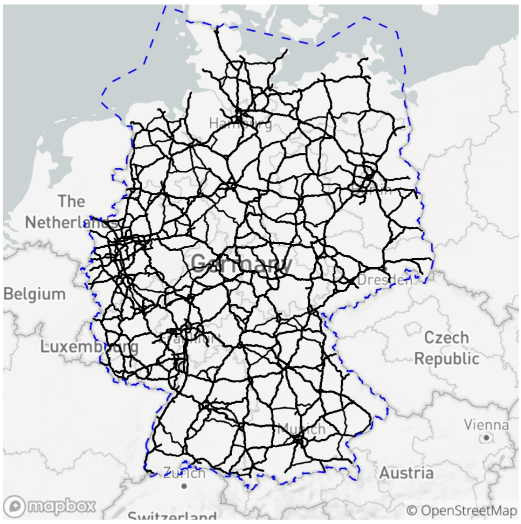

Fig. 10. The routes used are shown as black lines. The area considered for the road network and for assignment generation is indicated with a dashed blue line.

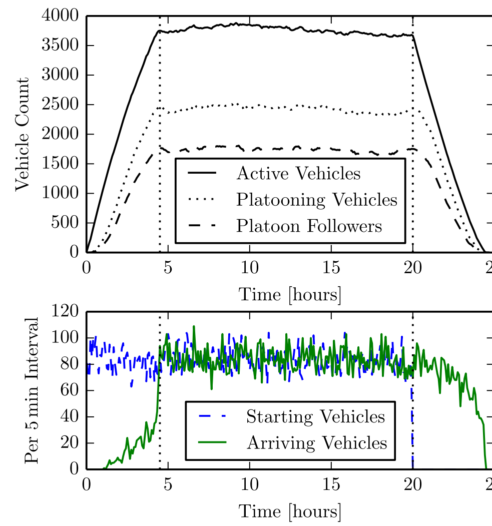

Fig. 11. The upper plot shows the number of active vehicles, the number of vehicles in a platoon, and the number of platoon followers. The lower plot shows the number of starting and arriving vehicles per 5-minute intervals. Results are evaluated in the time window indicated by the dotted vertical lines.

vehicle. For the selection of coordination leaders, the greedy algorithm (Algorithm 2) is used and initialized with coordination leaders from the previous iteration.

There are two mechanisms to model disturbances. The first mechanism is to reduce the maximum speed to a value between 80 km/h and 90 km/h. A platoon merge is considered to succeed if the difference in arrival time at the planned merge location is less than 0.5 km/80 km/h = 22.5 seconds. This mechanism is intended to simulate smaller disturbances coming from traffic, incorrect information of the vehicles performance, and so forth. The other mechanism is that some vehicles end their trips before reaching the destination. This is to model that vehicles actually stop due to unexpected breaks by the driver or technical issues, but also that the vehicle could get stuck in a severe traffic jam.

4.2 Simulation Results

Figure 11 shows the number of active vehicles over time for 20,000 vehicles starting over the course of 20 hours. In this scenario, $T_{\text{upd}} = 5$ minues, $T_{\text{hor}} = 0$ minutes, and no disturbances are added. Since assignments have maximum duration $t^{\text{D}} - t^{\text{S}}$ of 4.5 hours, the number of active vehicles converges after 4.5 hours to approximately 3,800 with some small fluctuations around that value. After 20 hours, no more vehicles start, and the number of vehicles declines to zero. The total simulated distance driven is 4,695,658 km, which is approximately 13% of the average daily distance traveled by road freight vehicles on inner German trips of more than 150 km distance [27]. Thus, the simulated amount of coordinated heavy-duty vehicle traffic is in the right order of magnitude for the road network considered. The average distance of a route in the simulation is 234 km. Between 4.5 and 20 hours, the number of platooning vehicles and the number platoon followers is almost constant and follows the trend in the number of active vehicles.

