Heavy-Duty Vehicle Platoon Formation for Fuel Efficiency

Kuo-Yun Liang, Jonas Mårtensson, *Member, IEEE*, and Karl H. Johansson, *Fellow, IEEE*

***Abstract*—Heavy-duty vehicles driving close behind each other, also known as platooning, experience a reduced aerodynamic drag, which reduces the overall fuel consumption up to 20% for the trailing vehicle. However, due to each vehicle being assigned with different transport missions (with different origins, destinations, and delivery times), platoons should be formed, split, and merged along the highways, and vehicles have to drive solo sometimes. In this paper, we study how two or more scattered vehicles can cooperate to form platoons in a fuel-efficient manner. We show that when forming platoons on the fly on the same route and not considering rerouting, the road topography has a negligible effect on the coordination decision. With this, we then formulate an optimization problem when coordinating two vehicles to form a platoon. We propose a coordination algorithm to form platoons of several vehicles that coordinates neighboring vehicles pairwise. Through a simulation study with detailed vehicle models and real road topography, it is shown that our approach yields significant fuel savings.**

***Index Terms*—Decision making, intelligent transportation systems, road transportation, velocity control.**

I. Introduction

THE emand for freight transportation is continuously increasing while the environmental impacts need to be reduced significantly. Transportation is responsible for the main part of the increased oil consumption during the last decades and it is expected to continue to grow. Fortunately, the developments within intelligent transportation systems (ITS) has enabled solutions to mitigate the environmental impact. One approach is to form heavy-duty vehicle (HDV) platoons, which are convoys of HDVs driving at small inter-vehicle distances, such that the trailing vehicles experience reduced aerodynamic drag, as illustrated Fig. 1. This reduces the overall fuel consumption and therefore it reduces the operational cost for vehicle owners in addition to reduce greenhouse gas emissions.

Fig. 1. Five HDVs platooning on a Swedish highway.

While research into vehicle platooning originated from studying the traffic dynamics and behaviors more than 50 years ago [1], [2], in the form of string stability analysis [3], most of the work has been focusing on vehicles already in a platoon. For example, air drag reduction [4], control designs [5], [6], inter-vehicle communication [7], string stability [8], [9], and safety [10], [11], have been studied for vehicle platoons. Most of the early work was mainly theoretical and it was only during the last two decades that it was possible to implement the platooning concept. Some recent projects aiming at demonstrations of HDV platooning include GCDC [12], KONVOI [13], PATH [14], PROMOTE-CHAUFFER [15], SARTRE [16], and Energy ITS [17]. The projects [14]–[17], as well as recent experimental evaluation of platooning [18], [19] have shown fuel savings of 5–20% depending on the intermediate distances between the HDVs and other variables. A Federal Highway Administration funded project, led by Auburn University, aims to commercialize the platooning concept [20].

The majority of the literature on vehicle platooning has focused on vehicles staying in the platoon throughout the trip. However, in practice, vehicles have different origins and destinations meaning that platoons will have to be formed, merged, and split. Many studies have been conducted regarding how vehicles should enter or leave platoons in traffic on on- and off-ramps, respectively [21]–[24]. The focus was on safety and performance rather than fuel efficiency. Studies about fuel-efficient platoon coordination are scarce and have been neglected until recently. In [25], the authors attempt to increase platooning throughout a network by using data-mining techniques to identify common routes where platoons can be formed. The authors in [26] introduce controller at junctions in a road network with each controller coordinating and rerouting vehicles to form platoons for fuel savings. In [27], real vehicle position data were

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K.-Y. Liang is with the ACCESS Linnaeus Centre and the Department of Automatic Control, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden, and also with the Department of Research and Development, Scania CV AB, 151 87 Södertälje, Sweden (e-mail: kyliang@kth.se; kuo-yun.liang@scania.com).

J. Mårtensson and K. H. Johansson are with the ACCESS Linnaeus Centre and the Department of Automatic Control, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden (e-mail: jonas1@kth.se; kallej@kth.se).

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studied in order to analyze platooning potentials through simple coordination schemes. The authors in [28] propose a centralized coordination scheme to form platoons at junctions of a network based on each vehicle's shortest path to its destination. Lastly, the work in [29] studied through simulations how traffic would influence and delay a platoon formation.

In this paper, we study how several HDVs should adjust their speeds in order to form a platoon such that the platoon formation is more fuel efficient than if no formation was performed. We allow all the vehicles to act, meaning that the trailing vehicles may increase their speeds and the lead vehicles may slow down, in order to form the platoon. A speed increase of the trailing vehicles leads to a higher fuel consumption. However, the additional fuel cost can be regained from platooning long enough. A speed decrease of the lead vehicles leads to a delayed transport, which has to be compensated for with a speed increase once the platoon is formed in order to deliver the cargo in time. This coordination action implies that all the trailing vehicles will arrive to their destinations earlier than if no action were taken. Further fuel savings can be obtained by letting the vehicles slow down once the platoon splits, but this is not considered in this paper.

We are aware that in practice today, it might not be feasible for the HDVs to increase their speeds since most of the vehicles are already driving at their maximum allowed speed. This is mainly because the HDV drivers cannot predict the traffic ahead of time and therefore they drive at maximum speed in order to ensure that the goods are delivered in time. However, with improved traffic predictions, the drivers can drive at a lower speed, which enables the possibility to form platoons through speed adjustments. Additionally, if it is a frequent transport mission, the fleet owner can plan the transport more carefully with past traffic experiences from the drivers allowing for more leeway.

