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Networked control challenges in collaborative road freight transport

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ABSTRACT

Freight transport is of major importance for the European economy and is growing thanks to increasing global trade. About three quarters of inland freight transport in the European Union is on roads. It has the potential to go through a dramatic change over the next decades thanks to the recent development of technologies such as wireless communication, cloud computing, sensor devices, and vehicle electronics. They enable a new integrated goods transport system based on optimized logistics, real-time traffic information, vehicular communications, collaborative driving, and autonomous vehicles. In this paper, we discuss challenges in creating a more efficient and sustainable goods road transportation system and how some of them can be tackled with a networked control approach. In particular, we discuss a method to improve the efficiency of the transportation system by minimizing the number of empty transports needed to fulfill the assignments on a given road network. Assignments with overlapping route segments might lead to further improvements, as the formation of vehicle platoons yields reduced fuel consumption. For realistic scenarios, it is shown that such collaboration opportunities arise already with relatively few vehicles. The fuel-efficient formation and control of platoons is also discussed. Some of the presented methods have been tested on real vehicles in traffic. The paper shows experimental results on automatic formation of vehicle platoons on a Swedish highway. The influence of traffic density on the merge maneuver is illustrated. The results indicate that platoon coordination could be improved by support from appropriate traffic monitoring technologies.

1. Introduction

The need for mobility services is steadily growing and tightly linked to economic development. The transport system supports the local, regional, and global movement of people and goods, but the transportation sector is also responsible for a major part of the world's energy consumption and emissions [35]. In the European Union (EU) road transportation amounts for about a quarter of the total energy consumption and a sixth of all greenhouse gas emissions [13]. For another estimate of the importance of the road transport sector, recall that goods transport in the EU amounts to 3.5 trillion tonne-km per year and that 3 million people are employed in this sector, whereas people transport amounts to 6.5 trillion passenger-km and 2 million employees [13]. With increased specialization and globalization, freight transport is an ever more essential part of the manufacturing value chain. There is thus a strong social and economic motivation for developing a more sustainable and fuel-efficient freight transportation sector.

A rapid technical development has enabled self-driving vehicles, fuel-optimized cruise-controllers, and cooperative driving capabilities. We are on the cusp of a new era with major advances being introduced into the market and society over the next couple of decades. For example, vehicular communications [40,21] enable a large set of new applications, such as collision warning and avoidance [39], automated intersections [11], and vehicle platooning [24,2]. Vehicular position and velocity data are readily available today [16]. For freight transportation, such data can be combined with advanced vehicle models to make decisions on fuel-optimal routes. Transport systems spanning over large geographic areas with real-time data gathering can be used for increased efficiency and flexibility in the planning of transport assignments.

The development of a new freight transport system architecture based on these emerging technologies poses several obstacles. One challenge is simply the overall scale of the system: in the EU there are about 2 million heavy trucks[1] [3], the

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[1] A heavy truck has a maximum loaded weight of more than 16 tonnes and is mainly used for transportation over long distances.

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motorway network is about 73 000 km [13], and there are many fleet owners, drivers, and customers involved. Another challenge is the legacy of the system, as only a small percentage of the vehicles is renewed every year and the road infrastructure sees few and often very costly updates. Over the last twenty years, several ambitious proposals on how to build automated highway systems have been presented [47,37,18,43]. The focus of these proposals is on improving traffic flow on highways by automated vehicles and real-time controlled road networks [4]. For freight transport systems, it is argued in [9] (see also [29]) that the planning needs to be done on three decision levels: strategic long term planning at the highest level that requires large capital investments, tactical medium term planning aiming at rational resource allocation, and operational short term planning by local management. The control problems discussed in this paper are mainly on the efficiency and integration of the lower two decision levels, but they might have implications also on the strategic level.

The main contribution of this paper is to present control challenges in a future freight transportation system that targets the large-scale optimization of vehicle fleets in order to increase transportation efficiency through collaboration, as sketched in Fig. 1. For this system, networked control problems ranging from efficient utilization of the vehicle fleet to fuel-efficient formation and operation of vehicle platoons are discussed.

In particular, we start by discussing the efficiency of the transportation system based on the number of empty vehicle movements that are needed to fulfill all transport assignments in a given geographic area. Namely, studies have estimated that up to 40% of both the total traveled distance and the cost in various transportation systems are due to empty vehicles [12]. Even though the optimization of fleet management systems is actively pursued [10], the resulting optimization problems are generally of high complexity. We instead present an approach for the minimization of the traveled distance of empty vehicles by solving an optimal allocation problem to link vacant vehicles to available transport assignments. Herein, the allocation problem is cast as a network flow problem. A further efficiency improvement is targeted by finding transport assignments with (partially) overlapping routes. Namely, on such overlapping parts, vehicles with potentially different transport assignments have the opportunity to form a closely spaced group known as a platoon, see Fig. 2. This leads to a reduced aerodynamic drag and fuel savings of up to 10% [2,8]. For large vehicle fleets and large numbers of transport assignments, finding collaboration opportunities is a challenging task due to its combinatorial nature. Some approaches are given in [30,48]. In this paper, we propose a computationally efficient approach for obtaining a set of collaboration opportunities. At this point, we stress that the improvements in efficiency obtained by minimizing empty vehicle transports and finding collaboration opportunities increase dramatically as larger vehicle fleets are considered. As such, this provides a clear motivation for increased collaboration within the road freight transportation sector.

An identified collaboration opportunity guarantees that a platoon can be created, but doing so is not necessarily the most fuel-efficient way to execute the associated transport assignments. To decide whether to form a platoon, we discuss a method for computing fuel-optimal platoon formation maneuvers and the associated cost will be compared to the case of each vehicle operating on its own. Besides providing a basis for decision making, this approach also specifies the desired merging maneuver in case a platoon needs to be formed. However, the density of the surrounding traffic has a large influence on the duration of the merging maneuver and we provide an approach to quantify this effect. Next, we present a control architecture that encompasses the tasks of fleet management, platoon coordination, and vehicle control, see also [7]. As such, an integrated approach for the optimization of the road freight transportation system is developed taking into account the platooning decision, the real-time formation of the platoon, and the regulation of the inter-vehicle distances in the platoon.

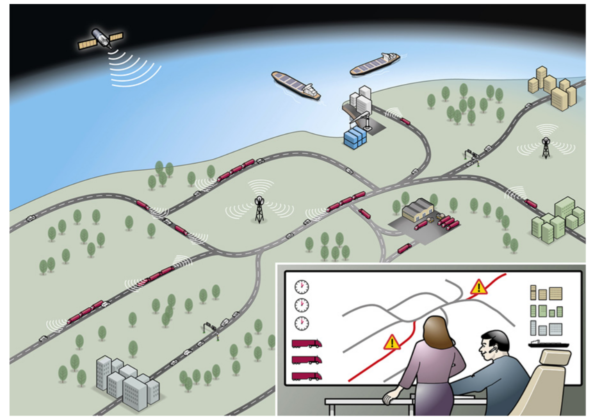


Fig. 1. Illustration of a future freight transport system with large-scale optimization of vehicle fleets and platoons.

Fig. 2. A platoon of five trucks driving close together to save fuel.

Finally, we present experimental results on trucks performing merging maneuvers on a public highway under varying traffic conditions. These results confirm the influence of traffic density on the duration of the merging maneuvers and indicate that traffic conditions need to be taken into account for the accurate prediction and control of merging maneuvers for platoon formation.

The outline of the paper is as follows. Section 2 discusses transport efficiency, in particular, the problem of minimizing the number of empty transports. Opportunities for vehicles to cooperate are investigated in Section 3, where transport assignments with partially overlapping routes and compatible timing are computed. When such opportunities are found, platoons can be formed using the fuel-optimal control formulation of Section 4. The coordination of the platoons and the regulation of the inter-vehicle distances are described in Section 5. Experimental results illustrating how to form vehicle platoons in real traffic are presented in Section 6. The paper is concluded in Section 7.

2. Transportation efficiency

In this section, the problem of minimizing the number of empty transports is considered in a collaborative setting. To this end, a transportation flow formulation is utilized.