Table 1. Aggregated Simulation Results from Different Scenarios

Scenario	T_{upd}[min]	T_{hor}[min]	N_{sim}	ΔF_{sim} [%]	P_{plf} [%]	P_{pla} [%]	P_{del} [%]
Spontaneous	5	0	20,000	1.41	11.82	22.11	0.00
Regular 1	5	0	20,000	5.09	46.87	65.23	0.00
Regular 2	30	0	20,000	4.76	43.93	61.39	0.00
Regular 3	60	0	20,000	4.35	40.25	56.66	0.00
Regular 4	300	0	20,000	1.73	15.99	23.68	0.00
Regular 5	5	10	20,000	5.21	47.88	66.61	0.00
Regular 6	5	30	20,000	5.26	48.27	67.51	0.00
Regular 7	5	60	20,000	5.27	48.20	67.52	0.00
Regular 8	60	60	20,000	5.25	48.12	67.04	0.00
Regular 9	300	300	20,000	5.09	46.36	64.71	0.00
Batch	—	—	20,000	5.05	45.85	63.88	0.00
Deadline	5	0	20,000	7.01	41.83	55.03	0.00
Simple F.M.	5	0	20,000	4.52	47.62	64.00	0.00
Deadl. Simple F.M.	5	0	20,000	5.84	49.20	64.21	0.00
Dropout 20%	5	0	20,000	4.83	44.43	62.67	0.00
Dropout 50% 1	5	0	20,000	4.40	40.40	58.19	0.00
Dropout 50% 2	60	60	20,000	4.44	40.76	59.09	0.00
Dropout 50% 3	300	300	20,000	3.95	36.23	53.45	0.00
Max. Speed 20%	5	0	20,000	4.96	45.21	63.39	5.72
Max. Speed 50% 1	5	0	20,000	4.74	42.70	60.61	14.41
Max. Sp. 50% Plan.	5	0	20,000	4.82	43.62	63.05	0.00
Max Speed 50% 2	60	60	20,000	4.77	42.75	61.62	14.49
Max Speed 50% 3	300	300	20,000	4.59	40.87	59.20	13.65
Spontaneous 1,000	5	0	1,000	0.07	0.60	1.20	0.00
Regular 1,000	5	0	1,000	1.03	10.49	19.93	0.00
Spontaneous 5,000	5	0	5,000	0.40	3.35	6.59	0.00
Regular 5,000	5	0	5,000	3.10	29.82	48.46	0.00
Spontaneous 10,000	5	0	10,000	0.79	6.61	12.80	0.00
Regular 10,000	5	0	10,000	4.02	37.79	57.11	0.00

Table 1 shows the results from the different simulations scenarios. The number of simulated assignments is denoted as N_{sim}. Four statistics are computed for each scenario in the time window of 4.5 to 20 hours: the reduction of fuel consumption compared each vehicle driving the simulated distance alone at a of speed of 80 km/h, denoted as ΔF_{sim}; the percentage of distance driven as platoon follower as P_{plf}; the percentage of distance driven in a platoon as P_{pla}; and the percentage of assignments that get delayed as P_{del}. For all groups of scenarios with the same number of assignments, the start times and routes are the same. In the following, we discuss the scenarios in detail:

- **Spontaneous:** This serves as a baseline scenario approximating fuel savings that can be obtained with local coordination, so-called spontaneous platooning. It is computed by rejecting all adapted plans that deviate from the default plan more than 0.5 km/80 km/h = 22.5 seconds, corresponding to an inter-vehicle distance of 500 m at 80 km/h.
- **Regular 1–9, Batch:** These scenarios differ in their values for the update interval T_{upd} and the preview horizon T_{hor}. In the "Batch," all plans are computed at once. We can see

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that more frequent plan updates and longer horizons lead to improved platooning benefits and higher platoon percentage. It is remarkable that "Regular 1" with no preview horizon outperforms the "Batch" scenario. The interpretation is that the when plans are updated, a vehicle can be assigned to another platoon overcoming the limitation that an adapted plan can only adapt to one coordination leader. It also happens that a coordination leader and follower swap roles in an update so that both vehicles adapt.