The main contribution of this paper is the proposal and study of a novel algorithm to coordinate scattered vehicles to form platoons for fuel savings. The algorithm is based on coordinating vehicles pairwise. Furthermore, a coordination decision is made only when the vehicles are driving on the same road. For the two vehicle case, we formulate this problem as an optimization problem. We show the strengths of our proposed algorithm for several different scenarios. Our work is a natural and significant extension of [30], which addresses a single HDV increasing its speed to catch up with other vehicles or platoons. In this case, the catch up is beneficial if the fuel savings when platooning exceed the additional fuel cost of catching up. Furthermore, only the trailing vehicle makes the action to form a platoon while the lead vehicle[1] maintains its speed. In the current paper, the proposed algorithm involves all vehicles to act in order to form the platoon as fuel efficiently as possible without delaying the transports. Note that the algorithm does not guarantee that individual vehicle saves fuel but the vehicles will guaranteed save fuel in total.

The outline of this paper is as follows. First, the problem formulation is presented in Section II. Then, in Section III, we present the model that is used for the coordination decision. We formulate the optimization problem for coordinating two scattered vehicles to form a platoon and compare it to a pure catch up in Section IV. We extend the coordination concept in Section V and propose a coordination algorithm to form platoons with several scattered vehicles. In Section VI, we evaluate our approach through simulations. Lastly, in Section VII we conclude our work and give an outlook for future work.

[1]Lead and trailing vehicle do not necessary mean that the vehicles are in a platoon, only that one vehicle is first and another vehicle is somewhere behind it.

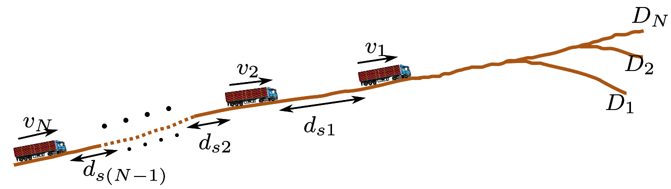

Fig. 2. N scattered vehicles on the road driving at speeds v_i, $i \in [1, \ldots, N]$, with different destinations denoted by D_i. The vehicles are separated by the distances $d_{s1}, d_{s2}, \ldots, d_{s(N-1)}$.

II. Problem Formulation

We consider a scenario with N scattered HDVs driving on a road as illustrated in Fig. 2. Each vehicle may have a different destination (denoted by D_i), hence will exit the highway at different road junctions. Each HDV is driving at the speed v_i, $i \in [1, \ldots, N]$. The nominal case is when no vehicle platoons. The objective is to minimize the total fuel cost through platooning without delaying the HDVs. Each vehicle's time constraint is modeled as their distance to destination (or highway exit) divided by the speed v_i, i.e., $t_c^i = d_f^i / v_i$ where t_c^i is the time constraint and d_f^i the distance to destination for vehicle i. Given these N vehicles, it is not evident how to minimize the fuel cost by forming platoons. The number of possible platoon formations grows exponentially with N and it is not obvious which vehicles should form platoons and how to form them in a fuel efficient manner.

Consider a pairwise formation of platoons, i.e., pair the two closest HDVs to form a platoon and then pair the two closest sub-platoons to form a larger platoon and so on. The pairwise formation will be executed only if the pair of vehicles saves fuel compared to their nominal case. This allows a formation of a (eventually) long platoon. For each pairwise formation of platoons, there is a lead and a trailing vehicle. In order to form a platoon with two HDVs, both vehicles potentially have to adjust their speeds, i.e., the lead vehicle slows down while the trailing vehicle drives faster. Once the platoon has been formed, the platoon will drive such that the transport mission will not be delayed. Hence, each pairwise formation have both speed and time constraints that need to be fulfilled. Note that the pairwise formation does not guarantee that each vehicle saves fuel. One vehicle might not benefit, while the other vehicle benefits greatly resulting in a total fuel saving.

The problem we solve in this paper is thus the following: compute the fuel-optimal speed for two vehicles in order to form a platoon that yields fuel savings without delaying the transport and then introduce an algorithm that enables forming platoons of several vehicles by pairwise coordination.

III. Modeling

In this section, we present a fuel model that will serve as a basis for the analysis and optimization problem. We describe the fuel model and how a coordination decision can be simplified before setting up the problem as an optimization problem in Section IV.

A. Fuel Model

A longitudinal vehicle model can be derived from Newton's second law of motion as

$$\begin{aligned}\frac{\mathrm{d}s}{\mathrm{d}t} &= v\\ m_t\frac{\mathrm{d}v}{\mathrm{d}t} &= F_v - F_{\text{roll}} - F_{\text{gravity}} - F_{\text{airdrag}}\\ &= F_v(t) - mgc_r\cos\theta(s) - mg\sin\theta(s)\\ &\quad - \frac{1}{2}\rho A c_d v^2(t)\Phi(d_r)\end{aligned} \tag{1}$$

where t denotes time, s the position of the vehicle, v its velocity, F_v the force produced by the vehicle, m the mass of the vehicle, m_t the effective mass, θ the slope of the road, g the gravitational constant, c_r the rolling resistance coefficient, ρ the air density, A the maximum cross-sectional area of the vehicle, c_d the air drag coefficient, and $\Phi(d_r) \in [0, 1]$ the air drag ratio, which depends on the inter-vehicle distance d_r when platooning. For simplicity, we assume a fixed air drag ratio when platooning, i.e., $\Phi(d_r) = \phi$ when platooning and $\Phi(d_r) = 1$ when driving solo. The vehicle force F_v is the force produced by the engine minus the force of braking, with only one of the terms active at a time. We consider only the longitudinal direction and the vehicle to be a point mass. Also, we assume that the parameters are identical for all HDVs apart from their masses.