2.1. The transportation flow problem

The road transportation sector relies on a fleet of vehicles to fulfill their transport assignments, i.e., the tasks of transporting freight from one location to another. The allocation of the available

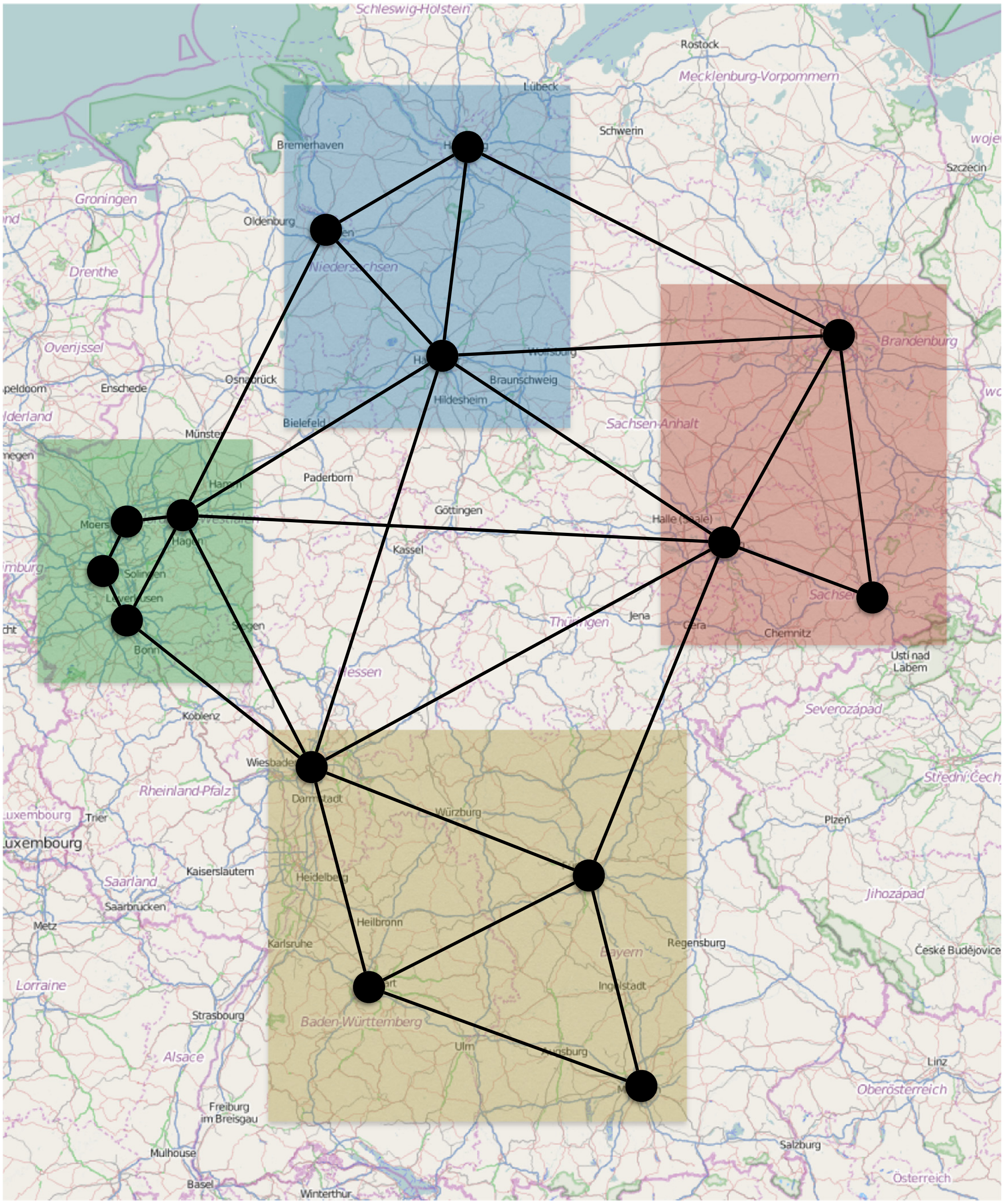


Fig. 3. The road network between Germany's 14 largest cities represented as a graph. The cities are also grouped into four geographical regions. (Map courtesy of OpenStreetMap.)

vehicles to the transport assignments is a significant challenge. In this section we target the empty vehicle problem, which aims to minimize the traveled distance of empty vehicles by exploiting collaboration while satisfying the transport assignments. This optimization is based on an efficiency measure introduced in [42], which characterizes the maximum number of empty vehicles that could be removed from a transportation system. First, the static allocation problem is discussed. Then, a time-slotted multi-day scenario will be considered.

The transportation system is modeled as a directed graph $\mathcal{G}=(\mathcal{N},\mathcal{E})$, where $\mathcal{N}$ is the set of junctions (nodes), and $\mathcal{E}\subset\mathcal{N}\times\mathcal{N}$ is the set of road segments (directed edges) connecting the junctions. A vehicle driving on the roads is represented by a path in the graph. A weight $w:\mathcal{E}\rightarrow\mathbb{R}_+$ is associated with each edge $(i,j)\in\mathcal{E}$ in the graph, representing the cost (for example in terms of distance, fuel or time) for traveling across the edge. Let a_i be the available number of empty vehicles at node $i\in\mathcal{N}$, and let d_i be the number of vehicles demanded at node $i\in\mathcal{N}$ to fulfill the transportation assignments originating from that node. The node supply of vehicles is then defined as $b_i=a_i-d_i$ for all $i\in\mathcal{N}$.

The empty vehicle problem now amounts to minimizing the total cost of allocating the empty vehicles to the transport assignments. Here, it is assumed that the total number of available (empty) vehicles is equal to the total number of assignments, i.e., $\sum_{i\in\mathcal{N}} b_i=0$. This optimal allocation problem can be cast as a network flow problem, which describes the movement of vehicles through the network. To this end, for each edge $(i,j)\in\mathcal{E}$, we associate the transportation flow $f:\mathcal{E}\rightarrow\mathbb{R}_+$, describing the

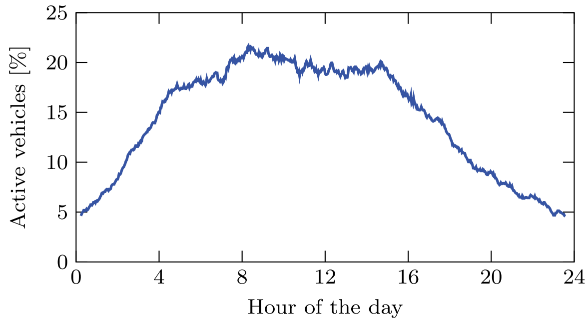


Fig. 4. The proportion of actively moving vehicles during 24 h. Data from Scania's fleet management system [26].

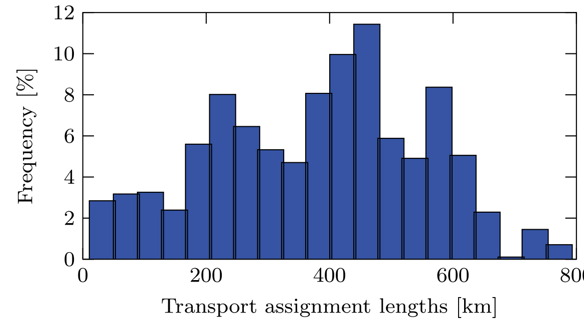


Fig. 5. The length distribution of the transportation assignments in the collaborative freight simulation.

number of (empty) vehicles traveling over that edge. Let us recall the single commodity minimum cost flow problem formulation [1], which can be stated as

$$\begin{aligned} \min_{f} \quad & \sum_{(i,j) \in \mathcal{E}} w(i,j) f(i,j) \\ \text{s.t.} \quad & 0 \le f(i,j) \le c(i,j), \quad \forall (i,j) \in \mathcal{E}, \\ & \sum_{j,\,(i,j) \in \mathcal{E}} f(i,j) - \sum_{j,\,(j,i) \in \mathcal{E}} f(j,i) = b_i, \quad \forall i \in \mathcal{N}, \end{aligned}$$

where $c(i,j) \in \mathbb{R}_+$ is the edge capacity. Assuming that a feasible solution exists, the network flow with minimal cost solves the empty vehicle problem. In fact, the minimum cost flow solution determines the optimal allocation of the empty vehicles, and this method will now be used to study different collaboration scenarios.

2.2. Collaboration efficiency

Let us consider three collaboration scenarios for a long haul freight transportation system, where a set of vehicles fulfills transportation assignments over the German road network in Fig. 3.