- **Deadline, Simple F.M., Deadl. Simple F.M.:** For "Simple F.M.," the platoon planner uses a simple fuel model that does not take speed into account and assumes a fuel saving of 10% when platooning. It performs slightly worse than the regular fuel model highlighting the importance for accurate fuel consumption estimation. In the scenario "Deadline," all deadlines are extended by half an hour. This gives much larger fuel savings than the "Regular 1" scenario but less distance platooned. In "Deadl. Simple F.M.," the simple fuel model is used and more distance is traveled in platoons. This indicates that the platoon coordinator selects plans with a long merge phase at low speed and hence low fuel consumption in the "Deadline" scenario. Recall that default plans have a minimum speed of 80 km/h, whereas the speed during the merge phase is allowed to drop to 70 km/h. In "Deadl. Simple F.M.," the distance traveled as platoon follower is slightly higher, whereas the distance traveled in a platoon is slightly less than in "Regular 1," which means that the increased flexibility is used to create larger platoons and save more fuel.
- **Dropout 20%, Dropout 50% 1–3:** In "Dropout 20%" and "Dropout 50% 1–3," 20% and 50% of the vehicles, respectively, end their trip at a random point on the route not known to the platoon coordinator, simulating unexpected events. Clearly, this negatively affects the fuel consumption reduction, although not dramatically. It also highlights the need for feedback. Whereas "Regular 1" and "Regular 9" lead to approximately the same ΔF_{sim}, "Dropout 50% 1" performs better than "Dropout 50% 3," as the platoon coordinator can react to new situations.
- **Max. Speed 20%, Max. Speed 50% Plan., Max. Speed 50% 1–3:** In these scenarios, the maximum speed of 20% and 50% of the vehicles is reduced to a value between 80 km/h and 90 km/h, which is sampled randomly for each vehicle. These disturbances lead to a mild reduction in fuel savings compared to the corresponding disturbance-free "Regular" scenarios. In the scenario "Max. Speed 50% Plan.," the true maximum speed of the vehicle is considered in the plan computation, which can partially compensate for the disturbance effects. A full compensation is not possible because the ability of vehicles to catch up to platoon partners is reduced. When the disturbance is not known to the platoon coordinator, some vehicles miss the deadline because a higher speed during the last part of the adapted plan is assumed than what is actually possible.
- **Regular {1,000, 5,000, 10,000}, Spontaneous {1,000, 5,000, 10,000}:** These are scenarios with different numbers of assignments. Not surprisingly, the fuel savings from platooning increase with more assignments as there are more platoon opportunities. However, this value saturates, as it is theoretically limited by the fuel consumption reduction of the trailing vehicle in the platoon. We can also notice that the coordination significantly improves the fuel savings from platooning even for a small number of assignments.

The simulations indicate that the proposed coordinated platooning system has the potential to make efficient use of platooning. It improves significantly compared to the case where platooning technology is used only with local coordination. By updating plans frequently, the system can efficiently coordinate platooning with a short preview horizon and under the presence of disturbances.

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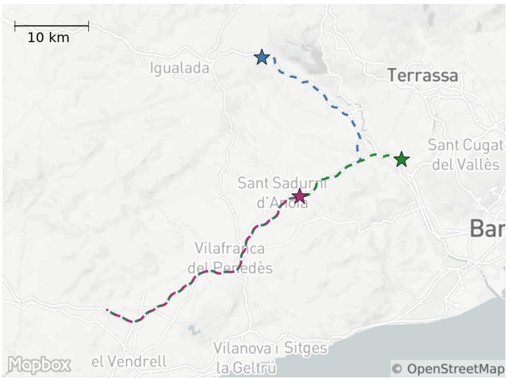

Fig. 12. Overview of the routes driven during the experiment. Stars mark the starting point of vehicles. The destination is the same for all three vehicles and located on the lower left of the map.

