2014 IEEE Intelligent Vehicles Symposium (IV)
June 8-11, 2014. Dearborn, Michigan, USA

Fuel-Saving Potentials of Platooning Evaluated through Sparse Heavy-Duty Vehicle Position Data

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Abstract— **Vehicle platooning is important for heavy-duty vehicle manufacturers, due to the reduced aerodynamic drag for the follower vehicles, which gives an overall lower fuel consumption. Heavy-duty vehicle drivers are aware this fact and sometimes drive close to other heavy-duty vehicles. However, it is not currently well known how many vehicles are actually driving in such spontaneous platoons today. This paper studies the platooning rate of 1,800 heavy-duty vehicles by analyzing sparse vehicle position data from a region in Europe during one day. Map-matching and path-inference algorithms are used to determine which paths the vehicles took. The spontaneous platooning rate is found to be 1.2 %, which corresponds to a total fuel saving of 0.07 % compared to if none of the vehicles were platooning. Furthermore, we introduce several virtual coordination schemes. We show that coordinations can increase the platooning rate and fuel saving with a factor of ten with minor adjustments from the current travel schedule. The platooning rate and fuel savings can be significantly greater if higher flexibility is allowed.**

Fig. 1. Five HDVs platooning on the highway.

I. INTRODUCTION

Today the use of fleet management system (FMS) is increasing among the fleet operators and most heavy-duty vehicle (HDV) manufacturers offer such systems. The FMS enables the fleet operator to analyze and monitor the operation and condition of her vehicles, such as coasting, idling, braking, fuel consumption, speed, and position. This allows the owner to cut costs. Since the position of the vehicle is a key component, a global positioning system (GPS) device is needed in the vehicles. Vehicle position data is known as floating car data (FCD) or probe data and consists of timestamped vehicle longitude and latitude, and, optionally, other relevant information. Although recording vehicle location can be done frequently, transferring high volumes of data is costly. Therefore, probe data is usually transferred at intervals of minutes or longer.

HDV platooning is to form a string of HDVs driving close behind each other to reduce the air drag, see Fig. 1. Since the fuel costs represent a third of the total operational costs of an HDV [1], there is an incentive to drive in platoons. HDV platooning has shown potentials of fuel savings from 5 % to 20 % [2]–[4] depending on the intermediate distance between the vehicles. Platooning may also improve safety and road throughput [2], [3]. There are a wide range of related work regarding probe data as well as vehicle platooning, and only a few recent work are mentioned here. Studies using probe data have been conducted for map-matching algorithms [5]–[7], path inference [8], [9], and travel time estimations and predictions [10]–[12]. Many aspects in platooning has been studied, such as string stability [13]–[15], vehicle control [16], vehicle-to-vehicle (V2V) communication [17], and fuel savings [18], [19]. For surveys of vehicle platooning and architectures, see [20], [21].

Few studies have been conducted regarding forming platoons through coordination or incentive means. In [22], data-mining is used to study platoon coordination. A vehicle is allowed to wait at certain meeting points if it deems that the platooning benefit is higher than the waiting cost. This is done by comparing the vehicles' routes and check if there are any overlaps. In [23], a game-theoretic approach is studied to understand how various factor influence two different types of vehicles' incentive given traffic flow on the day and dynamic congestion tax. One vehicle type can be seen as a car where traveling at preferred time weighs more than the tax cost and the other type is a HDV where platooning opportunities and tax cost weigh more than preferred time. In [24], a comparison is made to see if a catch up followed by platooning is more fuel efficient than maintaining current speed. The lead vehicle maintains a constant speed till its destination and the follower vehicle has the choice to either drive faster to catch up to the lead vehicle and then platoon with the lead vehicle's speed, or to keep its current speed till the destination. The catch up was shown to be desirable when the distance to destination is at least 17 times longer than the distance to the lead vehicle. In [25], local controllers are introduced on junctions on a road network to maximize the platooning benefit. By knowing the vehicle's position, speed, and destination, the local controller can decide how the vehicle's speed should be adjusted to platoon with other vehicles in the near future. Furthermore, the real vehicle data that was used in the second part of the paper is the same

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data set (except with no heading information) used in this paper. However, the platooning analysis in that paper only studies the distances between the vehicles through the raw GPS points of the vehicles.

For HDVs today, the driver often drives a predefined route or uses her common sense to reach the destination. If the HDV platoons with other HDVs along the route, then it most likely occurred by chance rather than by driver's decision on the route (unless maybe the driver sees another HDV close ahead). It has been shown that driving behind another HDV reduces the fuel consumption, but taking longer detours to platoon or form platoons do not yield any noticeably additional fuel savings compared to taking the vehicle's own optimal route [25]. With the knowledge that the route intervention is limited, speed is the only option to change in order to form platoons on the fly. One relevant coordination scheme was studied in [24]. However, it is not known how many HDVs today that are actually driving within close distance to benefit from the lowered air drag, and how much fuel the vehicles could be saving through platooning.