The transportation network is given by the 14 largest cities in Germany, where the weights are given by the travel distance between the cities in kilometers. Transportation assignments consist of a pickup time and location, and a drop-off location. The locations are randomly selected with probability proportional to the population size of the cities. The pickup times are randomly generated from the distribution of actively moving trucks during 24 h of a fleet management system, see Fig. 4 and [26] for details. The average length of the generated assignments is shown in Fig. 5.

Consider the following three examples of generated transportation assignments:

```
2015-01-01,03:45,Leipzig,51.3938,12.2523,
   Berlin,52.5018,13.2123
2015-01-01,04:11,Dortmund,51.4374,7.6016,
   Dresden,51.0503,13.6646
2015-01-01,04:17,Bremen,53.1032,8.8689,
   Munich,48.0983,11.6457
```

Each line specifies one assignment with the pickup date and time, the pickup location by city name and latitude–longitude coordinate, and the drop off location by city name and coordinate.

As a base scenario, we consider perfect collaboration among all vehicle operators, where a central planner is minimizing the total empty transportation flow for completing all assignments. The second scenario considers four competing, non-collaborating, vehicle operators. Each operator receives a fourth of all assignments, and is only concerned about minimizing its own fleet's empty transportation flow. The final scenario considers four non-collaborating regional operators, each operator located in one of the four regions shown in Fig. 3. The company operating in a region receives all transportation assignments with the pickup location in that region, but may need to deliver the cargo outside its region.

Given a set of 5000 assignments per day, we optimize the transportation flows once per hour, considering all new assignments. The vehicles that have completed their assignments are available at their destination for a new assignment, while the vehicles still moving are unavailable. If there are not enough vehicles to serve all assignments, then the companies can add new vehicles, but at a randomly selected node with probability proportional to the population of the city. For the regionally restricted companies, the vehicles appear only within the company's region. Similarly, if there are more vehicles available than assignments, then the company needs to return the vehicles to some nodes, selected by the same random distribution. The computation of the minimum cost flow produces the minimum total traveled distance for the empty vehicles to satisfy all transport assignments. We repeat these Monte Carlo simulations for 1000 days in order to produce a daily average traveled distance.

The total traveled distance per hour in the three scenarios is shown in Fig. 6. With full collaboration, the total traveled distance of the empty vehicles is only 10% of the total traveled distance (comprising both the assignments and the empty vehicles), while with four identical non-collaborating vehicle operators, the empty traveled distance increases to 17% of the total. Notice that the empty traveled distance thus increased by 70%. However, with geographically divided regional companies that do not take advantage of collaboration, and thus have no backhauling when returning to their region, the empty traveled distance increases to 47% of the total traveled distance. This clearly illustrates the importance of collaboration in the freight transportation system.

3. Collaboration opportunities

In the previous section, the potential for reducing the traveled distance of empty vehicles was explored when freight carriers jointly optimize the usage of their vehicle fleets. In the current section, we aim to improve the efficiency of the remaining transports by computing collaboration opportunities. An important example of such opportunity is platoon formation of a group of vehicles in order to collaboratively save fuel. To this end, all pairs of transport assignments need to be identified that have partially overlapping routes and have compatible timing to meet somewhere on this joint route segment, see Fig. 7.

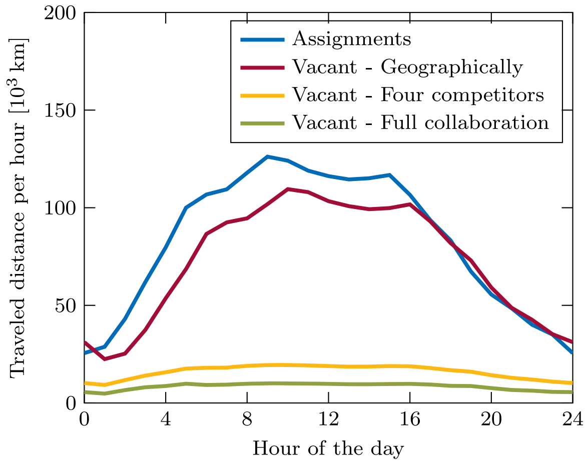


Fig. 6. Evaluation of the transportation efficiency simulation for the three collaborative scenarios. The blue line shows the traveled distance for the assignments, while the other lines show the traveled distance for the empty vehicles in three scenarios. The first case is with four geographically restricted companies, the second case with four competing companies, and the final case is with full collaboration. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

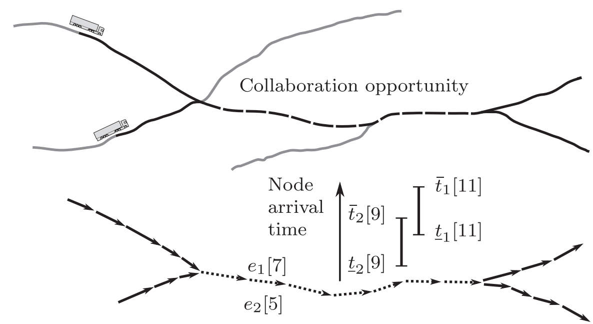


Fig. 7. Two vehicles share a subsection of their paths (upper part) which means they have common links on which the interval of the node arrival times overlaps (lower part). They could for instance form a platoon at the intersection.

3.1. Modeling collaboration opportunities

We start by modeling what we mean by collaboration opportunity. To this end, let $\mathcal{A}$ be a set whose elements identify transport assignments, where each transport assignment consists of a route and time intervals along this route. A route is a sequence $\mathbf{e}_a = e_a[1], e_a[2], \ldots, e_a[N_a]$ of edges in a road network graph, where N_a denotes the number of edges in the route for transport assignment $a \in \mathcal{A}$. To each edge, we associate a coordinate in $\mathbb{R}^2$, e.g., the geographic coordinates of the beginning of the road segment modeled by the edge. Furthermore, we associate with each edge on the route a lower bound $\underline{t}_a$ and an upper bound $\bar{t}_a$ on the time at which the vehicle may pass this edge. This information can be computed based on the allowed speed range along the route, start time, and arrival deadline. The flexibility in the timing can be achieved through adaptation of stops or speed. Similar to the sequence of edges, we introduce sequences of these time bounds as $\underline{\mathbf{t}}_a = \underline{t}_k[1], \underline{t}_a[2], \ldots, \underline{t}_a[N_a]$ and $\bar{\mathbf{t}}_a = \bar{t}_a[1], \bar{t}_a[2], \ldots, \bar{t}_a[N_a]$. Fig. 7 illustrates this notation.

The goal is to find all pairs of transport assignments that have a partially overlapping route and compatible time bounds. In this case there is a possibility for the two vehicles to collaborate. We call the set of assignment pairs that can collaborate the coordination set and denote it as $\mathcal{C}$. Then, a pair of assignments $(a_1, a_2) \in \mathcal{A} \times \mathcal{A}$ is an element of $\mathcal{C}$ if and only if the assignments have at least one edge in common, i.e., there are indices i_1,i_2 such that $e_{a_1}[i_1] = e_{a_2}[i_2]$, and their time intervals for traversing this edge overlap, i.e., $[\underline{t}_{a_1}[i_1], \bar{t}_{a_1}[i_1]] \cap [\underline{t}_{a_2}[i_2], \bar{t}_{a_2}[i_2]] \neq \varnothing$.

3.2. Pairing for collaboration

The coordination set $\mathcal{C}$ can directly be computed on the basis of its definition. However, this approach is computationally expensive as, for each possible assignment pair, the set of route edges needs to be tested for intersection and, subsequently, the overlap in time bounds for these intersecting edges needs to be checked. Instead, we propose an approach in which a candidate set $\hat{\mathcal{C}}$ satisfying $\mathcal{C} \subset \hat{\mathcal{C}} \subset \mathcal{A} \times \mathcal{A}$ is computed first, after which the coordination set can be obtained on the basis of the candidate set $\hat{\mathcal{C}}$ rather than $\mathcal{A} \times \mathcal{A}$. Here, it is crucial that a small candidate set $\hat{\mathcal{C}}$ can be obtained in a computationally fast way. To this end, we construct the candidate set by considering so-called features from the transport assignment. A feature can for instance be the time interval given by the earliest start time and latest arrival time of an assignment. Two assignments of which one starts after the other arrives cannot collaborate and comparing two intervals is computationally a lot cheaper than testing the intersection of two sets with hundreds of edge identifiers. This approach follows the same line of thought as in computer graphics when collisions of a large number of objects are computed [20,5].