Fig. 13. View from the cockpit of the green vehicle while trailing the blue vehicle in the platoon. The on-board HMI can be seen in the dashboard. The computer on right side of the image is used to monitor and collect data from the on-board system.

5 EXPERIMENTAL EVALUATION

In the scope of the COMPANION European research project [15], a demonstrator was developed, which can coordinate test vehicles on public roads. It implements the strategic, tactical, and operational layer as introduced in Section 2. We present experimental results that demonstrate the feasibility of the proposed coordination system under realistic conditions.

5.1 Experiment Scenario

The experiment was conducted on public motorways in Spain west of Barcelona in September 2016. Figure 12 shows a map with routes and the start positions of the assignments. It involved three tractor trailer combinations (Figure 13) equipped with a custom on-board system, on-board human-machine interface [42], and vehicle-to-vehicle and vehicle-to-infrastructure (mobile broadband) communication capabilities. All three vehicles started at different positions close to motorways and were given the same destination and the same arrival deadline. The initial start times were determined by the coordinator as part of the initial plan computation. The flexibility of freely adjusting the start time was necessary to create a situation where platooning would occur with only three vehicles. Since platooning capabilities are currently only present on a few test vehicles, experiments with larger numbers of vehicles are not feasible. The experiment took place in regular traffic around 10 a.m. on a weekday, that is, under realistic conditions. The off-board system was running on multiple cloud computing instances.

5.2 Experimental Results

The initially computed plans entailed that the first two vehicles, whose data are shown in blue and green in the figures, would merge at the motorway intersection depicted in Figure 14(a) and platoon until their destinations. On the way, the first two vehicles would pass the start location of the third vehicle, whose data are shown in purple in the figures. In the following, we refer to the vehicle as the blue, green, and purple vehicle according to the color used in the plots. The purple vehicle would join the platoon at that point shown in Figure 14(b). Figure 15 shows the distance driven over time with a common reference on the overlapping part of the route. We can see that due to the alignment of the start times, no planned adaptation prior to the merge points had to be

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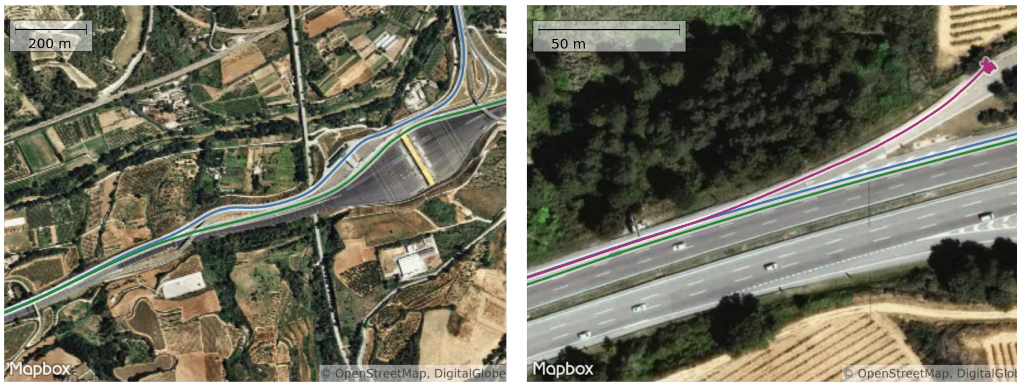

(a) At the first merge point, both vehicles first have to pass a road toll booth before merging onto the same road in the lower left of the image.

(b) At the second merge point, the starting position of the red vehicle is located on the upper right of the image on a parking lot next to the highway.

Fig. 14. Aerial photography of the two merge points with the GPS traces of the first two vehicles.

