Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems (ITSC 2013), The Hague, The Netherlands, October 6-9, 2013

Coordinated Route Optimization for Heavy-duty Vehicle Platoons

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***Abstract*— Heavy-duty vehicles traveling in platoons consume fuel at a reduced rate. In this paper, we attempt to maximize this benefit by introducing local controllers throughout a road network to facilitate platoon formations with minimal information. By knowing a vehicle's position, speed, and destination, the local controller can quickly decide how its speed should be possibly adjusted to platoon with others in the near future. We solve this optimal control and routing problem exactly for small numbers of vehicles, and present a fast heuristic algorithm for real-time use. We then implement such a distributed control system through a large-scale simulation of the German autobahn road network containing thousands of vehicles. The simulation shows fuel savings from 1-9%, with savings exceeding 5% when only a few thousand vehicles participate in the system. We assume no vehicles will travel more than the time required for their shortest paths for the majority of the paper. We conclude the results by analyzing how a relaxation of this assumption can further reduce fuel use.**

Fig. 1. Four heavy-duty vehicles platooning to reduce the fuel consumption for the following vehicles.

I. INTRODUCTION

Environmental and economic concerns have lead to an increased interest in reducing the fuel consumption of heavy-duty vehicles (HDVs). One approach is to form platoons, see Fig. 1, a collection of vehicles driving at close proximity in a single file. The concept is to reduce the air drag for the following vehicle and thus reduce the fuel consumption. While the idea has been studied since the 1960's [1], [2], most research has addressed inter-vehicle control design and maintenance of vehicle platoons. Several studies [3]–[6] indicate huge fuel consumption reductions while platooning, depending on the distance between the vehicles. For surveys of the platooning and inter-vehicle control literatures, see [7]–[9].

Most of the platooning literature concerns vehicles already in a platoon. For example, issues such as string stability [10]–[12], control designs when platooning [13], and inter-vehicle communication through limited bandwidth channels [14] or channels with communication delays [15] have been addressed. While there has been some contributions in the control of platoons and individual HDVs, they focus on single highways or congestion control. For example, [16] analyzes the formation of platoons on a single highway with multiple entry and exit points, using a traffic flow model and focusing on traffic throughput ratios. The simulations in [17] employ a traffic flow model to calculate platoon paths on an intelligent highway system in order to optimize traffic performance. Studies suggest platooning can reduce fuel consumption by 4-7% in [5] or up to 21% in [4], depending on the spacing of the vehicles within a platoon. Similar paradigms of control have been shown to reduce congestion for all vehicles on the road as well [18].

While the control of individual HDVs and platoons has been studied extensively, the large-scale coordination of HDVs throughout a large-scale real-world road network has largely been neglected up to now. In this paper, we develop a system of distributed controllers providing slight adjustments to HDVs' speeds and routes in order to form platoons and decrease fuel use. The controllers are placed at major intersections in the road network, similar to the hierarchical systems of [19], [20]. As multiple HDVs approach an intersection, a local controller detects whether some of them could feasibly adjust their speeds to form a platoon. If forming the platoon is possible and the fuel required to do so is less than the possible fuel savings from platooning, the local controller informs the HDVs to form a platoon. The controller ensures that the vehicles will arrive at their destination at the correct time, never routing an HDV so it travels more than its shortest path time. We implement this system in a large-scale simulation of the German autobahn road network, and show fuel decrease of up to 9%. The amount of fuel savings is naturally dependent on the number of vehicles in the network; more vehicles driving on the roads provide more platooning opportunities. Only a few thousand vehicles are required to achieve these savings. This

This work was supported by VINNOVA - the Swedish Governmental Agency for Innovation Systems within the FFI program, under contract 2011-01144, the Swedish Research Council, the Swedish Foundation for Strategic Research, and the Knut and Alice Wallenberg Foundation.

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978-1-4799-2914-613/$31.00 ©2013 IEEE

is a relatively small number of vehicles for the German road network, which has approximately 400,000 registered HDVs [21].

Our work can be employed in a variety of platooning paradigms, from systems where infrastructure provides constant inter-vehicle communication to systems where every HDV is equipped with minimal smart technologies and left to act individually. (For example, our distributed controller could adjust an HDV's speed by communicating with the vehicle's cruise control management system or by simply informing the driver through the dashboard.) We consider the flexibility to work in various paradigms to be a significant strength as large changes to infrastructure proposed throughout the literature may take considerable time and costs. As an example, some proofs-of-concept in [22] and [23] use magnetic reference markers in the road to control platooning vehicles.