The main contribution of this paper is the development of a method that takes a digital road network and vehicle probe data in order to analyze spontaneous platooning and how the platooning possibilities can be increased through coordination schemes. The method is divided into four steps, where the two initial steps are to map the vehicles' positions to the road network and infer the path the vehicles took. This is done through simple map-matching and path-inference techniques. The last two steps are to analyze HDV platooning rate and fuel savings from the provided vehicle probe data and to investigate possible platooning through coordination. We obtained vehicle probe data from Scania's FMS on one day over a region in Europe and used OpenStreetMap (OSM) as the digital road network. We are mainly interested in the highway road network, since that is where platooning has most benefits. This enables us to investigate the current HDV platooning rate and fuel savings from spontaneous platooning. Furthermore, coordinating scattered HDVs on a road network for fuel saving can be done in several ways. In this work, we propose three different coordination schemes to improve the fuel savings and platooning rate, namely; a catch-up coordination scheme where the follower vehicle drives faster and catch up [24], a departure coordination scheme where the lead vehicle adjusts its departure time to match with other vehicles to platoon, and a transport coordination scheme where we analyze the possibility to adjust the transport schedule in order to increase the platooning rate.

The remaining part of this paper is outlined as follows. Section II describes the problem formulation. Section III introduces the methods. Section IV presents the evaluation results using data collected over a day in a region in Europe. Lastly, Section V concludes the paper.

II. Problem Formulation

We consider a road network with HDVs, see Fig. 2. A node, in the road network, is a geographical point described with a unique id, longitude, and latitude. It can have attributes such as altitude or speed sign. A way, in the road network, is an ordered list of nodes that describes the road and the road type such as a highway or a small street. The way

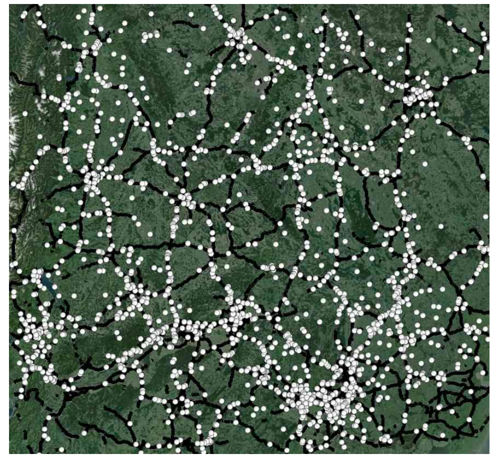

Fig. 2. A snapshot of all vehicles on the OSM road network. Black lines are the OSM road network and the white dots are vehicle probe data.

consists of a unique id and at least two nodes. A vehicle traveling on the road network is described with a unique vehicle id and timestamped location with longitude, latitude, and heading. We introduce the term link, for simplicity, as an edge between two nodes in the road network. Note that there is a unique way for each direction of the road.

The problem we consider is to determine the platooning rate of N vehicles scattered on a network given their timestamp and locations. We want to study the impact platooning and coordination have on fuel savings on a network with several roads and several vehicles traveling on it. It is difficult to estimate what impact platooning has on a more regional perspective when studying platooning on vehicle level, because those studies might differ from each other depending on factors such as vehicle type, control, and driver. Therefore, a study on a network gives a more general understanding what impact platooning has.

The method of this study consists of several steps; map matching, path inference, spontaneous platooning analysis and platoon coordination potentials. In map matching, the probe data is projected into the underlying road network. Path inference then finds a trajectory through the map-matched probe data. Third, we analyze how many vehicles have platooned given their time and path. Lastly, we study if we can increase the platooning rate and the fuel savings from the spontaneous platooning state through vehicle coordinations based on the existing situation.

Fuel Model and Platooning Rate

In order to analyze the fuel savings through platooning, a fuel model is needed. There are sophisticated fuel models presented in [3], [24], however since neither the mass of the vehicles nor the slope of the roads are known, we chose a simple fuel model. Since the air drag force is proportional to the velocity squared, we propose the following simple fuel model:

$$f = K_E v^2 d \phi(d_r)$$

where f is the fuel cost, K_E is an energy conversion constant, v is the velocity, and d is the traveled distance. Since platooning leads to reduced fuel consumption, we

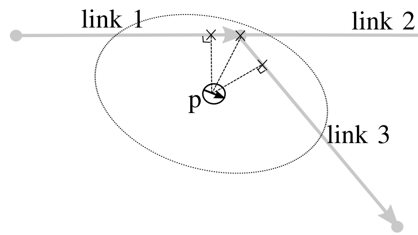

Fig. 3. An example where the probe data p has three link intersecting the neighborhood. Each intersected link gets a projection of the probe data and is a candidate link for path inference. In our case, in a junction we only keep the exiting links, hence only link 2 and 3 are the candidate links.