We derive a fuel model based on the energy required to propel an HDV. The fuel cost is proportional to the consumed energy, which can be described as

$$f_c = k_E \int \delta(t)F_v(t)v(t)\,\mathrm{d}t = k_E \int \delta(s)F_v(s)\,\mathrm{d}s \tag{2}$$

where the second equality is a transformation from temporal to spatial domain. In (2), k_E is an energy conversion constant based on energy density of diesel and engine combustion efficiency and δ an indicator function to prevent negative energy when the vehicle is braking:

$$\delta = \begin{cases} 1 & \text{if } F_v \geq 0\\ 0 & \text{otherwise.}\end{cases}$$

With (1) and (2), we obtain the fuel model as

$$f_c = k_E \int \delta\left(m_t v\frac{\mathrm{d}v}{\mathrm{d}s} + k_r\cos\theta + k_g\sin\theta + k_a v^2\phi\right)\mathrm{d}s \tag{3}$$

where $k_r = mgc_r$, $k_g = mg$, and $k_a = (0.5)\rho A c_d$. The acceleration is transformed as $(\mathrm{d}v/\mathrm{d}t) = (\mathrm{d}v/\mathrm{d}t)(\mathrm{d}s/\mathrm{d}s) = v(\mathrm{d}v/\mathrm{d}s)$. The parameter values for (3) can be found in [31].

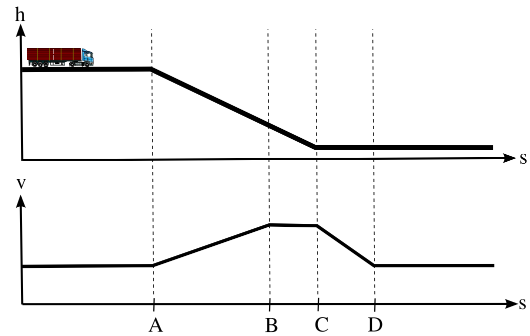

Fig. 3. Altitude (top) and speed (bottom) profiles of an HDV with CC and DHSC on a steep descent. The vehicle travels at set speed on the flat road, when it enters the descent (A) the vehicle starts to accelerate from coasting. The descent is long enough for the DHSC to activate (B) maintaining the vehicle at constant speed before exiting the descent (C). The vehicle coasts down to set speed again (D) and continue driving at set speed on the flat road.

B. Simplifying the Coordination Formation Decision

Before setting up the problem as an optimization problem we will show, based on the proposed fuel model (3) and with a few assumptions, that the air drag is the main deciding factor when making a coordination decision. The platoon formation we consider is adjusting the vehicles' speeds while keeping their original paths. We are interested in comparing whether an optimal platoon formation is more fuel efficient than the nominal case when the vehicles are maintaining the original strategy and drive to their destination alone. Thus, we check if

$$J^*_{\text{coordination}} + c_{\text{th}} < J_{\text{nominal}} \tag{4}$$

where $J^*_{\text{coordination}}$ is the optimal total fuel cost for merging and platooning the vehicles, J_{nominal} is the nominal total fuel cost that the vehicles would use if they were driving alone, and c_{th} is a threshold that needs to be overcome to consider it worthwhile to form a platoon. We will look into three aspects that will simplify the problem. We first motivate why it is reasonable to make the assumption that $\delta = 1$ at all times. This enables us to simplify the problem further by omitting the terms in (3) that correspond to acceleration and deceleration, roll resistance and gravity. The only remaining term is then the air drag resistance, which will be used for the coordination decision.

1) Steep Descent: Due to the typical large mass of an HDV, it often accelerates on descents. We define a steep descent as when an HDV can accelerate on a descent without injecting any fuel. If the steep descent is long, then the HDV will start to overspeed. To avoid this, the HDV is equipped with a feature called downhill speed control (DHSC) in order to aid the driver. The DHSC is used together with cruise control (CC) or adaptive cruise control (ACC) and its default value is often set to about 5 km/h above the set speed. When the vehicle gains speed without injecting fuel and the speed reaches 5 km/h above the set speed, the DHSC will intervene (mainly by applying retarder brakes) to avoid the vehicle from gaining more speed. This intervention corresponds to $\delta = 0$ in (3). After the steep descent, the vehicle will coast back to the set speed. This is illustrated in Fig. 3. The behavior is similar for any entry speed and slope (given that it is steep enough), but the points where DHSC intervenes and how far the vehicle will coast will differ. If the

TABLE I
ENERGY DIFFERENCES WITH VARYING δ AND ASSUMING $\delta = 1$ AT ALL TIMES ON A ROAD PROFILE WITH FLAT ROAD FOLLOWED BY A STEEP DESCENT AND A FLAT ROAD AFTERWARDS, WITH EACH SEGMENT BEING 350 m LONG SIMILAR TO FIG. 3. THE ENERGY IS CALCULATED FROM (3) WITH $k_E = 1$

v_{nom} [km/h]	v_{coord} [km/h]	Mass [t]	Slope [%]	Energy difference [kJ] $\delta \in \{0, 1\}$	$\delta = 1$
80	90	40	-2	171	484
80	70	40	-2	-213	-556
80	70	60	-2	95	487
80	90	60	-2	-138	-551
80	70	20	-3	245	484
80	90	20	-3	-288	-541
80	70	40	-3	171	492
80	90	40	-3	-213	-554
80	70	60	-3	95	494
80	90	60	-3	-138	-557

descent is short, the vehicle might not reach the DHSC limit and will just coast back to set speed on the flat road. Note that the DHSC intervenes ($\delta = 0$) between point B and C while there is no fuel injection from point A to D.