We consider our work to be closely related to [24], which addresses the interesting case of two HDVs that are traveling in the same direction on the same road, but are some distance apart. In this case, it might benefit the trailing HDV to speed up (temporarily using more fuel) in order to catch a leading vehicle and start saving fuel from platooning. Naturally, such a speed up is beneficial only if the platoon is maintained long enough to justify the extra expended fuel. Furthermore, our work is a natural extension of the eco-routing concept [25], [26] where minimum-fuel-use routes are desired over minimum-distance routes. Likewise, the shortest path may not be most fuel efficient when considering platoons as well.

It should be noted that we only consider HDVs speeding up to form platoons, though one could easily consider slowing down as an alternative. From our experience, HDV drivers generally dislike increasing travel times; this motivates our consideration of speeding up only. Also, for most of this work, we only consider adjusting the path of a HDV to routes that have an overall time identical to the time required to travel its shortest path from start to finish. With this restriction, vehicles in most networks will stick mostly to their shortest path. The only difference will be small adjustments to speed in order to synchronize with other vehicles in the network and form platoons.

The main goal of this paper is to develop and analyze a real-time system for fuel-efficient platoon formation, which can operate in a distributed manner; no central planner coordinating HDVs is required. In Section II, we describe our model and introduce the local controller problem whose solution is the heart of our method. We show an efficient algorithm for optimally solving this control problem when two HDVs are approaching a local controller in Section III-A. Next, we show one possible relaxation to this problem when many HDVs could possibly form a platoon in Section III-B, and show how these techniques can greatly reduce fuel use in large-scale simulations in Section III-C. In Section III-D, we analyze how the average fuel saving increased with increased number of HDVs on the network. Lastly, we examine in Section III-E additional fuel-saving possibilities if vehicles accept travel times slightly longer than those determined by their shortest paths. Section IV concludes the paper.

II. Problem Description

In the following, we present a framework for modeling vehicles traveling on a road network and then outline our local controller system to coordinate platoon formation.

A. Road and Vehicle Platoon Models

We can model a given road network as a graph $G = (V, E)$ where the edges E represent the road segments in the network and the vertices V are nodes connecting the road segments. Furthermore, we define a vertex $\nu \in V$ with more than two connecting road segments as a junction. Without loss of generality, we can assume that the edges of E all have unit length. Any longer edges in an initial graph can be subdivided to satisfy this assumption. With these conditions, the vertices V represent possible HDV locations when traveling through the network. Of course, in reality, the vehicles are continuously traversing the edges. Considering HDVs at vertices is equally valid, much easier to handle computationally, and provides a natural platooning indicator: if two HDVs are at vertex ν_i at time t and an adjacent vertex ν_j at time $t+1$, then we consider them to have platooned over edge e_{ij}.

For each HDV k_i in the road network, we can assign a current starting location $s_i \in V$ and destination $d_i \in V$. HDVs that platoon save a fraction $\eta \in (0, 1)$ of the fuel compared to traveling solo (though η can be up to 21% [4], we assume 10% throughout). It is true that a lead vehicle in a platoon will use less fuel; since these savings are considerably less than the trailing vehicles, we assume only $n-1$ vehicles in an n-vehicle platoon obtain the 10% reduction in fuel use. We want to minimize the total fuel expended in order for all k_i to reach their destinations. Of course, to accurately describe reality, there must be additional constraints on the solution space. Real-world HDV drivers will not go significantly out of their way in order facilitate platooning formation. If $D(s_i, d_i)$ is the time required to travel the shortest path from s_i to d_i, we must ensure k_i does not travel more than time than $D(s_i, d_i) + m_i$. For the majority of this work, we consider $m_i = 0$ as most drivers will not drive any more time than necessary.

B. Local Vehicle Routing for Platooning Models

A global controller attempting to coordinate the routes of every HDV in a real-world scenario is beyond current capabilities, not only because no such controller currently exists, but also because coordinating every vehicle in a network centrally is computationally intractable. We therefore simplify the problem considerably by distributing controllers at junctions in the road network. We will refer to such a local controller as a "Local Route and Platooning Coordinator" (LRPC).