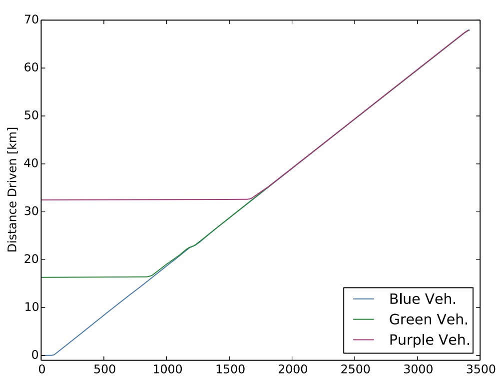

Fig. 15. The distance driven along the vehicles' routes. The starting distance was adjusted in a way that two vehicles at the same location on the common section of the route have the same driven distance.

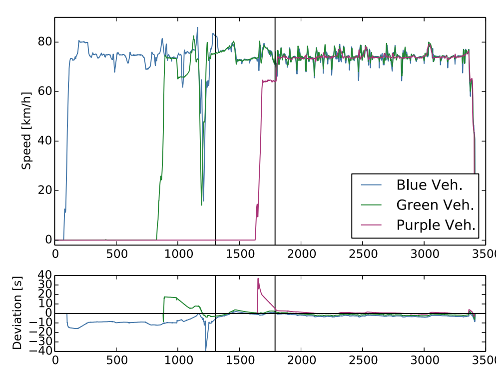

Fig. 16. The measured speed and measured deviation from the plan of all three vehicles. The actual merge times according to the on-board system are indicated as vertical black lines.

done. We also see that the relative distances of the vehicles in a platoon are very small compared to the total distance driven, which supports the assumption made in the planning that vehicles are at the same position when they platoon.

Figure 16 shows speed measured by the GPS receivers, the merge times according to the on-board system, and the deviation from the latest computed plan by the off-board system. New plans were computed only when a vehicle exceeded a deviation of 30 seconds. We can see that the blue vehicle starts approximately 15 seconds too late and the second vehicle approximately 17 seconds too early. This is partly because the starting point was on the motorway due to restrictions in the routing module, and the off-board plan neglects the initial acceleration phase of the vehicle. However, also in a setting where the vehicle is operated by a human driver, such small deviations in the planned starting time are likely to occur. Both vehicles' on-board controllers manage to reduce the deviation considerably during their journey. The large spike in the deviation of the

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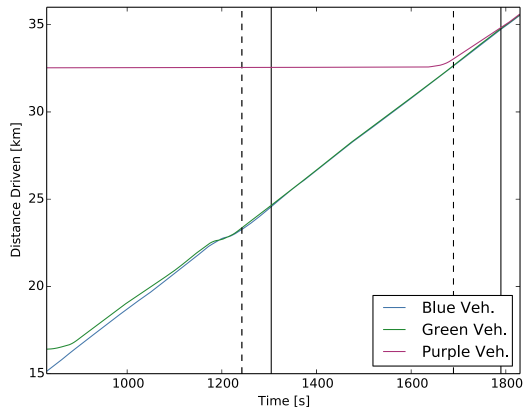

Fig. 17. Zoom into Figure 15. Additionally, the planned merge times are indicated with dashed black vertical lines, and the actual merge locations according to the on-board system are indicated with vertical black lines.

blue vehicle at 1,125 seconds is a glitch in the deviation computation of the on-board system and triggered a recomputation of the plans. The purple vehicle starts 36 seconds too early. This was done intentionally since the second merge point shown in Figure 14 has no acceleration lane, and the back-end plan did not consider the initial acceleration phase needed. Furthermore, the driver has to wait for a gap in the stream of traffic to be able to enter the highway without an acceleration lane. Normally, this would be resolved by the platoon coordinator updating the plans; however, due to the small number of test vehicles in the demonstration and the short distance driven after that point, this was handled by starting ahead of time and then having the on-board controller lower the vehicle speed compared to the plan. Finally, one can notice the strong occasional variations in speed in the second half of the experiment when all three vehicles are platooning. This was due to a minor time synchronization problem that sometimes triggered the platoon controller to increase the headway as a safety precaution. Since the purpose of the demonstration was the coordinated formation of platoons, this was not considered to be a problem in the experiment.