More generally, the spatio-temporal separation of the transport assignments can be used as a basis for feature extraction. Namely, a transport assignment can be characterized by a collection of points in a three-dimensional space. Each edge gives rise to two points representing the upper and the lower bound on the edge arrival time as well as the common edge position. Then, after projecting these points on a given line, the feature is given by the interval on this line containing all projected points. Note that projection on the time axis gives the feature discussed in the previous paragraph. In addition, if a collaboration opportunity exists for two transport assignments, their (feature) intervals overlap. Consequently, if we let $\hat{\mathcal{C}}$ be the set of all pairs with overlapping intervals, then it is clear that $\mathcal{C} \subset \hat{\mathcal{C}}$. Moreover, $\hat{\mathcal{C}}$ can be computed with worst-case complexity that is less than quadratic in the number of assignments. More details on this approach can be found in [46].

3.3. Illustrative simulation

We illustrate the computation of collaboration opportunities in a simulation study. We use the assignments generated for the simulation in Section 2. Here, we sample the exact start and goal location of an assignment uniformly in a square that covers the respective city and calculate shortest routes with the Open Source Routing Machine [28]. Fig. 8 shows the routes for all assignments of one day. We use a velocity of 80 km/h to calculate the lower time bounds, where the lower bound at the start edge is equal to the start time of the assignment. To obtain the upper bounds, a constant value is added to the lower bounds. We call this difference the adaptation interval.

We take the 5000 assignments of one day and compute all possible collaboration opportunities $\mathcal{C}$. This is done using the efficient computation of $\hat{\mathcal{C}}$ based on a number of features as described previously. From this information the number of collaboration opportunities for each truck and the fraction of the truck's route for which collaboration opportunities exist are derived. Then, the average of these values is computed over all transport assignments for this day. We simulated 100 days and took the mean of the results. Note that this example is limited to the computation of the opportunities, and does not detail how the collaboration should be done. See [45] for further details.

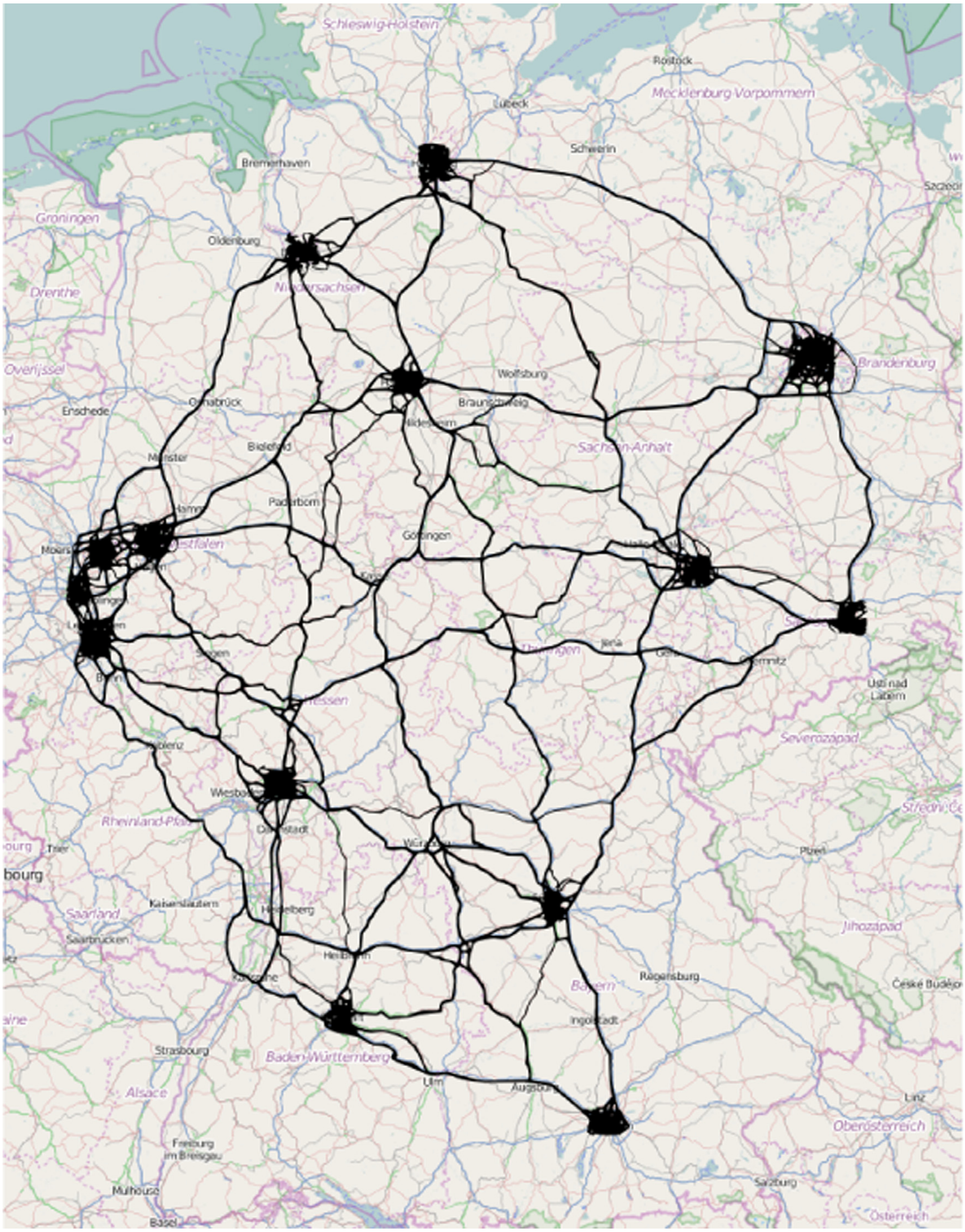


Fig. 8. The 5000 routes that correspond to the transportation assignments of one day used in the simulations presented in Section 2. The exact start position was sampled uniformly in the area of the respective city. (Map courtesy of OpenStreetMap.)

In Fig. 9, the results for a varying number of assignments per day are depicted, where the assignments are obtained by uniformly sampling a subset of the 5000 assignments. The adaptation interval was set to 15 min. We can see that the number of collaboration opportunities per truck increases almost linearly with the number of assignments with approximately 3.2 opportunities per 1000 assignments a day. The percentage of the route with collaboration opportunities rises quickly and saturates above 80%. This can be explained by considering the routes in Fig. 8. Namely, the collaboration opportunities mainly arise on the highways, where many routes concentrate. However, the starting points of transport assignments generally differ, so that few collaboration opportunities exist close to these starting points. A similar argument holds for the destinations.

Fig. 10 shows the simulation results for a varying adaptation interval. The curves are qualitatively quite similar to the ones in Fig. 9. This means that we can compensate for less assignments that are available for coordination with larger flexibility in time and vice versa. In this scenario, an increase of the adaptation interval by 20 s has the same effect as 1000 additional

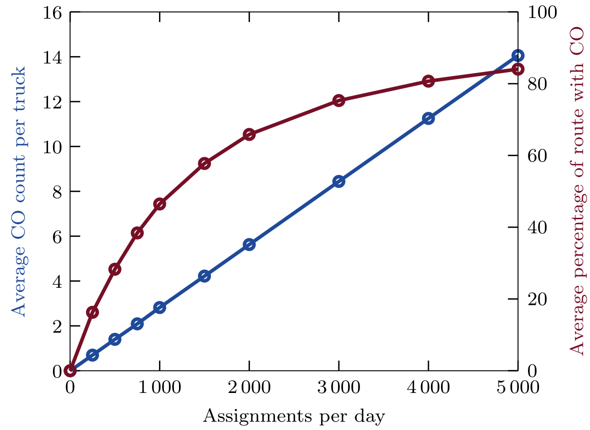


Fig. 9. The plot shows how the average number of collaboration opportunities (CO) and the average percentage of the route with collaboration opportunities change with the number of assignments per day using an adaptation interval of 15 min.