For example, consider a snapshot of a portion of a larger network in Fig. 2. Two HDVs are approaching a location where they could possibly form a platoon. Knowing only the HDVs' current location, speed, and final destination, the

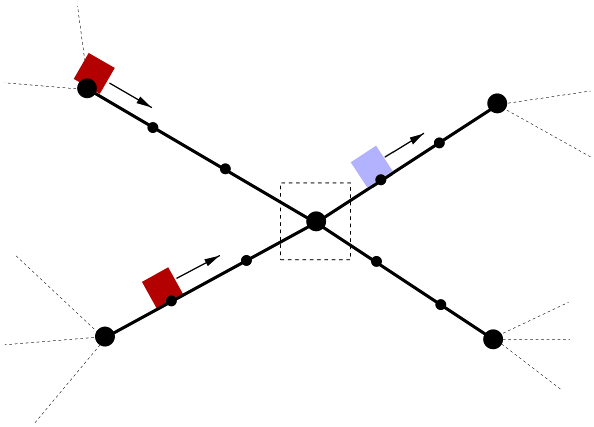


Fig. 2. An example of two HDVs driving towards a junction with a local controller node (dashed square). A third HDV is driving away from the junction, and therefore does not influence the route planning of the other two.

controller can decide whether the HDVs should adjust their speeds to form a platoon at the intersection or keep traveling alone. We define this problem as the "local controller problem". By placing local controllers at junctions, our method can coordinate fuel-efficient platoons in a distributed fashion while only slightly altering an HDV's route. Pseudocode for the local controller's logic can be found in Algorithm 1.

Note that in the preceding and following discussions, we considered two HDVs approaching an intersection. Of course, more than two HDVs could be easily considered, as well as replacing one or more HDVs with a preexisting platoon.

Algorithm 1: Pseudocode for the LRPC logic.

```
if Approaching HDVs can feasibly adjust their speeds
to form a platoon then
    if Test of sufficient savings then
        Inform the HDVs to adjust their speeds to form
        a platoon
    end
end
```

Determining whether the platoon can be formed only requires a comparison of the vehicles current velocity and the legal speed limit. If the additional fuel required to form the platoon is less than the savings the vehicles will incur in the platoon, then the controller will facilitate platoon formation.

III. RESULTS

The following is a variety of results showing the strengths and savings of our platooning control methodology.

A. Shortest Path vs. Local Control

We now present a single instance of a LRPC facilitating HDV platooning. Consider the map of Minnesota in Fig. 3 where two HDVs, numbered 1 and 2, are approaching a junction s (denoted by the square) and each HDV has a different destination d_1 and d_2 (denoted by the stars). We assume that if the HDVs were independent they would each take their respective shortest paths, shown in Fig. 3 (top). However, if one HDV slightly adjusts its speed so both arrive at the junction simultaneously, they could form a platoon. The local controller, located at the square, must decide if the additional fuel required to form the platoon will be offset by the savings from platooning.

Assuming that the LRPC has access to the all-pairs shortest path matrix $D(i,j)$, it can quickly determine the most fuel efficient route for the HDVs, comparing at most $|V|$ values in Algorithm 2. Notice that in this example, we only consider alternative paths with length equivalent to the shortest paths for each HDV (since $m_i = 0$ for all i). That is, neither HDV must increase its travel time in order to follow the recommendations from the local controller. We consider increasing m_i slightly in Section III-E. We see in Fig. 3 (bottom) that the most fuel efficient routes returned from Algorithm 2 can allow for considerable platooning savings.

Algorithm 2: LRPC savings calculation for two HDVs.

Input A starting node s and two destinations d_1, d_2, and the matrix $D(i,j)$ with entries corresponding to the fuel required to go from i to j;
Output The node where the platoon should split N_s and the savings SV;
Start:
$N_s \leftarrow s$; $Best \leftarrow D(s,d_1) + D(s,d_2)$;
$m_i \leftarrow 0 \; \forall i$;
for ν *in* V **do**
  if $((2-\eta)D(s,\nu) + D(\nu,d_1) + D(\nu,d_2) < Best)$ & $(D(s,\nu) + D(\nu,d_1) \leq D(s,d_1) + m_1)$ & $(D(s,\nu) + D(\nu,d_2) \leq D(s,d_2) + m_2)$ **then**
    $N_s \leftarrow \nu$;
    $Best \leftarrow (2-\eta)D(s,\nu) + D(\nu,d_1) + D(\nu,d_2)$;
    Update m_1 or m_2 if needed;
  end
end
$SV = D(s,d_1) + D(s,d_2) - Best$;