Figure 17 shows a detail of Figure 15. Additionally, the planned and the actual merge times are indicated. We can see that in both cases, the vehicles merge a little later than planned. The second merge happens later than expected since the vehicle has to start ahead of time, as discussed previously, and then has to wait for the other two vehicles by driving slower than what was planned. For the first merge, the blue vehicle gets delayed due to incorrect information on the speed restriction after the toll booth. It seems that this was caused by a wrong association of the current segment. This error would also explain the incorrect computation of the deviation. Figure 18 shows more detail at this point. Already when arriving at the toll booth, it is slightly delayed. After passing the toll booth, where the speed dips below 20 km/h, the back-end plan used the average speed driven by probe vehicles at this point while the on-board system recommended the maximum speed according to the incorrect legal speed limit of 30 km/h indicated in the map. Since the speed was controlled manually at this point passing the toll booth, the driver kept a low speed of 65 km/h. This speed was higher than the recommended 30 km/h to be safe in traffic, but it was lower than the one in the platoon plan. Therefore, the vehicle got delayed and had to catch up to the blue vehicle. Furthermore, it is clearly challenging to accurately predict the speed profile at a toll booth due to merging zones and possible waiting times highlighting the need for real-time feedback.

Another aspect that can be seen in Figure 18 is the update of plans in case of deviations larger than 30 seconds. The real deviation at this point would actually not be large enough to trigger

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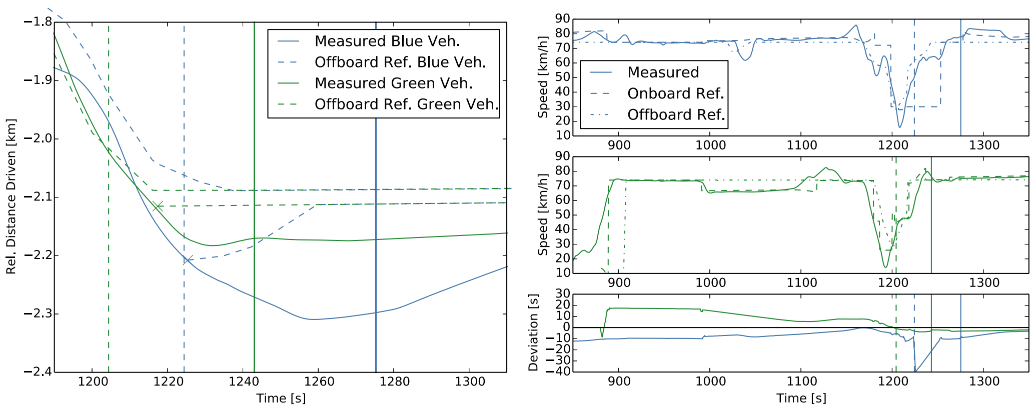

Fig. 18. The first merge. The left plot shows the distance driven relative to a vehicle that would drive from time 0 with speed 74 km/h and is otherwise similar to Figure 15. The data is shown relative to a virtual vehicle for visual presentation reasons only. Additionally, the planned distance driven is shown with dashed lines for the original plan and the first update. The first data points of the update are marked with crosses. The two plots on the upper right show the measured speed, the on-board speed reference, and the speed reference according to the plan computed by the back-end system. The plot on the lower right shows the measured deviation from the plan. In all four plots, the vertical dashed lines indicate when the latest position was sent that was used in the replanning. The solid vertical lines indicate when the new plan was received on the respective vehicle. Note that the time scale of the left plot is different from the others.

an update, but due to the error in the computation of the deviation, it exceeds the threshold for a short time. The time at which the deviation message and the vehicle position is sent is indicated in the plot by a vertical dashed line. The latest position update used in the new plan of the green vehicle is indicated with a green dashed vertical line. We can see that the planner assumes that the reported speed is kept until the beginning of the next segment, which becomes the first segment of the vehicle's route in the new plan. The computed plan assigns the green vehicle to be coordination leader and to follow a default speed profile to arrive at the destination in time. The blue vehicle gets the role of coordination follower and is supposed to select a higher speed to catch up with the green one. However, as indicated by the solid vertical lines, the blue vehicle receives the plan after this catch-up phase due to delays in the computation and communication. Therefore, the updated plan does not have any effect, and the merge is facilitated by the on-board controller.