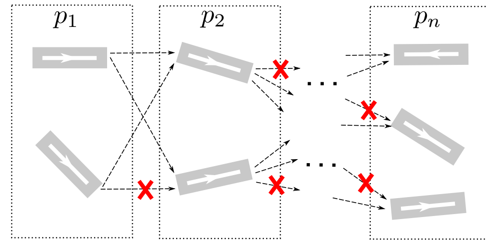

Fig. 4. To infer the path for a set of probes requires one to check each possible combination of each possible probe pairs.

assume a 10 % lower fuel cost for the follower vehicle when platooning, that is:

$$\phi(d_r) = \begin{cases} 0.9 & \text{if } d_r \leq \text{platoon distance} \\ 1 & \text{otherwise} \end{cases}$$

where $d_r > 0$ is the relative distance to the vehicle in front, hence always positive, and platoon distance is a constant that we set, which will be described later on. Our base scenario that we compare with are when vehicles are driving alone with no platoon benefits, i.e. $\phi = 1$.

We define platooning rate as the distance platooned for all vehicles (including the lead vehicle despite not gaining any fuel savings from platooning) over the total distance driven:

$$PR = \frac{\sum_i d_i(\text{platooned})}{\sum_i d_i}$$

III. Methodology

We use OSM as the digital road network, where the road attribute of motorway, motorway_link, trunk and trunk_link were extracted from OSM. This is obtained through osmfilter. The vehicle probe data set is obtained from Scania HDVs equipped with GPS units over one whole day in spring 2013 over a 500,00 km^2 region in Europe. The data set contained 7634 HDVs, which includes both long-haulage and local-distribution HDVs. The probe data consists of timestamped longitude, latitude, heading information, and an id which is unique for each vehicle with the GPS unit. Each vehicle asynchronously sent their position information to the FMS with an interval of 5-10 minutes.

A. Map Matching

Due to errors in the GPS measurement and the digital road network, probe data of a vehicle is usually not located on a link in the digital road network. The map-matching process identifies a set of candidate links within the neighborhood of the probe by looking in a geometrically defined neighborhood around the current position. The choice of shape and size of the neighborhood should be chosen wisely since it affects the computational complexity. With larger neighborhood comes more possible candidate links and with too small neighborhood comes the risk of not enclosing any links. For each candidate link, a projection of the probe is made, see Fig 3. We chose a rotated ellipse with respect to the heading of the vehicle probe as our neighborhood with a radius of 50 m in x-direction (the direction of the vehicle) and 20 m in y-direction. We also had a maximum angle difference, between the vehicle's and link's heading, threshold set to 30° in order to remove the opposite road direction. Additionally, if there are several candidate links with the same way id, we only keep the one that has the shortest distance to the probe. Furthermore, if there is a junction (like in Fig. 3) within the neighborhood then there will be at least three candidate links, which some will give the same path when inferring the path (like in Fig. 3, link 1 will also contain link 2 or 3, depending on which of those goes to the next map-matched probe). Therefore, to reduce the amount of candidate links, only the outgoing links in a junction will be considered as candidate links. Since we are looking at the highway road network, we will have many GPS probes that are not map matched into the road due to HDVs driving on smaller roads and into the cities. Therefore, to have a consistent good data set, we put a minimum threshold of at least ten map-matched points (not necessarily consecutive) needed for each vehicle, otherwise we discard that vehicle data.

This whole process is also known as topological map matching where the probe is matched to a link. The other two types are geometric, which matches the probe to a node, and advanced, which uses advanced techniques such as Kalman filter, fuzzy logic, etc. to match a probe correctly to the road network.

B. Path Inference

To infer the correct path a vehicle has taken between two points, a simple approach was used since the possible paths taken on the highway road network are only a handful. The method is a brute-force method. We look in every possible path between two map-matched points and take the shortest path of them all. However, we do not look further than a distance limit, which is how far an HDV can travel within the time between two points. We also calculate the average speed between points to ensure that the HDVs did not travel beyond its capability, which is set to 100 km/h. The average speed is used when calculating the fuel cost.