If the platooning savings are more than the cost of forming the platoon, the controller can advise a platoon to be formed. To calculate the platoon formation cost as two HDVs approach a node s, let v_1, v_2 be their respective velocities and let L_1, L_2 be their respective distances from s. Assume HDV 1 must speed up in order for the platoon to be formed (i.e., $\frac{L_1}{v_1} > \frac{L_2}{v_2}$) and the fuel cost is $F_i = 0.5 L_i v_i^2$. (While vehicles decreasing their speed is another option for platoon formation, we only consider increasing speed.) For the platoon to be formed

$$\Delta v_1 = \frac{L_1}{L_2} v_2 - v_1 \text{ and } \Delta F_1 = 0.5 L_1 \left(\left(\frac{L_1}{L_2} v_2 \right)^2 - v_1^2 \right) \tag{1}$$

where ΔF_1 is the fuel increased cost for HDV 1 over L_1. If ΔF_1 is less than the platooning savings SV from Algorithm 2, the platoon should be formed.

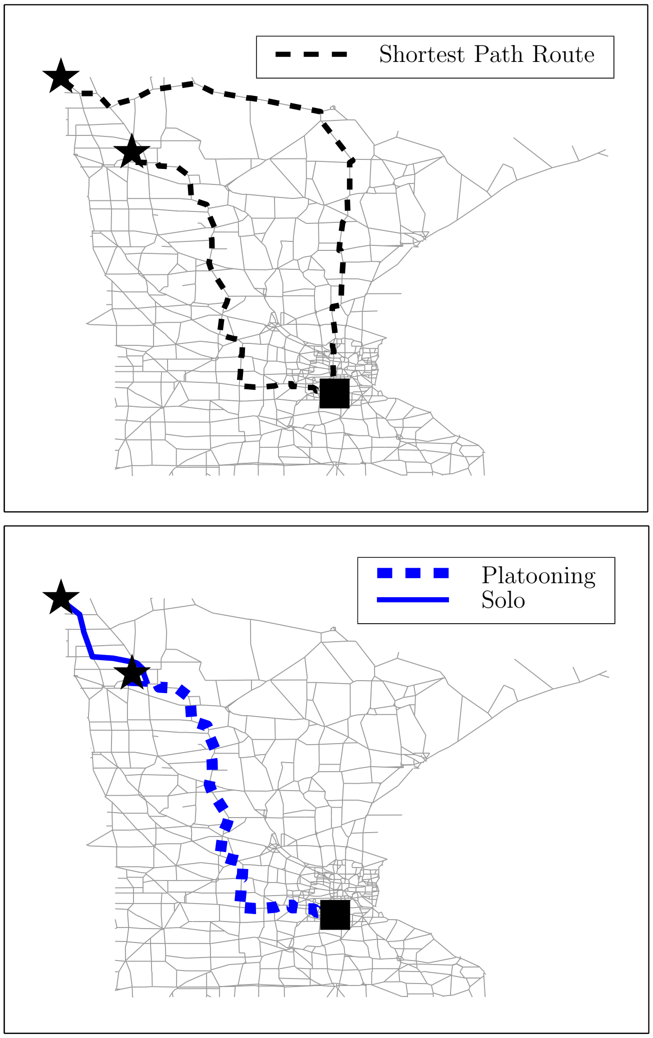


Fig. 3. Two HDVs taking their shortest paths (top) versus a more fuel-efficient routing (bottom)