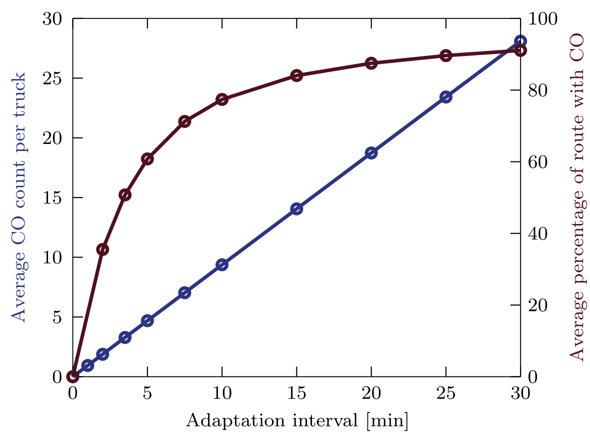


Fig. 10. The plot shows how the average number of collaboration opportunities (CO) and the average percentage of the route with collaboration opportunities change with the timing flexibility of the trucks with 5000 assignments per day.

assignments in the system per day. The total distance traveled in this simulation amounts to $0.7 \cdot 10^9$ km per year. This number can be compared to an estimated $12.7 \cdot 10^9$ km per year traveled by loaded trucks with start and destination within Germany and routes longer than 150 km [22]. This means that approximately 6% of this traffic category can be sufficient to have in average 14 collaboration opportunities per truck with a timing flexibility of just 15 min. The results motivate that this kind of collaboration is feasible in practice even if only a fraction of the vehicles can participate.

4. Platoon formation

In this section we discuss the problem of the formation of platoons. Fig. 11 shows a vehicle that will merge with an existing platoon of three vehicles when they reach the intersection. Specifically, from the coordination set defined in the previous section, one assignment pair will be considered and it will be decided whether platoon formation is beneficial. Moreover, the effect of traffic on the merging maneuver will be analyzed.

4.1. *Control of merging maneuver*

Consider one pair of assignments from the coordination set $\mathcal{C}$ defined in the previous section. The aim of this section is to decide

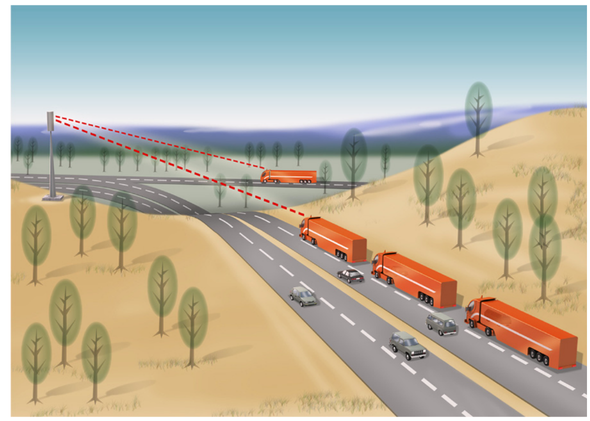


Fig. 11. Automatic control of a merging maneuver, where a single vehicle is about to merge with a three-vehicle platoon after a road intersection. The operation is supported by vehicle-to-infrastructure communication.

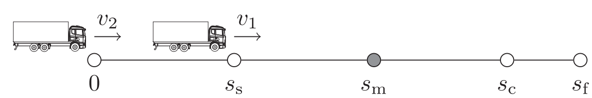


Fig. 12. Optimal merge point s_m and fuel critical point s_c in a merging maneuver. It is important that the trucks merge between these two points in order to ensure fuel savings when forming a platoon to the final destination s_f.

whether it is beneficial to exploit the collaboration opportunity by forming a platoon, i.e., whether platoon formation yields a reduced fuel consumption with respect to both vehicles fulfilling their transport assignments independently. To make this decision, a fuel-optimal formation of a platoon is considered and its fuel cost is compared to that of independently driving vehicles.

In order to determine the fuel-optimal formation of a platoon, a time instant is considered at which both vehicles are already on the road, leading to the situation in Fig. 12. Here, s_s represents the initial distance between the two vehicles, whereas s_f denotes the end of the road segment on which they can platoon, e.g., as their routes split or one vehicle reaches its destination. As these distances are typically large, vehicle dynamics can be neglected and it is assumed that vehicles drive at a constant velocity, even though this velocity may change once the platoon has been formed.

Let s_m be the point at which the platoon is formed. Then, the total fuel cost for reaching s_f is given as

$$J = v_1^2(s_m - s_s)\phi_1 + v_2^2 s_m \phi_2 + v_p^2(s_f - s_m)\phi_p. \tag{1}$$

Here v_1 and v_2 are the velocities of vehicles 1 and 2, respectively, before they reach the merge point s_m. The corresponding air drag coefficients are given by ϕ_i, $i \in \{1, 2\}$. The velocity of the platoon (between s_m and s_f) is given by v_p with ϕ_p being the air drag coefficient. Note that $\phi_p < \phi_1 + \phi_2$, which characterizes the reduced air drag due to platooning. In addition, the merge point can be expressed as

$$s_m = s_s \frac{v_2}{v_2 - v_1}. \tag{2}$$

Then, the optimal merging point (and corresponding vehicle and platoon velocities) can be found by solving the following fuel-optimal platoon formation problem:

min Total fuel consumption (1),
s.t. Constraint on the merge point (2),
  Constraints on the average velocities.

Here, the constraints on the average velocities guarantee that platoon formation does not lead to a delayed arrival at the destination s_f nor that road speed limits are violated. If J^* denotes the

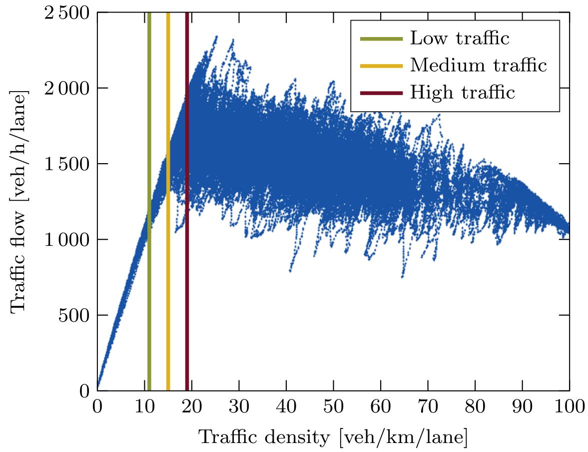


Fig. 13. Fundamental diagram from simulation of a two-lane road with a maximum traffic flow of 2200 veh/h/lane, which corresponds to traffic density of 21 veh/km/lane. The colored lines indicate the simulated traffic densities. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

optimal cost, then a platoon is formed if this cost J^* is smaller than the cost corresponding to the two vehicles driving alone, i.e.,

$$J^* < v_{\text{nom},1}^2(s_f - s_s)\phi_1 + v_{\text{nom},2}^2 s_f \phi_2, \tag{3}$$

with $v_{\text{nom},i}$ denoting the nominal velocity of vehicle i. Details on this fuel-optimal control of the merging maneuver can be found in [27].

Based on the fuel-optimal platoon formation problem, we can maximize the fuel savings by defining at what velocities the pair of vehicles should drive and where to meet. However, surrounding traffic may disturb the merging maneuver and may delay the merge. If the delay is large enough, the vehicles may consume more fuel than what they would have when driving individually. Fig. 12 indicates the optimal merge point s_m as well as the critical point s_c at which the platoon has to be formed in order to save fuel. Therefore it is important to ensure that the vehicles merge before the critical point in order to save fuel despite disturbances from other vehicles. In the next section, we will study how surrounding traffic may affect the merge point.

4.2. Simulation of merging maneuver in traffic

To examine how a merging maneuver interacts with the surrounding traffic, simulations in the traffic simulation tool VISSIM were conducted [25]. The simulation setup considers a 50 km long two-lane road on which the traffic behaves according to the fundamental diagram depicted in Fig. 13. A fundamental diagram describes the relation between traffic density and traffic flow on a macroscopic level [17]. In Fig. 13, we can see that the maximum traffic flow is approximately 2200 veh/h/lane which corresponds to a traffic density of 21 veh/km/lane. At maximum flow, the mean speed of the vehicles is 105 km/h (as given by the slope between this maximum flow point and the origin). The straight line from the origin to the maximum flow is usually referred to as the free flow branch where the vehicles on the road can more or less drive uninterrupted at their desired speeds. The more outspread area (from approximately 18 veh/km/lane in density and above) is often known as the congestion branch. For increasing traffic density on the congestion branch, the more the mean speed of the traffic drops and platooning becomes less and less relevant due to insignificant fuel saving from air drag reduction at lower speeds.