To infer the path from start to end for each vehicle, each possible combination between the probes has to be checked as seen in Fig. 4. The more candidate links there are, the more combinations have to be checked, hence the need of a wisely chosen neighborhood in the map-matching process. Since there is a possibility that some probes were not map matched, the path inference can sometimes yield no result between two map-matched points. We then split the results into segments with uninterrupted paths and after computing all possible combinations we keep only the segment with most probes. If there are several segments with the same

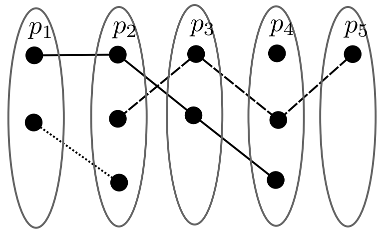

Fig. 5. An example of path inference for five probes p_i, each node represent a candidate link. Here we have three different segments; lined, dashed and dotted. Since both the lined and dashed segments are the ones with the most probes, we have to check the traveled distance on each of them and keep the one which is the longest.

amount of probes, then out of those we keep the segment with the longest driven distance, see Fig. 5. The segment should at least consist a minimum of seven probes, otherwise the whole vehicle data set is discarded. In Fig. 6, we see an example of a vehicle's GPS locations (red line), map-matched data (yellow line), and path inferred data (blue line). We can see that all probe data were not map matched, there are several points (upper left of the figure) where the vehicle were outside the road network. The next point that was map matched will have a much higher timestamp and this means that the average velocity between the two map-matched points will be really low. This will most likely yield to no platooning possibilities even though it could have platooned in reality until it drives out from the highway. An example in Fig. 6, assume that the vehicle is on the highway at t_1, then drives off the highway at t_3 and comes back at t_7. The vehicle records the GPS position at t_1, t_4, and t_7, which means that the probe at t_4 will not be map matched since it is outside the highway. If the path inference manages to find a path between t_1 and t_7 then it will result in a low average speed, which leads to no platooning opportunities, despite that it might have been able to platoon between t_1 and t_3 in reality. Nonetheless, we still keep the data despite having a part with really low velocity.

C. Spontaneous Platooning

To be able to study whether the vehicles did platoon with each other or not, we have to check if there were any vehicles in front the other vehicle. Before analyzing spontaneous platooning, we need to match the timestamps of the vehicles, this is done by interpolating the path with respect to the time. Since the vehicles are map matched and path inferred into the road network, it is sufficient to look whether there are vehicles ahead or not on the same path. By looking at the vehicle's own path a certain distance ahead, that we call platoon distance, and if another vehicle is within the platoon distance, we assume they platooned. This has to hold for two consecutive time instances for the vehicle to have platooned over the distance. That is, if there is a vehicle in front within a certain distance at time instance t_i and t_{i+1}, then the vehicle has platooned the distance between the time instances. If it only holds for one time instance, for example the platoon splits midway, then we assume that platooning did not occur. Furthermore, the relative speed should not differ more than 5 km/h at both time instances, otherwise it will not be considered as platooning. This is to ensure that the vehicles were most likely driving behind each other. This analysis will tell us how many vehicles are platooning today and approximately how much they save in fuel compared to have driving alone. This result will also be compared to the savings when doing platoon coordination at the next step.

Fig. 6. An example of a vehicle's raw probe data (red line), map-matched data (yellow line), and the inferred path (blue line). Notice that some probe data are outside the road network and could therefore not be map matched, however the path inference managed to find a path between all map-matched points.

D. Coordinated Platooning

In order to investigate what the possibilities are to increase the platooning rate, we consider three coordination schemes; catch-up coordination, departure coordination, and transport coordination.

Catch-up Coordination: As the name suggests, we consider the possibility for vehicles to catch up to each other. A follower vehicle drives faster and merge with the lead vehicle and platoon until they split or reach destination. At each time step t_i we check if there are any vehicles within a horizon ahead, that we call coordination horizon. For each candidate vehicle within the coordination horizon, we check which of those candidates give us the highest fuel savings if a catch up is made. The catch up is simply driving +15 km/h (with maximum speed of 100 km/h) of the vehicle's own speed profile until we merge and then we drive at the lead vehicle's speed profile until we no longer can platoon together. After split we resume with the vehicle's own speed profile. This is done by finding the common path of both vehicles then calculate the fuel cost compared to have maintained its own profile. If it deems beneficial to catch up, then we set a flag on the lead vehicle so it does not consider catching up to other vehicles ahead of it. This way, we avoid having a vehicle catching up a vehicle catching up to another vehicle. We only coordinate vehicles that are driving alone and they can either form platoon with other vehicles or platoons, but we do not execute catch ups on vehicles already in a platoon.