We will assume that the HDVs are driving on a moderate hilly road, where there are both some moderate and steep slopes. For moderate hilly road, we suggest assuming $\delta = 1$ at all times in order to simplify the calculations. We justify this assumption with an example. Consider a road segment as in Fig. 3 where the flat road before the steep descent, the steep descent, and the flat road afterwards are each 350 m long. We assume that the nominal speed is 80 km/h and depending on the coordination strategy, the vehicle can either drive at 70 or 90 km/h. Table I shows the energy difference $J_{\mathrm{nominal}} - J^*_{\mathrm{coordination}}$ from (4) for one vehicle. We see that the difference between varying δ (i.e., $\delta = 1$ when fuel is injected and $\delta = 0$ when braking) and assuming $\delta = 1$ at all times is large, in the order of 10% of the total energy required. The energy difference is for one vehicle, however, the idea of platoon formation is for both vehicles to cooperate. We therefore sum up the energy differences for both vehicles (slower and faster vehicle) for each scenario with varying δ and assuming $\delta = 1$ at all times, respectively. In this case the sum of the differences between the two cases is much smaller and almost negligible when the total energy for driving the whole road profile is in the order of MJ. We will therefore assume that $\delta = 1$ at all times in (3).

2) Acceleration: In a coordination formation, the vehicle will need to accelerate (or decelerate) and deviate from its nominal speed in order to form the platoon. As long as the vehicle does not brake, the energy from acceleration and deceleration will cancel each other out and only depend on the difference between initial and final velocity. Suppose that the initial and final velocities (v_s and v_f, respectively) are the same, then

$$\int v \frac{\mathrm{d}v}{\mathrm{d}s}\, \mathrm{d}s = \int v\, \mathrm{d}v = \frac{v_f^2 - v_s^2}{2} = 0. \tag{5}$$

Hence, we can omit the acceleration term from the fuel cost (3) when making a coordination decision.

3) Mass and Road Characteristics: The vehicle mass and the road characteristics significantly affect the fuel cost of an HDV. The heavier the vehicle is, the higher the fuel consumption will be. Each vehicle has to overcome the road friction in order to transport the goods. The gravity, depending on the road slope, can either be a resistive force that increases the fuel consumption or be an assistive force which can reduce the fuel consumption. We are interested in comparing the cost as in (4), hence the relative fuel cost contributed by the rolling resistance and gravity will cancel out since they are not speed dependent. We can therefore omit them from (3) when making a coordination decision.

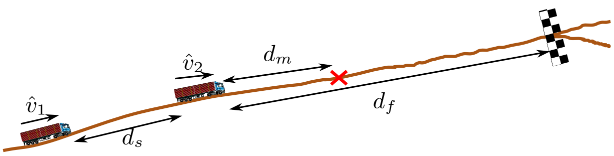

Fig. 4. Nominal case where two scattered vehicles on the road are driving at the speed $\hat{v}_1$ and $\hat{v}_2$ with a distance d_s from each other. If a coordination action is executed, they merge at d_m and platoon onwards.

IV. OPTIMAL FORMATION OF TWO HDVS

In this section, we formulate our coordination decision as an optimization problem based on the simplifications made previously. We compare the results with a pure catch up from [30] to show that further savings can be achieved with the proposed cooperative formation.

A. Optimization Problem

We have shown, based on few assumptions, that what influences a coordination decision is the energy contributed by the air drag force. Consider the scenario in Fig. 4 where the nominal case is when both vehicles are driving solo with the speeds $\hat{v}_1$ and $\hat{v}_2$, respectively, to their destinations. Consider forming a platoonThere will be two phases: a merging phase where the vehicles will merge at the red cross indicated in Fig. 4 and a platoon phase where both vehicles drive together. For simplicity, let us assume that the trailing vehicle experiences reduced air drag only when in a platoon and not during merging. We then formulate an optimization problem as

$$\min_{v_1, v_2, v_p, t_m} \underbrace{\int_0^{t_m} \left(v_1^3(t) + v_2^3(t)\right)\, \mathrm{d}t}_{\text{merge}} + \underbrace{\int_{t_m}^{t_f} v_p^3(t)\phi_p\, \mathrm{d}t}_{\text{platoon}} \tag{6}$$

where v_1, v_2, and v_p denote the speed of lead vehicle, trailing vehicle, and platoon, respectively. ϕ_p denotes the air drag of the platoon (the sum of lead and trailing HDV's air drag), t_f the time to reach the destination for the platoon, which is fixed and defined by the vehicle with tightest time constraint, and $t_m \in [0, t_f]$ the time for lead and trailing vehicle to form a platoon which is defined as

$$\int_0^{t_m} \left(v_2(t) - v_1(t)\right) \mathrm{d}t = d_s \tag{7}$$

where d_s is the initial distance between the vehicles.