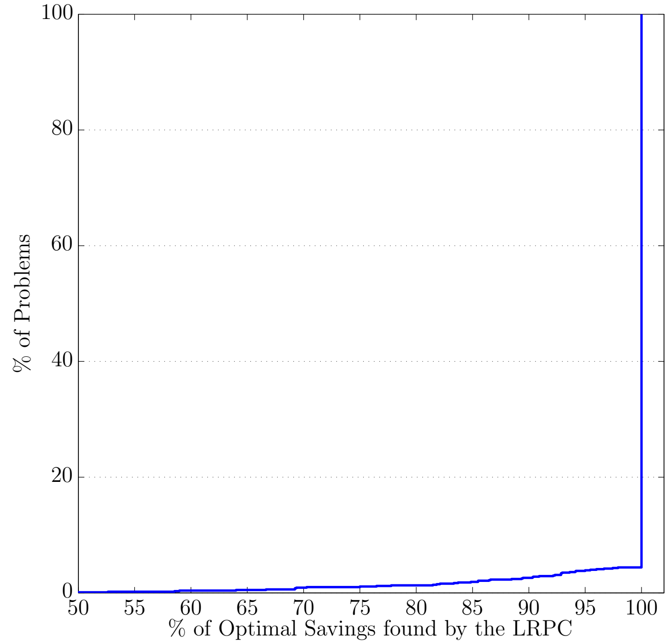


Fig. 4. Cumulative distribution function of the percentage of the amount of fuel saved by the LRPC compared to the optimal solution for 4 HDVs, 1000 random starting points and destinations.

Algorithm 2 assumes all vehicles arrive at the controller simultaneously. The LRPC therefore compares if the savings SV from Algorithm 2 is more than the cost ΔF_1 from (1). If $SV > \Delta F_1$, the controller informs the HDVs that a platoon should be formed.

B. Control for More Than Two HDVs

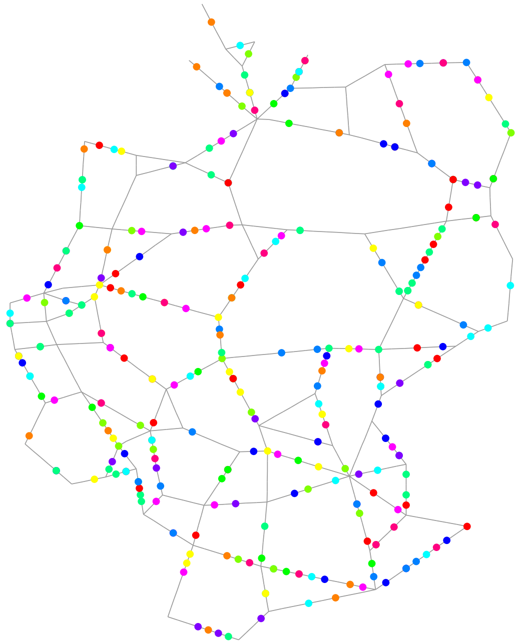
Before showing the benefit of multiple LRPCs distributed throughout a large-scale network, we must first generalize Algorithm 2 for more than two HDVs. As we developed above, when two HDVs are approaching a LRPC at s, at most $|V|$ quantities must be examined to find the most fuel efficient route. If g HDVs are approaching the same controller, finding the optimal platooning route becomes computationally intractable for $g \geq 4$. We therefore propose a fast heuristic to closely approximate the optimum.

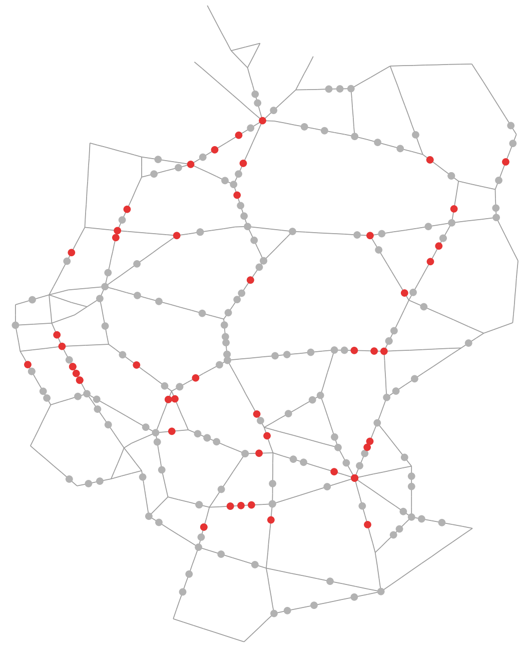
If g HDVs are approaching a controller, finding a fuel efficient route can be broken down into $\binom{g}{2}$ pairwise decision problems, which can quickly be solved by Algorithm 2. If no pair of HDVs has platooning savings that outweigh the cost of formation, no controller action is taken. Otherwise, the pair of HDVs that incurs the largest savings considered fixed, that platoon is formed and considered one unit. This process is repeated with $\binom{g-1}{2}$ pairs of HDVs and continues until every vehicle is assigned to a platoon, or none of the pairwise savings from Algorithm 2 outweigh the cost of platoon formation.