Departure Coordination: In this coordination scheme, we consider the possibility for the vehicles to adjust its departure time in order to match other vehicle in order to increase the platooning rate. We first check which vehicles platoon at least once during the day and exclude them from adjusting their departure time. At each time step, each vehicle checks if there are any vehicles within the coordination horizon (similar to the catch-up coordination). For each candidate vehicle within the coordination horizon, we check how long it takes for the follower vehicle to reach the candidate vehicle's current location and also how far they can travel together. The relative velocity has to be within 5 km/h at all times, otherwise we assume that the common path ends when it no longer holds. The fuel saving for platooning the common path is calculated. We do this for each time step

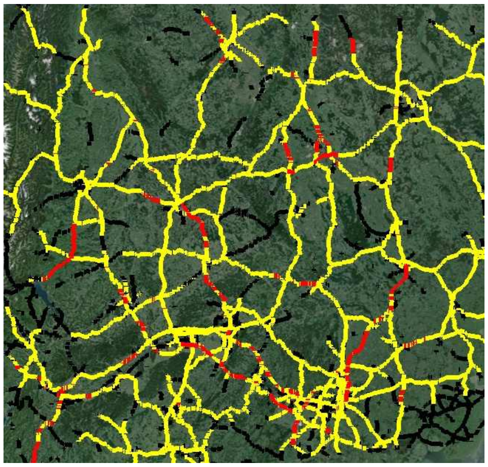

Fig. 7. The path inferred vehicles on the OSM road network. Black lines are the road network, the yellow lines are the path-inferred vehicles and the red lines are the distances were the vehicles spontaneously platooned. The vehicles covered most of the road network.

and for each vehicle and store it as vehicle pairs in a global candidate vehicle list. Notice that a lead vehicle in a platoon can check for candidate vehicles, however all the vehicles in a platoon cannot be candidate vehicle since they platoon at least once during the day. We then check which vehicle pair (one vehicle can be in several other pairs) saves the most fuel and execute it. We remove the vehicle pair from the list and also in any other pair the vehicles might be included in, then we repeat until the list is empty. This way we avoid having vehicle one adjusting its departure to vehicle two and vehicle two adjusting its departure to vehicle three, ending with vehicle one driving alone again with adjusted departure. This coordination scheme can also be seen as the lead vehicle, instead of adjusting its departure time, is stopping for a break or refueling, or the follower vehicle departures earlier.

Transport Coordination: In transport coordination, we look the problem in a different perspective. Instead of looking at the vehicles, we are looking at the road segments. A road segment often starts and/or ends in a junction. Note that the direction of the road segment matters. Since we already path inferred the vehicles and have the timestamps, we can check when each vehicle enters a road segment. By checking at each road segments the time a vehicle enters the road segment, if several vehicles enter the same road segment within a time interval, we say that those vehicles platoon the whole road segment despite if they are not within the platoon distance. Example, if we set a time interval of one hour, we check each road segment if there are vehicles entering between 00:00–00:59, 01:00–01.59 and so on until 23:00–23:59. If there are more than two vehicles entering the same road segment within the same time interval, we assume they platooned the whole road segment. We then sum up the results of all intervals. Furthermore, we do not change the vehicles' time or speed profiles, we mainly analyze the possibilities for platooning through possible transport rescheduling. Since this approach is different from the previous two coordination schemes, a different fuel model is used;

$$f = \begin{cases} K_{\tilde{E}} d_{road}(1 + (N-1)\phi) & \text{if } N \geq 2 \\ K_{\tilde{E}} d_{road} & \text{if } N = 1 \\ 0 & \text{if } N = 0 \end{cases}$$

where f is the fuel cost which is 0 if no vehicles enters the road, N is the amount of vehicles entering the road, $K_{\tilde{E}}$ is an energy conversion constant, d_{road} the length of the road segment, $\phi = 0.9$ is the reduced fuel cost for platooning.

IV. Results

After the map-matching and path-inference processes, only 1,773 vehicles remained out of 7,634. The reason for so many discarded vehicle data is due to the probe data contain many local-distribution vehicles that drove on smaller roads. Figure 7 depicts in yellow the paths at least one of the 1,773 vehicles took on the road network. The amount of active moving vehicles along the day can be seen in Fig. 8. Note that most of the time we have between 250–350 vehicles active. The minimum and maximum distance traveled out of the 1,773 HDVs are 24 and 948 km respectively. The total distance traveled for all HDVs are 505,945 km.

In order to investigate the spontaneous platooning rate, we set the platoon distance to 100 m[1]. If there are vehicles ahead on the same path within the platoon distance for two consecutive time steps, we assume the vehicle has platooned over that time. The result for spontaneous platooning rate is 1.21 %, which means that 1.21 % of all the vehicles' traveled distance were traveled in platoons. Since only the follower vehicles gain 10 % fuel savings in a platoon, this only gave an overall fuel savings of 0.07 % compared to have driven alone and not considering the platooning effect. This can also be seen in Fig. 9 were the amount of platoons (blue line) stayed very low throughout the day, which means that not many vehicles are platooning in this data set. The reason for fluctuations is that the distance to the vehicle ahead fluctuated around 100 m. Which part in the region where the vehicles platooned can be seen in Fig. 7 (red lines). We increased the platoon distance to 1 km in order to see if there are vehicles nearby for possible coordination. So if there are a vehicle within 1 km on the same path as the follower vehicle at two time steps, then the follower vehicle gains the platooning benefit. With no surprise, the fuel saving and platooning rate increased and they increased to 0.27 % and 4.85% respectively. This does not consider velocity changes to coordinate and form platoon, it just merely indicates that there are vehicles close by that could possibly platoon with.