The optimization problem (6) is difficult to solve in general, since the merging time t_m varies depending on the speed of the vehicles and on the road topography. As our aim is to coordinate vehicles to form platoons, and not control the instantaneous velocity of each vehicle, we simplify the problem by assuming constant (or average) speeds on each phase. The constant speed can be interpreted as a guidance speed that the vehicle or platoon should hold in average in order to form platoons. This speed is sent to a look-ahead control [32]–[34], which takes the road topography into account to drive fuel efficiently while maintaining the travel time based on the set speed. By using average speeds on each phase, we formulate the optimal formation problem for two HDVs as

$$\min_{v_1,v_2,v_p,d_m} \quad v_1^2 d_m + v_2^2(d_s+d_m) + v_p^2(d_f-d_m)\phi_p \tag{8a}$$

$$\text{s.t.} \quad t_c \geq \frac{d_m}{v_1} + \frac{d_f-d_m}{v_p} \tag{8b}$$

$$\frac{d_s+d_m}{v_2} = \frac{d_m}{v_1} \tag{8c}$$

$$v_1, v_2, v_p \in [v_{\min}, v_{\max}] \tag{8d}$$

$$d_m \in [d_{\min}, d_f] \tag{8e}$$

where $t_c = \min(d_f/\hat{v}_1, (d_f+d_s)/\hat{v}_2)$ denotes the tightest time constraint, d_m the distance to the merging point from the lead vehicle, and d_f the distance from the lead vehicle to the destination. We suppose $v_{\min} > 0$ and $d_{\min} \geq 0$. The constraint (8b), which is a time constraint, ensures that the time to reach the destination when coordinating and forming a platoon should be less than or equal to the nominal case. If the first vehicle slows down, it has to increase the speed once the platoon is formed in order to make up for the time loss. The constraint (8c) is the time to the merging point, which ensures that both vehicles are at the same spot at the same time. The constraint (8d) and the lower bound of the constraint (8e) can be adapted depending on the scenario, e.g., if the vehicles are on different roads but the road will merge at some point, then the earliest point where the vehicles can form a platoon is at the junction $d_{\min}$. Note that $d_m \leq d_f$ forces the mergence to occur before the vehicles reach the destination, this means that v_2 will always be higher than v_1.

The cost of (8a) should be less than the nominal cost, which is $\hat{v}_1^2 d_f + \hat{v}_2^2(d_s+d_f)$, as in (4), with the assumption that $c_{\text{th}} = 0$. In order to make the comparison simple, we will assume that $v = \hat{v}_1 = \hat{v}_2$ for the nominal case. By including the constraint (8c) into the cost function, we can rewrite (8) as the following platoon formation problem in (9).

Platoon Formation Problem

$$\begin{aligned}
\min_{v_1,v_2,v_p} \quad & r_d \frac{v_1^3}{v_2-v_1} + r_d \frac{v_2^3}{v_2-v_1} + v_p^2 \left(1 - r_d \frac{v_1}{v_2-v_1}\right)\phi_p \\
\text{s.t.} \quad & \frac{1}{v} \geq \frac{r_d}{v_2-v_1} + \frac{1 - r_d \frac{v_1}{v_2-v_1}}{v_p} \\
& v_1, v_2, v_p \in [v_{\min}, v_{\max}] \\
& v_1 \frac{r_d}{v_2-v_1} \in \left[\frac{d_{\min}}{d_f}, 1\right]
\end{aligned} \tag{9}$$

where $r_d = d_s/d_f$.

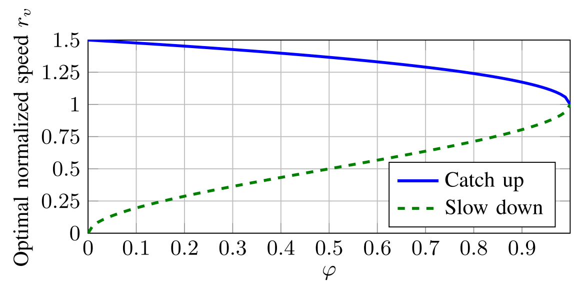

Fig. 5. Optimal normalized speed for a pure catch up and slow down, respectively, when only one vehicle acts.

The platoon formation problem can easily be extended to forming larger platoons from either two platoons or one vehicle and a platoon, by just multiplying the first term with ϕ_1 and second term with ϕ_2 in the cost function. ϕ_i would represent the total air drag of vehicle/platoon i. We use a nonlinear solver (*fmincon* in Matlab) to solve the non-convex problem (9).

B. Special Cases

We will investigate two special cases to get more insights, namely a catch-up and a slow-down scenario.

Catch Up: A catch up is where the trailing vehicle drives faster and merge with the lead vehicle, while the lead vehicle maintains its nominal speed v. Once the platoon is formed, the platoon keeps driving at the nominal speed. Hence, $v = v_1 = v_p$ and the objective function of (9) becomes:

$$\min_{v_2} \quad \frac{v^3}{v_2 - v}(1-\phi_p) + \frac{v_2^3}{v_2-v}. \tag{10}$$

The optimum can be found through the extreme points, which are given by the solutions to

$$2r_v^3 - 3r_v^2 + \varphi = 0 \tag{11}$$

where $r_v = v_2/v$ and $\varphi = \phi_p - 1$. This gives us one solution with $\varphi \in [0,1]$ and $r_v \geq 1$. The result is shown in Fig. 5 for different values of φ, which reproduces the results from [30]. The optimum speed only holds if we guarantee that the vehicles merge before the destination (final constraint in (9)), otherwise the trailing vehicle has to drive faster in order to guarantee that a platoon is formed.