To study how a merging maneuver is affected by the surrounding traffic, we simulate three traffic densities. A scenario is considered in which both trucks drive on the right lane of the road

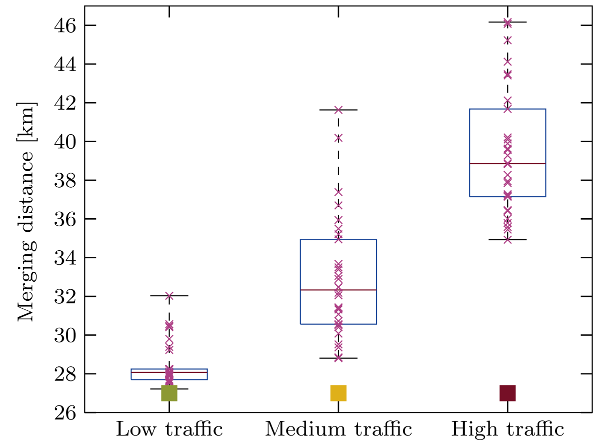


Fig. 14. Box plot of the merge points for low, medium, and high traffic where the lead truck drives at 80 km/h and trailing truck at 90 km/h. The whiskers indicate the minimum and the maximum value, the blue box indicates the 25 and 75 percentile, and the red line indicates the median. Each individual simulation result is plotted with purple "×". The nominal merge points are depicted with a green, yellow, and red square for low, medium, and high traffic, respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

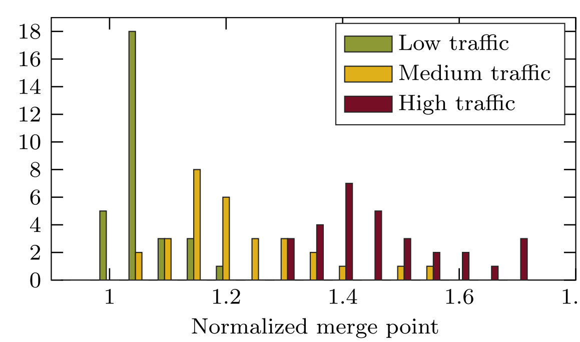


Fig. 15. Histogram of Fig. 14 normalized with the nominal merge point.

and they are initially 3 km apart. The lead truck drives at a constant speed of 80 km/h and the trailing truck tries to catch up at 90 km/h. We define that the merging maneuver is completed and that the trucks are platooning once the gap is less than 30 m and there are no cars in between. We simulate for three traffic densities, namely 11, 15, and 19 veh/km/lane, which we will call low, medium, and high traffic, respectively, and each density is simulated 30 times. The results are depicted as a box plot in Fig. 14. This figure also indicates the nominal merge point, which is the merge point (2) obtained through optimization and in the absence of traffic. Then, it is clear that the actual platoon formation takes place further downstream the road than one may expect on the basis of the nominal merge point. This is further supported by Fig. 15, which depicts the histogram of the simulation results and shows that the normalized merging distances were in average increased by 4%, 20%, and 45%, respectively, for low, medium, and high traffic and with respect to the nominal merge point. More details regarding these simulations can be found in [25].

The delay in the merge can be explained by considering the congestion in front of the merging trucks as caused by the lead truck. A truck that travels on the road is often driving slower than the surrounding cars due to traffic regulations and may therefore reduce the traffic throughput. This can be explained by analyzing how traffic conditions evolve in time on a macroscopic level using the fundamental diagram [17]. Consider the scenario in Fig. 16 where a truck is driving on the right lane. Since the truck is driving slower (at speed v as depicted with red lines in the figure) than the surrounding traffic, it will represent a moving bottleneck on the road [33,23,31]. The truck is essentially blocking a lane for the traffic to run smoothly such that the left lane will be at full capacity, see Fig. 16. This is also represented by area B in the space–time plot and the fundamental diagram. This limited capacity will lead to a separation in traffic condition before and after the truck. Namely, there will be a free flow downstream (D) of the moving bottleneck and a congestion upstream (C) of the moving bottleneck. Cars driving in the upstream congestion will drive slower due to the throttled flow by the truck (the slope from C to the origin). Once a car passes the truck, it is able to drive faster (at its own desired speed). Note that the trailing truck, which initially drives in the free flow region A, needs to pass the congested region C at which its speed is reduced. It is this reduced speed that causes the delay in the formation of the platoon. In addition, for increasing traffic density, the congestion region will propagate backwards at a higher rate. This means that the trailing truck experiences a larger congestion region, such that an increased traffic density can be expected to lead to an increased delay in platoon formation. These observations match the simulation results in Fig. 15.

5. Platoon control

The execution of the merging maneuvers in the previous section as well as the regulation of the vehicles in the platoon once it is formed rely on the control architecture shown in Fig. 17 [44]. The platoon coordinator supervises the platoon operation by defining the desired behavior of the vehicle, while the vehicle controller realizes the platoon coordinator's requests by distributively controlling the vehicles in the platoon. In the following subsections these two layers are presented.

5.1. Platoon coordinator

The platoon coordinator supervises the operation of the platoon. It is responsible for its successful formation by managing the merging maneuvers and its correct operation by defining the set points for the lower layer. It is typically implemented locally in one of the platooning vehicles and communicates with the fleet management system from which it receives information on the planned route and potential requirements on the travel time. These requirements are necessary to guarantee that the platoon synchronizes with other platoons/vehicles which it is supposed to merge with or that the platoon meets the delivery deadline. According to the travel time requirements, the platoon coordinator computes the speed reference for the vehicle control layer. In its simplest implementation, the platoon coordinator computes a speed reference profile that is able to meet the time deadline and respects local speed limits of the planned road. The availability of more detailed information of the road ahead, such as topography and traffic information, enables more advanced functions for such layer. Topography information, for example, can be exploited to optimize the speed of the platoon in order to minimize its overall fuel consumption [44,32]. Prediction on the intensity of traffic along the road can be used to guarantee the fulfillment of time constraints or, if this is not possible, to report the estimated delay to the fleet manager.

The platoon coordinator is finally responsible for defining the safety constraints necessary to guarantee the safe operation of the platoon. These constraints depend on the parameters of the platooning vehicles, such as mass and braking capability, and road condition, e.g., surface status.

5.2. Vehicle controller

The operation of platoons requires automatic control to safely achieve the short inter-vehicular distances that lead to reduced fuel consumption. Specifically, the control objective for the vehicle controller in Fig. 17 is to track the required velocity and inter-vehicular spacing.

The behavior of a controlled platoon formation is predominantly influenced by the choice of the so-called spacing policy (see Fig. 18), which, for two successive vehicles with longitudinal positions s_{i-1} and s_i, specifies the desired value of the

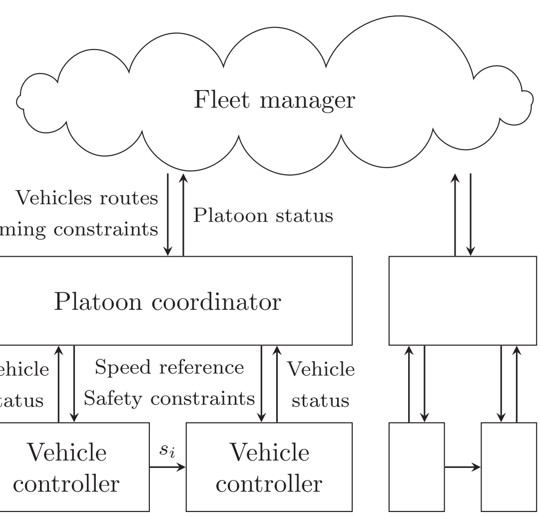


Fig. 17. Control architecture for platooning.