Since by increasing the platoon distance to 1 km showed a higher possible fuel savings, it would be interesting to see the actual fuel savings where the follower vehicle increases velocity in order to catch up and merge. For the catch-up coordination, we investigated four different coordination horizons; 1, 5, 10, and 20 km. The coordination horizon is the horizon length where we search for possible vehicle candidates to form platoons with. The follower vehicle only obtains the 10 % fuel saving when the relative distance to the lead vehicle is within the platoon distance of 100 m at two

[1]We consider this a reasonable distance for platoon benefits due to the reason that the gap can be shortened very easily with no need of coordination.

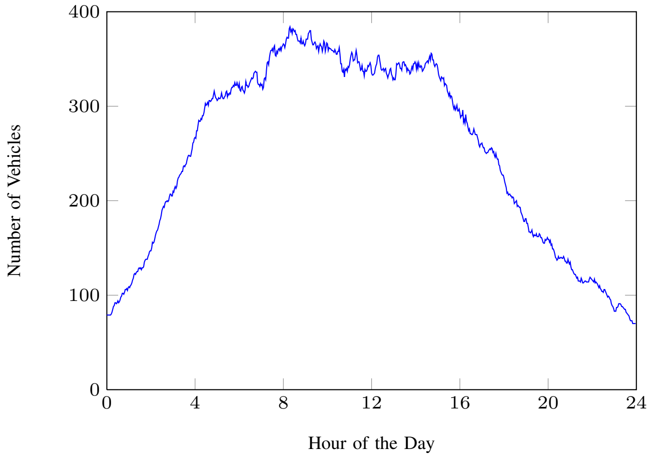

Fig. 8. Total vehicles moving at a given point throughout the 24-hour period.

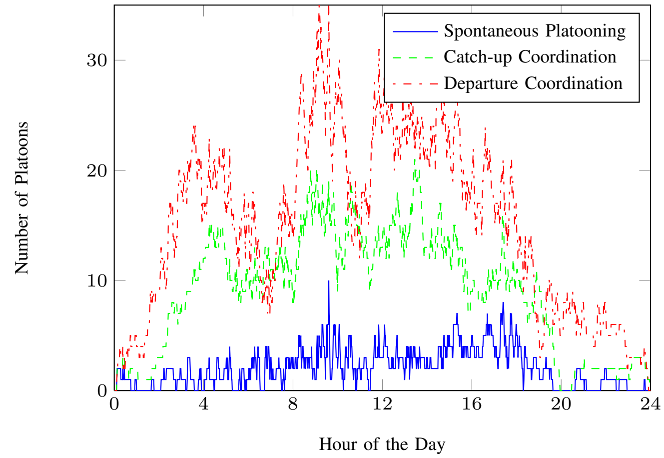

Fig. 9. Amount of spontaneous platoons and platoons through catch-up coordination and departure coordination throughout the day. The platoon distance and coordination horizon is set to 100 m and 20 km respectively. The amount of platoons overall increases roughly five and eight times through catch-up coordination and departure coordination, respectively, compared to spontaneous platooning.

consecutive time steps. This also applies when calculating the platooning rate. However, we do not consider coordinating vehicles already in a platoon. The results can be seen in Table I.

TABLE I
RESULTS WITH CATCH-UP COORDINATION.

Coordination horizon	Fuel saved	Platooning rate	Catch ups made	Minutes saved
1 km	0.17%	4.66%	157	158
5 km	0.21%	6.59%	204	245
10 km	0.22%	6.94%	209	267
20 km	0.22%	6.97%	210	268

As it can be seen, with a longer coordination horizon, the more possible candidate vehicles there were to platoon with and hence it gave more catch-up possibilities which increased both the platooning rate and fuel saving. The fuel saved is compared to vehicles that drive alone and that do not benefit from platooning. The fuel saving is an average over all vehicles and not the average of the vehicles that platooned, which would be much greater since most vehicles are not in a platoon. We can notice that the results between 5, 10, and 20 km do not differ significantly, this means that most of the beneficial catch-ups are done with vehicles close by. The amount of platoons during the day is depicted in Fig. 9 (green dashed line) and it can be seen that it has increased overall by an average of approximately five times compared to spontaneous platooning.