Slow Down: Similar to a catch up, the lead vehicle can slow down in order for the trailing vehicle to merge. In order to get an insight in how a slow down occurs, we will ignore the time restriction (the first constraint) of the problem, and assume that only the lead vehicle will act while the trailing vehicle drives at nominal speed v throughout the whole process, hence, $v = v_2 = v_p$. This means that the lead vehicle has the same delivery time as the trailing vehicle. The objective function can then be written as:

$$\min_{v_1} \quad \frac{v_1^3}{v-v_1} + \frac{v^3}{v-v_1} - v^2 \frac{v_1}{v-v_1}\phi_p. \tag{12}$$

This gives us the same third order equation as in (11) to solve (where $r_v = v_1/v$). However the solution differs since we are now considering a slow down within the boundaries $r_v \in [0,1]$. The optimal speed is shown in Fig. 5. Note that although we

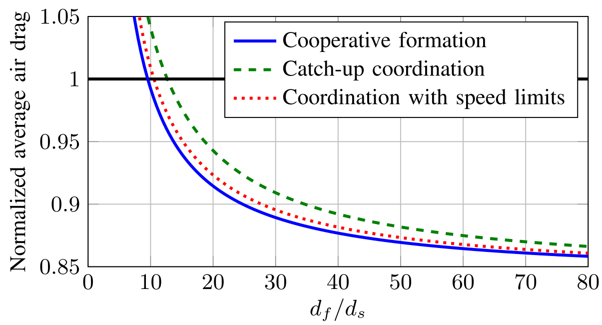

Fig. 6. The results of the objective function value from (8) for cooperative formation compared to a pure catch-up coordination from [30] and compared to cooperative formation with speed limits set to $\pm 12.5\%$ from nominal speed.

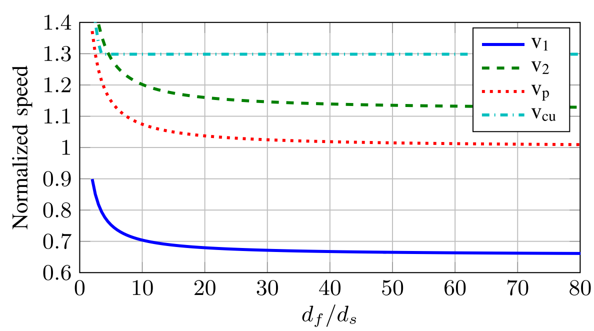

Fig. 7. The optimal speeds for cooperative formation (v_1, v_2, v_p) compared to a pure catch-up coordination (v_{cu}).

ignore the time restriction, the lead vehicle does not stop and wait for the trailing vehicle. Note also that the slow-down coordination is always more fuel efficient than the nominal case, since the average speed is lower due to the removed time constraint.

A realistic air drag reduction is 32% ($\varphi = 0.68$) [19], which corresponds about 10 m gap between the vehicles when platooning. This means that for a pure catch up, the trailing vehicle should drive 30% faster to form a platoon. For a pure slow down, the lead vehicle should slow down 38% of its nominal speed for a platoon formation. In the next section, we instead study how a cooperative formation performs.

C. Cooperative Formation

We will now show how cooperative formation compares to a pure catch up. Initially, we consider the case when (9) is unbounded, i.e., $d_{\min} = 0$, $v_{\min} = 0$, and $v_{\max}$ unbounded. We set $\phi_p = 1.68$ (assuming no air drag reduction for the lead vehicle and a 32% air drag reduction for the trailing vehicles in the platoon) and set different initial values for r_d. The solution is depicted in Figs. 6 and 7. The cost is normalized with $v^2(d_s + 2d_f)$, which is the nominal case and the speeds v_1, v_2, and v_p are normalized with the nominal speed v. We compare the cooperative formation with the pure catch-up coordination from Section IV-B (as well as from [30]). We see in Fig. 6 that the break-even ratio (the distance ratio d_f/d_s when the cost of the coordination action is equal to the nominal case, which is when the objective function value is equal to one) is lower, $d_f/d_s = 9.5$ for cooperative formation compared to $d_f/d_s = 12.5$ for pure catch up.[2] In Fig. 7, we see that the speed up (v_2) is considerably lower than for the catch-up case (v_{cu}) due to the fact that the lead vehicle assists the coordination by slowing down (v_1).

Although the cooperative formation is more fuel efficient than a catch up, as the distance ratio d_f/d_s grows the savings converge to the same value. A large distance ratio essentially means that the vehicles can platoon long enough and the objective function will converge to ϕ_p/N where N.

Let us now consider a realistic case, where the HDVs are driving at 80 km/h on the highway as the nominal case. We set $v_{\min} = 70$ km/h and $v_{\max} = 90$ km/h. The resulting optimal average speeds are $v_1 = 70$ km/h and $v_2 = 90$ km/h, with v_p something in between (depending on r_d) to ensure the transport delivery. The objective function for this case with speed limits is depicted in Fig. 6, showing a break-even ratio of $d_f/d_s = 10.5$. We note that the cost of the bounded problem does not differ much from the unbounded problem.