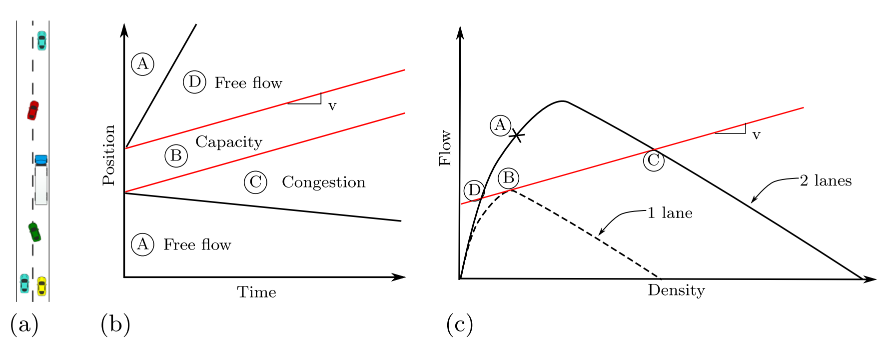


Fig. 16. (a) A truck is a moving bottleneck on the highway blocking one lane. (b) The truck's movement in space and time and the evolution of traffic condition created by the truck. (c) Fundamental diagram of a 2-lane road and the corresponding diagram when one lane is blocked by the truck (dashed). The different traffic conditions that are created by the moving bottleneck are indicated in the space–time domain and the fundamental diagram. (For interpretation of the references to color in this figure, the reader is referred to the web version of this paper.)

inter-vehicular distance $s_{i-1} - s_i$. As such, this choice is crucial in achieving the desired control objectives. One classical approach is the constant spacing policy [41], which aims at maintaining a fixed distance $d > 0$ between two successive vehicles such that the spacing error $\Delta_i(t) = s_{i-1}(t) - s_i(t) - d$ satisfies $\Delta_i = 0$. However, it is known that this constant spacing policy does not achieve the attenuation of disturbances as they propagate through the platoon [38]. To restore this disturbance attenuation (known as string stability [36]), the constant spacing policy can be relaxed to prescribe the desired position $s_{\text{ref},i}$ of the follower vehicle as

$$s_{\text{ref},i}(t) = s_{i-1}(t) - (d + hv_i(t)), \tag{4}$$

with v_i being the velocity of the follower vehicle and time-headway gap $h > 0$, see [19,14]. The disturbance attenuation property of this constant headway spacing policy can be seen by considering the kinematic relation $\dot{s}_i = v_i$ and by assuming that the policy (4) is exactly tracked, i.e., $s_i(t) = s_{\text{ref},i}(t)$. Then, the spacing error Δ_i satisfies

$$h\dot{\Delta}_i(t) = -\Delta_i(t) + hv_{i-1}(t), \quad hv_i(t) = \Delta_i(t). \tag{5}$$

This not only shows that the spacing error dynamics is asymptotically stable, but also that the velocity v_i of the follower vehicle is a filtered version of that of its predecessor. It is exactly this property, which is inherent to the spacing policy and not directly related to the details of controller design, that ensures the attenuation of disturbances for the constant headway spacing policy (4).

A different perspective is taken by the delay-based spacing policy

$$s_{\text{ref},i}(t) = s_{i-1}(t - \Delta t), \tag{6}$$

as analyzed in [6] (see also [34]). By specifying the desired trajectory of the follower vehicle to be a time-delayed version of that of its predecessor with time delay $\Delta t > 0$, it can be shown that all vehicles in the platoon achieve the same velocity profile in the spatial domain. This is an advantage as the desired velocity profile is typically determined by road properties such as bends and hills, making the delay-based spacing policy well-suited for potentially long platoons. Here, we remark that, by applying a similar relaxation as in (4), string stability properties of the delay-based spacing policy (6) can be guaranteed.

The delay-based spacing policy (6) thus ensures that the control objectives of tracking of a reference velocity profile and inter-vehicular spacing are aligned, making this policy most suitable for the control of platoons of heavy-duty vehicles. A distributed control approach on the basis of (6) is given in [6]. In addition to this tracking problem, the vehicle controller must guarantee that no collisions occur. Even though string stability can be regarded as a necessary condition for safety, the condition that the inter-vehicular distance should remain positive can explicitly be taken into account in control design, e.g., by using set-invariance techniques.

6. Experiments

In this section, we will describe experiments on merging maneuvers that were conducted on a public highway under varying traffic conditions, similar to the simulation results in Section 4.2.

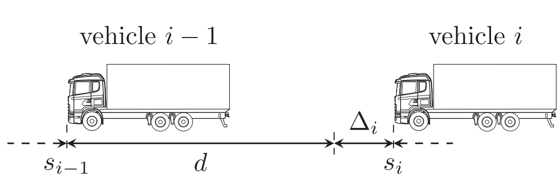
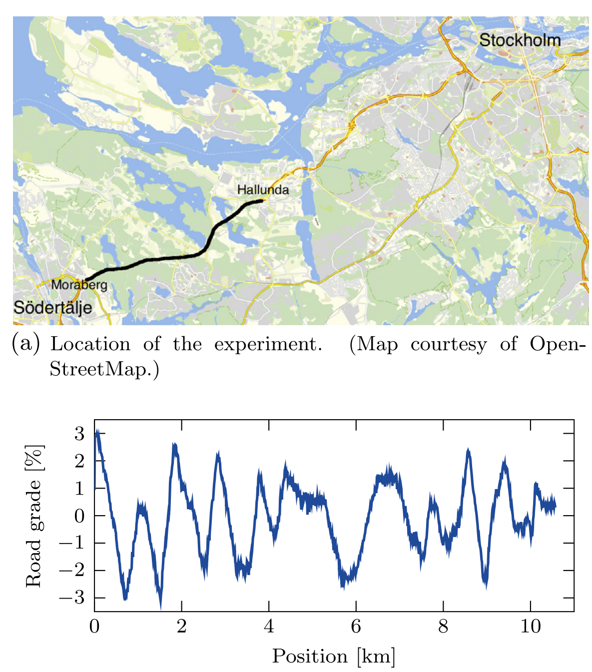


Fig. 18. Spacing $s_{i-1} - s_i$ between vehicles in a platoon.

6.1. Experimental setup

The experiments were performed during four weeks in November 2015 on a 11 km long three-lane highway stretch between Hallunda and Moraberg, southwest of Stockholm, see Fig. 19a. The road grade of this highway stretch is depicted in Fig. 19b. In each experiment, we tried to merge two trucks, depicted in Fig. 20, under varying traffic conditions. The lead truck had a trailer and a total weight of 37.5 tonnes, whereas the trailing truck had a ballast weight and a total weight of 15 tonnes. Both trucks were equipped with radar, camera, and GPS units. The trailing truck started each stretch with a delay of approximately one minute with respect to the lead truck in order to create the initial condition for the merging maneuver. To catch up and form a platoon, the cruise controllers of the lead and trailing truck were set to 80 km/h and 90 km/h, respectively. Once the platoon was formed, the platoon was driving at 80 km/h.

Data records from Stockholm's motorway control system were obtained for the duration of the experiment. This system uses doppler radars mounted on gantries over the highway to measure the number of passing vehicles and the harmonic mean speed for each lane within one-minute time intervals. There are 41 and 37 gantries in the north- and southbound directions, respectively. The gantries are within 200–400 m of each other. The traffic data from the whole set of highway cameras was collected during the four-week experiment period, i.e., 20 week days, 9 hours per day (4 h in the morning and 5 h in the afternoon). It allowed us to estimate the traffic density for different parts of the highway as well as the fundamental diagram for the whole route, see Fig. 21. The fundamental diagram based on the traffic data is similar to the fundamental diagram from the simulations in Fig. 13 if the outliers (low traffic flows with low traffic density), mainly caused by accidents, are ignored. The maximum flow is approximately at 2100 veh/h/lane with a corresponding traffic density of 22 veh/km/lane, resulting in a mean speed of 95 km/h. The free flow



(a) Location of the experiment. (Map courtesy of OpenStreetMap.)

(b) Road grade of the road in the northbound direction.

Fig. 19. The experiment took place between Hallunda and Moraberg, southwest of Stockholm, Sweden.

(a) Lead truck (b) Trailing truck

Fig. 20. Trucks used in the experiment.