We also analyzed departure coordination with the same coordination horizon as in catch-up coordination. A vehicle is allowed to adjust its departure only if it will not platoon at all throughout the transport delivery. Notice that these two coordination analyses are done separately. Also notice that a coordination horizon of 20 km corresponds approximately to 15 minutes drive of highway speed. The results can be seen in Table II.

Similarly to catch-up coordination, we see that the longer coordination horizon is, the higher platooning rate and fuel saving. Furthermore, a departure coordination gives a much higher fuel saving compared to catch-up coordination. This

TABLE II
RESULTS WITH DEPARTURE COORDINATION.

Coordination horizon	Fuel saved	Platooning rate	Total adjusted departures	Avg minutes adjusted
1 km	0.11%	2.08%	105	2.6
5 km	0.27%	4.91%	319	5.5
10 km	0.42%	7.56%	434	7.2
20 km	0.60%	10.76%	529	11.3

is mainly due to that a catch-up coordination consumes additional fuel during the catch up and has to win that back through platooning before starting to save fuel. While as, the departure coordination allows the vehicle to form platoons with no extra fuel cost, however in expense of adjusting departures while catch-up coordination saves time. Hence, the departure coordination do not saturate with longer coordination horizon as it does for catch-up coordination. Although the departure coordination adjusts the departure time, it is only changed by a few minutes, which in most cases are acceptable and within the time frame of the transport. The amount of platoons during the day has increased even more compared to catch-up coordination, which can be seen in Fig. 9 (red dashed-dotted line).

TABLE III
RESULTS WITH TRANSPORT COORDINATION.

Time interval	Fuel saved*	Platooning rate
5 min	0.68%	13.22%
10 min	1.19%	22.41%
15 min	1.64%	30.26%
30 min	2.74%	47.58%
1 hr	4.31%	68.07%
2 hr	5.94%	83.23%
3 hr	6.87%	89.93%
6 hr	8.06%	95.67%
12 hr	8.85%	98.38%
24 hr	9.37%	99.38%

*Different fuel model used compared to the two previous coordination schemes.