V. Cooperative Formation for N HDVs

In this section, we present our algorithm that enables platoon formations without looking into all possible combinations of platoon formations. We then give examples to illustrate the strengths and limitations of the algorithm.

A. Coordination Algorithm

Coordination of two vehicles to form a platoon is quite a straightforward approach. Either the coordination is executed or it is not, depending on whether fuel savings are obtainable. However, when several vehicles with different destinations are involved, it is no longer an easy task. By only considering different platoon formations (including no platoon as a formation) and not how they are executed, there are a total of $1+\sum_{k=2}^{N}\binom{N}{k}$ different formations. Even by considering a simpler scenario where all the vehicles have the same destination, there are a total of 2^{N-1} different platoon formations (since there will be no overtaking) that can be executed. This gets quickly out of hand with increased number of vehicles. We therefore suggest a coordination algorithm based on heuristics that will only consider the relevant candidates and in which the complexity grows in a gentler manner.

From the results in Section IV-C, we obtained two useful insights: the break-even ratio tells us how far (using the distance ratio d_f/d_s) a vehicle should look to find possible vehicle candidates to coordinate with, and the closer the candidate is, the higher potential fuel savings there is, given the same destination. From this we propose a coordination algorithm, as illustrated Fig. 8. The algorithm can also handle platoons to form larger platoons. A platoon's destination is where the platoon will split up. Also, vehicles and platoons that are in the process of forming a platoon are not considered as possible candidates for formation until the platoon has been formed.

We will first describe the coordination algorithm from top to bottom then describe the sidestep on the right side. Let H

[2]Note that the value of d_f/d_s here differs from the distance ratio in [30] with one unit, due to the distance ratio in [30] is defined as $(d_f + d_s)/d_s$.

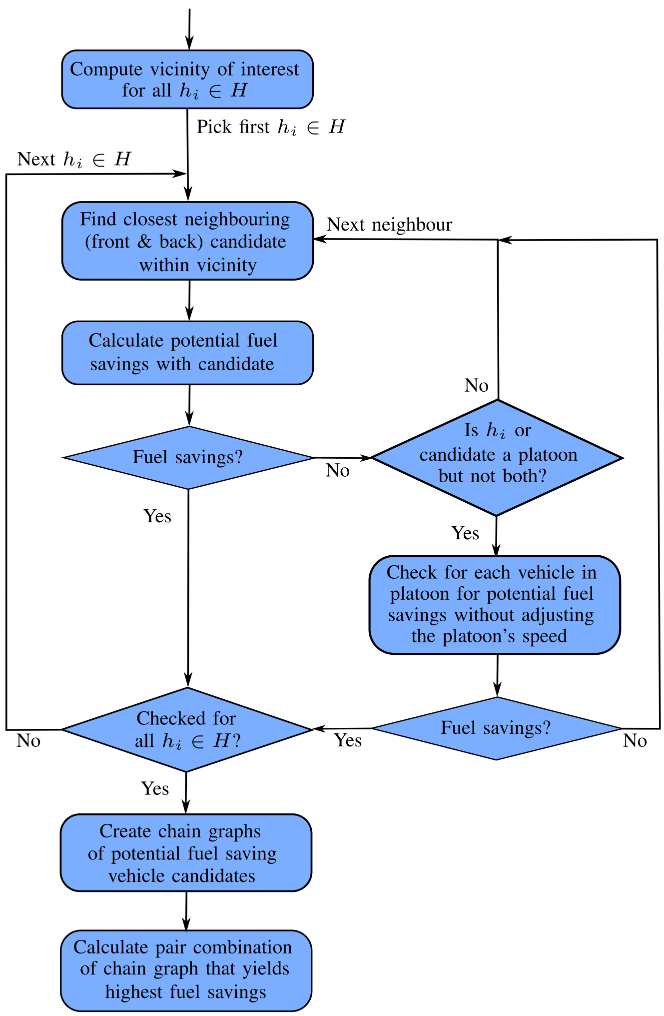

Fig. 8. Flowchart of the coordination algorithm.

be any ordered set of all the vehicles and platoons. Calculate the break-even ratio (for the unbounded problem in (9)) for all $h_i \in H$, this will serve as the vicinity of interest for each unit. Note that the vicinity will shrink as the vehicle travels closer to the destination. This only needs to be done at the start of the transport mission and when a platoon is formed or split up. Select the first unit in H, find the closest neighboring (both back and front) vehicles within the vicinity of interest and calculate the potential fuel savings from a cooperative formation (9). If the candidate also finds h_i to be the closest fuel-saving partner, then these will be a possible pair, which will be illustrated as a chain graph. This is repeated for all $h_i \in H$. We then build chain graphs of possible pairs where the edge weight represents the fuel savings. Note that each vehicle h_i can have up to two candidates, one in the front and one in the back. There might be multiple chain graphs, that are disjointed from each other. For each chain graph, the best pair combination can be easily calculated (the complexity grows linearly) for highest savings, since a node (h_i) can only pair up with the candidate in front or behind, but not both.