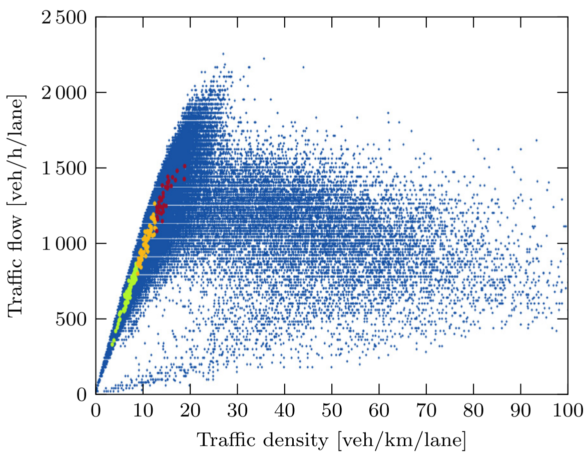


Fig. 21. Fundamental diagram from the traffic sensors during the entire experiment period. The green, yellow, and red colored dots represent the traffic conditions (low, medium, and high traffic) that occurred during the merging maneuver experiments. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

branch is a bit more spread out compared to the simulated fundamental diagram. Similarly, the congestion branch is more spread out but also slightly lower compared to the simulated fundamental diagram.

6.2. *Data analysis*

In total, 186 test runs (97 in northbound and 89 in southbound direction) were performed, of which 141 led to the successful formation of a platoon. To classify such completed merging maneuver, three criteria need to be satisfied. First, the relative distance based on the GPS should be less than 80 m. Second, the radar should have a target in front of it with similar relative distance. Third, the camera should detect the target in front and classify it as a truck. The remaining 45 attempts failed due to highly congested traffic conditions, a too large initial distance combined with limited length of the test stretch, or vehicles persistently driving behind the lead truck making it not possible to complete the merging maneuver.

Figs. 22 and 23 depict two examples of attempts where, in both cases, the trucks are initially 550 m apart. The large speed fluctuations are mainly due to road topography, as the road grade varies noticeably as shown in Fig. 19b. In Fig. 22, both trucks start approximately at their respective set speeds. Due to variations in road topography as well as disturbances from other cars, the distance between the trucks shrinks slower than in the nominal case. The nominal case is where both trucks can drive at their set speeds, such that the gap would shrink according to the nominal line. The trailing truck completes the merging maneuver and can then platoon steadily behind the lead truck. In Fig. 23, we have a similar situation. However, as the trailing truck closes in on the

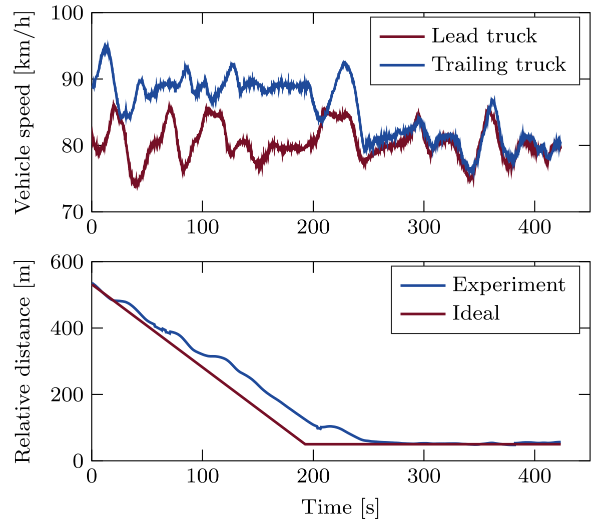


Fig. 22. An example of speed profiles and relative distance for both trucks. The trailing truck could smoothly catch up with the lead truck and complete the merging maneuver. The nominal case corresponds to that both trucks drive at their set speeds.

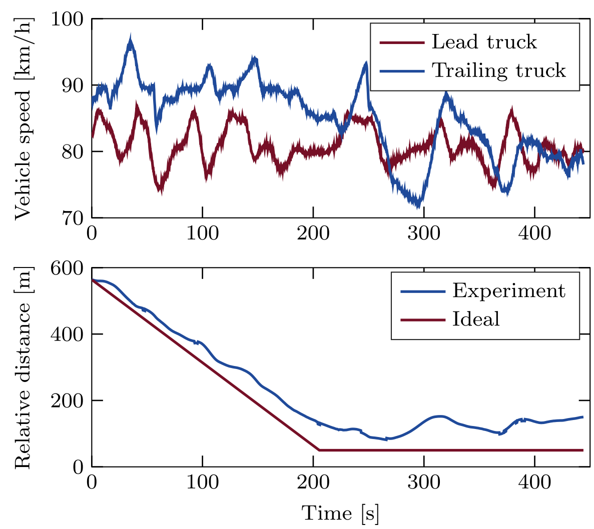


Fig. 23. Another example of speed profiles and relative distance for both trucks. The trailing truck could smoothly catch up with the lead truck, however another vehicle was in between making it impossible to complete the merging maneuver.

lead truck it cannot complete the merging maneuver. This is most likely due to a vehicle driving in between and persistently staying behind the lead truck. By using the camera, it was indeed confirmed that another truck was driving in between the trucks.

Fig. 24 summarizes the results of the 141 successful attempts in a histogram. The values on the horizontal axis represent the normalized merging point, defined as the actual merging point normalized with the nominal merging point. The value 1 indicates that the trucks were able to drive uninterrupted by traffic and could merge as intended. We have divided the runs into three categories according to the traffic condition. The green bars represent a low traffic density (lower than 9 veh/km/lane), yellow represents medium traffic density and is between 9 and 13 veh/km/lane, and red represents high traffic density (above 13 veh/km/lane). These are also depicted on the fundamental diagram in Fig. 21. (Note that the definition of low, medium, and high traffic used here differs from that in Section 4.) There is a total of 79, 67, and 40 runs for the low, medium, and high traffic density,

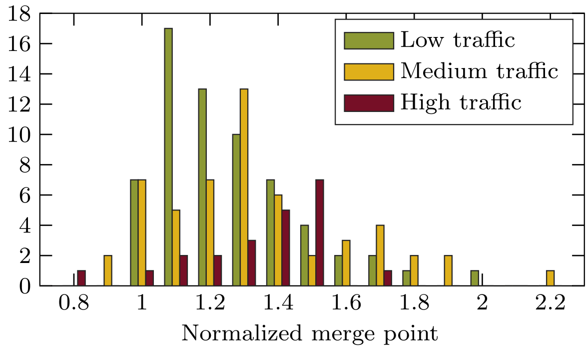


Fig. 24. Histogram over all 141 successful attempts. The colored bars represent different traffic conditions as depicted in Fig. 21. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

respectively. We can note that the mean shifts more and more to the right as the traffic density increases. Note that the histograms in Figs. 21 and 13 are different in the sense that the traffic densities in the simulation have distinct values, as opposed to the experiments, and therefore the shifts are not as clear as in the simulation. The three runs that have a normalized merge point below 1 are the result of the presence of slowly moving vehicles in front of the lead truck, such that its speed is lower than desired. These experimental results clearly show that traffic has a large influence on the merging maneuver for platoon formation. The experiments further show a correlation between the delayed merging time and traffic density, such that we believe it is plausible to find methods for predicting this delay if online traffic density measurements would be available. This would enable detailed prediction and control of the merging maneuver, taking the current traffic conditions into account.

7. Conclusions

Various networked control challenges in a future road freight transportation system were presented in this paper. Specifically, it was shown that the efficiency of such a system can be optimized by minimizing the number of empty transports and exploiting collaborative driving to reduce fuel consumption. To enable these improvements, an integrated system was proposed that incorporates tasks ranging from fleet management and routing to platoon formation and vehicle control. Moreover, experimental results on platoon formation on public roads and under varying traffic conditions were presented.

Much future work remains in the development of a sustainable and efficient road freight transportation system, but technology is currently developing at a rapid pace. Self-driving capabilities are already being tested in real traffic and cloud technologies enable the real-time coordination of large vehicle fleets. Future work will therefore focus on further experimental evaluation of the proposed technologies, herein considering an increasing number of vehicles. The collaboration between fleet owners as envisioned in this approach also calls for the development of business models in which the benefits are equally shared [15]. Finally, in order to further optimize freight transportation, a multi-modal approach might be developed to include other means of transport, such as by rail or waterway.

The ideas presented in this paper could also find application in passenger transport through the coordination of public transport or future ride-sharing systems. More generally, such coordination is useful in any large-scale system in which advantages can be obtained by collaboration, e.g., the power grid, smart cities, or wireless sensor networks.

Acknowledgments

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