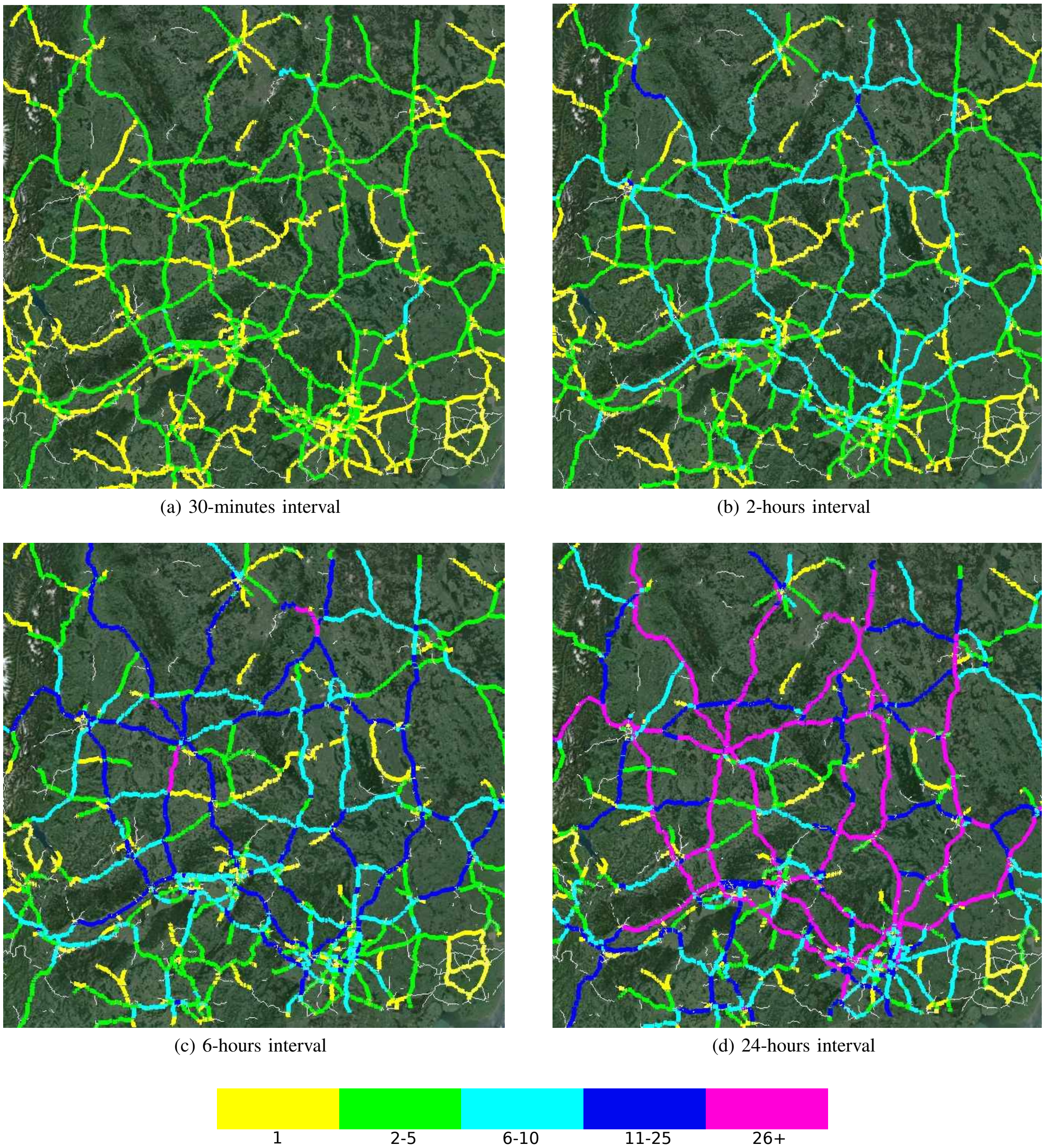

Fig. 10. Highest amount of platoons with transport coordination illustrated with line colors on the road network for four different time intervals, where the line colors represent the amount of vehicles entering the road segment within the same time interval. There are more possibilities to form more and longer platoons if all the vehicles can travel at the same time (d) compared to allowing small adjustments (a).

We noticed that the departure coordination showed promising fuel saving the more we let the vehicles adjust their departure time. This gives us incentive to study further with transport coordination and check the fuel saving potentials. The transport coordination scheme analyzes when vehicles enter the same road segment within the same time interval. We chose several different time intervals and the results can be seen in Table III.

We can see that with higher time interval, the more opportunities there are for vehicles to platoon with each other. Let us take 24-hours time interval for clarification. This means that we allow any vehicle to reschedule their transport to any time on the day and try to maximize the fuel saving by letting every vehicle travel together at the same time. For 12-hour time interval, there are two time slots and this means that it will be slightly less vehicles traveling on the same road segment within the time interval to platoon with. This is illustrated in Fig. 10 with four different time intervals, it shows the time slot with the highest amount of platoons on each road segment. For the 30-minutes time interval, we can see that most platoons consist of 2–5 vehicles while as for the 24-hours time interval the platoons consist of several vehicles. This explains why the fuel saving for 24-hours time interval is more than three times higher than 30-minutes time interval while the platooning rate only doubled, this is due to that the first vehicle does not reduce its fuel consumption in a platoon. Notice that 5-minutes and 10-minutes time interval are closely related (based on the average adjusted minutes) to 5 km and 20 km coordination horizon departure coordination, but the fuel saving and platooning rate differ noticeably. This is because with departure coordination, we adjust the vehicles' departure time and do not adjust the departure of the vehicles that will platoon at least once during its transport even if it is only for a short distance. There could have been possibilities that if the vehicle (that platooned at least once) adjusted its departure, the fuel saving would be even higher. For transport coordination, we do not consider changing the vehicles' speed or time profile, we only check when those enter a road segment. In practice, the vehicles would need to adjust their profiles which would then also affect the future road segment entrances. We can consider that the departure coordination gives us a lower bound and the transport coordination gives us an upper bound of possible fuel saving and platooning rate.

V. Conclusion

We have studied the platooning rate of Scania HDVs during a 24-hour period in a region in Europe through their low-sampled GPS positions. This is done with help of map-matching algorithm to infer the path the vehicles had taken. Unfortunately, the vehicles do not platoon spontaneously with each other that often. Only two, three active platoons out of 250–350 active vehicles throughout the day. Take note that this does not really reflect reality due to the reason that the HDVs might have platooned with other HDVs that were not equipped with GPS units or with other non-Scania HDVs. This only gives an indication that the platoon rate is quite low. This is not a surprise considering that a commercial platooning system does not yet exist unless the adaptive cruise control (ACC) is considered as one. Hence, the drivers are either using the ACC or driving manually close behind another vehicle. Furthermore, there are vehicles within a reasonable distance that one could possibly coordinate with, which we showed and were able to increase the platooning rate by a factor of nine through departure coordinations with a reasonable small adjustments on the departure time. Even though the fuel saving of 0.60 % for departure coordination seems quite low, this corresponds to approximately a total of 640,000 liter diesel fuel saved yearly (based on average fuel consumption of 0.3 liter/km and HDV traveling 200,00 km per year [3]). However, if we allow higher flexibility on their departure time and arrival time on the good transports then the fuel saving and platooning rate can be increased significantly, up to 9.37 % and 99.38 % respectively if all the vehicles traveled at the same time.

Acknowledgment

The authors would like to thank Jordi Badia Canal for his contributions.

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