Though the exact calculation of the optimal routes for general g is too time consuming in practice, we can examine how the proposed heuristic compares for moderately sized problems. Since the optimal solution for 4 HDVs is attainable within reasonable time, and a situation with 5 or more HDVs occurred rarely in our simulation, we chose to evaluate the heuristic for this number. We place 4 HDVs at a random node s in the Germany network (seen in Fig. 5(c)) and assign each a random destination. We can then compare the amount of fuel saved by the LRPC with the amount of fuel saved by the optimal solution. We repeat this random experiment 1000 times for 4 HDVs and show the relative difference between the two solutions in Fig. 4. From this figure, we observe that that the routes returned from Algorithm 2 finds less than 80% of the optimal savings for approximately 2% of the problem and finds the optimal path for over 90% of the cases.

C. Simulation of the German Autobahn Road Network

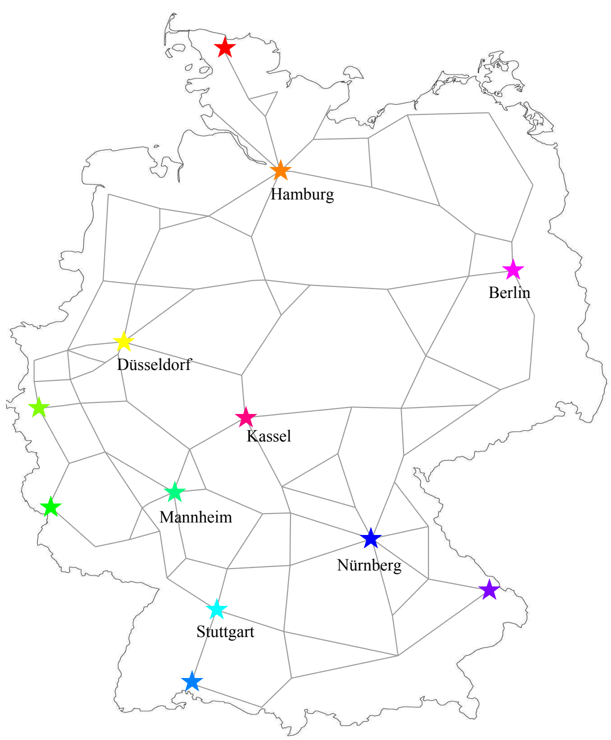
To evaluate the performance of our algorithm on a large scale, we use a simplified graph of the German autobahn network with 647 nodes, 695 edges and 12 destinations (see Fig. 5(c)). In this network, every edge is the same length so we assume that traversing every edge requires the same amount of fuel (though one could easily consider road gradients and congestion when determining fuel-usage rates).

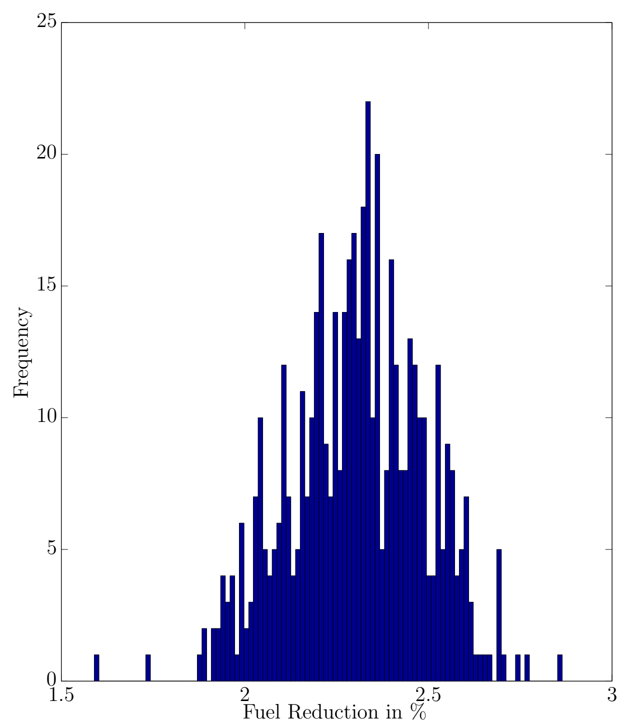




(a) A snapshot of an initial state of our system, with dots representing HDVs. The color of an HDV designates its destination according to Fig. 5(c)

(b) A snapshot of the same system as in Fig. 5(a) after 10 time steps. Platoons are depicted as red dots, single vehicles appear in gray.