Figure 18 shows also how the on-board controller compensates for small deviations from the reference plan. The reference speed can be adjusted with up to ±9 km/h, which proves sufficient to track the computed plans in the experiment.

5.3 Conclusions from the Experiment

We can conclude from this experiment that coordinated en route formation of vehicle platoons is feasible under realistic conditions. In addition to the experiment discussed in this section, several test runs in Sweden and Spain have been made, which suggest that the successful formation of platoons was not just a lucky coincidence. This complements the simulation results from Section 4, which features a large number of vehicles at the expense of modeling less detail on the lower control layers, which is fully present in the experimental results.

The results also show that further research is needed on how much and what kind of data should be considered in the planning process. Doing a more detailed planning can be quite challenging, particularly when it comes to considering the vehicle dynamics that depend on the vehicle's trailer,

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load, and engine characteristics, among others, and when influence of traffic should be taken into account. During a test run, a plan contained a segment with very low speed that was due to a traffic jam that was dissolved only shortly before the vehicle passed that area without being detected in time by the traffic information system. The system recommended this low speed, which had to be overwritten by the driver to maintain traffic safety. Even static map data such as the legal speed limit can change with time and can thus be sometimes outdated. The alternative is to rely more on the ability to dynamically react to disturbances by means of real-time feedback from the vehicles.

It should also be mentioned that the nominal speed of the vehicles in the experiment was 16.7% lower than the maximum speed, giving them the ability to both speed up and slow down to adjust their timing. When a coordinated platooning system will be used commercially in the future, the default speed might be closer to the maximum, which means that adjustments are mainly made by reducing the speed. This puts even more importance on the ability of the platooning systems ability to adapt and reconfigure plans across multiple vehicles since a vehicle that gets delayed cannot simply compensate by increasing its speed.

6 CONCLUSIONS AND FUTURE WORK

In this article, we present a framework for coordinating the en route formation of platoons. The central component is a platoon coordinator, which interfaces with FMS and computes time profiles that facilitate the fuel-efficient formation of heavy-duty vehicle platoons across multiple transport operators. The platoon coordinator receives assignments from the various FMS and computes in several steps the routes, time profiles, and platoon configurations that are conveyed to the FMS, which pass them on to the vehicles, which in turn execute them. Information is collected from static map data, traffic measurements, and weather data to compute accurate time profiles. The plan computation is a challenging problem, and heuristic methods are devised to efficiently compute plans for a large number of vehicles. Plans are periodically updated to account for disturbances and to accommodate new assignments. Simulations show that such a system has the potential to achieve significant fuel savings. Experiments with a demonstrator indicate that this approach is feasible under real-world conditions.

Despite the promising results we obtained, the development of the demonstrator and the experiments also revealed that there are some aspects that need further study before such a system can be deployed commercially. The experiments show that with the current technology, significant communication delays can occur and should be compensated for. An important aspect is the standardization of platooning technology to enable platooning between vehicles of various types and from different manufacturers and operators. Many aspects of the system are yet to be fine-tuned. To this end, simulations present an important tool. Tests with real vehicles are very expensive and therefore are not feasible at full scale. Developing appropriate simulations is a challenging task due to the large spatial and temporal scale. One particularly challenging area is taking into account surrounding traffic. Here, the coordinated vehicles could serve as probes, and better strategies could potentially be devised based on the available data once such systems are operational. More work is needed to integrate different data sources, such as traffic measurements, historic probe data, and weather measurements, into an appropriate traffic model for platoon coordination. This way, platoons can be formed reliably and fuel efficiently without compromising the average speed of the coordinated vehicle and the surrounding traffic.

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