(c) Visualization of the simplified German autobahn network used in our simulations (nodes are not shown). Possible HDV destinations are represented by stars.

(d) Percentage of fuel saved by our approach, compared to every HDV taking its shortest path, for 300 trucks, 500 times with random starting points and destination.

Fig. 5. Large-scale Simulation Results

For this simulation we have two restrictions about speeding up. First, HDVs already in a platoon do not speed up to catch another HDV or platoon. If platoons did speed up to catch another vehicle, all vehicles would incur additional fuel costs but only one would eventually receive aerodynamic savings. (In other words, the fuel savings for a third vehicle in a platoon is not noticeably different from the second.) Second, an HDV can only speed up to catch another vehicle if it is trailing by at most one edge length. Each edge length corresponds to roughly 13 km, which we consider to be a reasonable distance for an HDV to make up. Of course, this catch up of one edge length must be spread out over a stretch of road long enough to prevent illegal speed. For example, if two HDVs driving at the same speed are approaching a local controller, respectively 10 and 11 edge lengths away, the latter HDV could increase its speed by 10% to facilitate platoon formation. On the other hand, if the respective distances were only 1 and 2 edge lengths, the latter HDV could not double its speed to form a platoon.

We have simulated the system for 500 times for 300 trucks with random starting points and destinations. One possible initial state is depicted in Fig. 5(a), with HDVs represented by colored dots, where the color refers to the destination as marked in Fig. 5(c). In Fig. 5(b) we see the same simulation after 10 time steps; platoons are colored red, and single HDVs appear in gray. Approximately 30% of the vehicles have formed platoon at this stage.

Finally, in Fig. 5(d) we see the percentage of total fuel saved by the LRPC approach compared to every HDV taking its shortest path. We see that even for this relatively low number of HDVs the total fuel consumption has been decreased by 2-2.5%

D. Benefit of Increasing the Number of HDVs

In this section we analyze how the platooning benefit changes as the number of HDVs in the network changes. Intuitively, one would assume that if the density of vehicles in the network is low, there are few opportunities for platooning; few HDVs will take a route other than their shortest path. As the HDV density in the network increases, more HDVs will avail themselves of platooning options so more savings will be observed. Eventually, once the number of HDVs in the network approaches or exceeds the number of vertices, all opportunities for savings are extracted from the network topology; adding more vehicles will not decrease the average fuel use considerably.

We see this intuition is true in Fig. 6 where we compare increasing the number of HDVs on the German road network versus the average HDV fuel savings. We see fuel savings increase rapidly between 0 and 2000 vehicles - with only two thousand HDVs, savings of over 6% can be observed. As the network becomes "saturated" with vehicles, nearly every edge can be traveled in a platoon, so nearly every HDV uses 10% less fuel (compared to driving its shortest path alone), and adding more HDVs will only result in marginal savings. We observe that our system achieves a reduction of 9% with less than ten thousand vehicles in this network.

E. Increasing Allowable Detours

For the entirety of this paper, we have only considered vehicle routes that are the same length as their shortest path. This is mostly for practical reasons: anecdotal surveys of HDV drivers suggest that few are willing to spend any

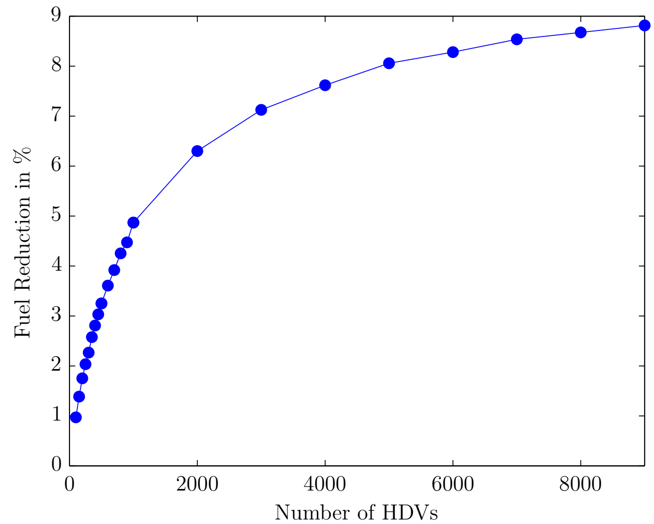


Fig. 6. The percentage of fuel saved by the LRPC method compared to every HDV takes the shortest path and does not platoon.

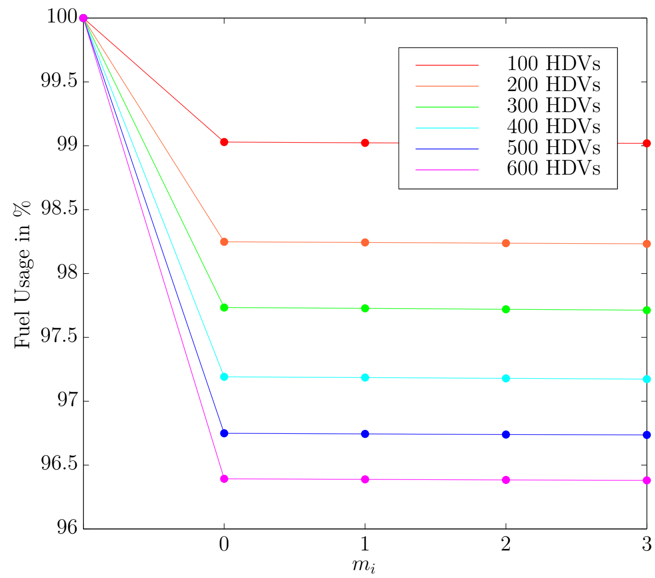


Fig. 7. The number of additional edges an HDV can travel versus the average fuel savings for various numbers of HDVs on the Germany network. Longer detours result in lower average fuel consumption but the benefits are very small for this network.

additional time behind the wheel in order to save fuel. Nevertheless, in the interest of completeness, we now examine the possibility of allowing routes for an HDV that are longer than the length of its shortest path to its start to destination.

One might expect that increasing the extra edges a vehicle could travel would have quickly diminishing returns. Allowing an HDV to travel 10 or 20 kilometers extra will help to improve the average fuel use because more platooning options will be available. But allowing an HDV 60 km of additional travel is unlikely to provide much additional savings; a vehicle that travels 60 km extra must be platooned an exceptionally long time in order to offset the costs of platoon formation.

We find this intuition holds in Fig. 7, where we partially resimulate our German road network with a slight modification to the Algorithm 2. Instead of defining $m_i = 0$ for all i, we assign each HDV k_i an upper bound m_i and ensure that the controller never returns a route for k_i which will result in a total travel time more than $D(s_i, d_i) + m_i$. For example, if $m_i = 3$ for some k_i and k_i has already traveled two additional edges before approaching an intersection, the local controller at $\nu \in V$ can only look for routes with one or zero edges more than $D(\nu, d_i)$.

The results of introducing m_i uniformly across every k_i seen in Fig. 7 suggest that the majority of the savings of our local controllers arise from synchronization. Since increasing m_i results only in almost imperceptible savings, we conclude that the LRPC is not routing HDVs off their shortest-path routes (at least in for the network in question). We see this as an asset in favor of our system's possible adoption: more HDV drivers are willing to participate in a system which doesn't significantly modify routes they are already traveling.

The impact of increasing m_i naturally depends on the structure of the graph; if many similar length routes exist, allowing slight detours will likely produce greater savings. We have also simulated more realistic scenarios where m_i as an increasing function of $D(s_i, d_i)$ (HDVs with longer travel times can tolerate more detours), but find the fuel savings to be nearly identical to the constant m_i case.

IV. Conclusion

In this paper we developed a distributed method for platoon formation. Using local controllers throughout a road network, we showed how significant fuel-savings can achieved by platooning vehicles together. This can be accomplished by keeping vehicles on their shortest path from start to destination, but slightly adjusting their speeds in order to synchronize travel with other HDVs. Lastly, we show that if vehicles are willing to incur slightly longer travel times, even more savings can be achieved. An interesting topic to investigate is the influence of congestion on our proposed method. Future work includes experimental evaluation of the approach proposed in this paper. For example, HDV platooning experiments are currently being performed with 25 HDV's traveling regularly between Södertälje in Sweden and Zwolle in the Netherlands.

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