If the unit h_i does not find any fuel savings with the candidate (sidestep in Fig. 8), then we check if either (but not both h_i and candidate) is a platoon. If either h_i or candidate is a platoon,

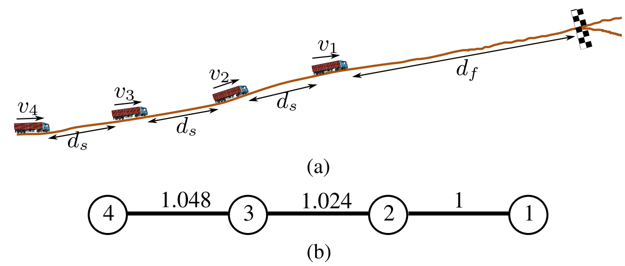

Fig. 9. Four vehicles equidistantly d_s from each other with the same destination. The algorithm represents this scenario as a chain graph with the potential fuel savings as edge weights.

then we check for each vehicle in the platoon if there are potential fuel savings when coordinating with one of the vehicles in the platoon given that we do not adjust the platoon's speed. For example, this can be when the platoon needs to split soon, however one of the vehicles travels to the same destination as h_i. Notice that we do not adjust the platoon's speed when we cannot find any fuel savings before the platoon's split point. This allows us to still coordinate platoons with platoons to form larger platoons given that they can save fuel before their respective split points. If we cannot find any fuel savings before the platoon's split point, then we check if there are any fuel savings if any single vehicle acts by itself.

B. Examples

We will give some examples to illustrate our proposed algorithm in different scenarios. Note that the algorithm can be executed several times.

1) Four Vehicles Forming a Large Platoon: Consider the scenario depicted in Fig. 9(a) with four HDVs that are equidistantly d_s from each other and the first vehicle is d_f from the destination. Let us assume that $d_s = 10$ km, $d_f = 400$ km, $v_{\min} = 70$ km/h, $v_{\max} = 90$ km/h, and nominal speed $v = 80$ km/h.

The first step is to compute each vehicle's vicinity of interest, which will be a factor of 1/9.5 (obtained from the unbounded platoon formation problem (9) for two vehicles) of the total distance to destination. In this case the vicinity will be 42, 43, 44, and 45 km respectively for vehicle 1–4, meaning that all vehicles are within each other's vicinity of interest. Starting with vehicle 1, the only candidate is vehicle 2. The distance ratio between vehicle 1 and 2 is 42, which according to Fig. 6 will yield fuel savings. Let us assume that the coordination will yield one unit of saved fuel. Next, we check vehicle 2 who has vehicle 1 and 3 as its nearest neighbors. The fuel saving between vehicle 1 and 2 has already been calculated. For vehicle 2 and 3, the distance ratio is 43 and therefore the fuel savings will yield 1.024 units. Continuing with the rest of the vehicles, we obtain a chain graph as depicted in Fig. 9(b). From this, it is easily concluded that the most fuel-saving pair combination is to pair vehicle 1 with 2 and vehicle 3 with 4. While all four vehicles are coordinating, they will not be considered in the algorithm until the platoons have been formed, which in this example will occur at the same time. Once the platoon mergence has occurred, the first platoon will be 365 km away from the destination (new d_f) and the second platoon will be 20 km behind it (new d_s). Both platoons will be within each other's vicinity of interest.

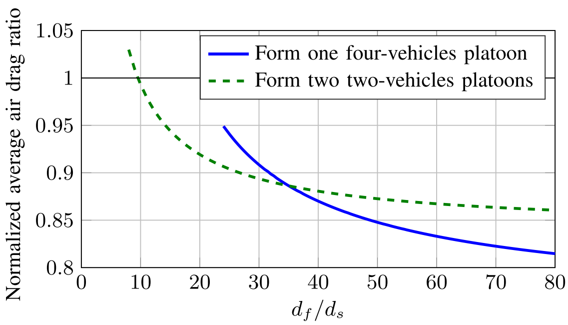

Fig. 10. Four vehicles forming a large platoon compared to forming two sub-platoons based on the scenario depicted in Fig. 9(a) with boundary values $v_{\min} = 70$ km/h, $v_{\max} = 90$ km/h, and $v = 80$ km/h. The distance ratio d_f/d_s is based on the two first vehicles.

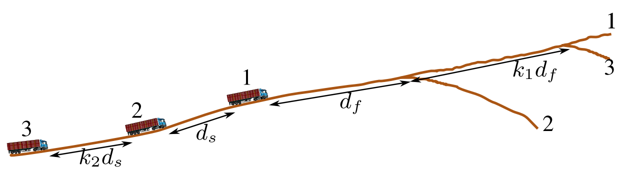

Fig. 11. Three scattered vehicles on the road with different destinations denoted by their respective numbers.

By calculating the fuel savings, it will be more efficient to form a larger platoon.

2) Four Vehicles Forming Two Sub-Platoons: Consider the same scenario as the previous example, but instead when $d_f =$ 300 km. In this case, the resulting chain graph will be similar to that in Fig. 9(b) with just slightly higher numbers, hence the algorithm will also pair vehicle 1 with 2 and vehicle 3 with 4. Again, the algorithm will reiterate once the platoons have been formed. Once the platoons have been formed, the first platoon will be 265 km away from the destination and the second platoon will be 20 km behind. With these conditions, the algorithm will not find it beneficial to a form a larger platoon and the sidestep of the algorithm will just be ignored since both vehicles are platoons. Hence the algorithm will stop with two sub-platoons. This can be more clearly seen in Fig. 10 where the cost of forming a large platoon compared to two sub-platoons is depicted. The cost is equal when $d_f/d_s = 35$, meaning that for lower distance ratio values, forming two sub-platoons is more fuel efficient than forming a larger platoon of four vehicles and vice versa.

3) Three Vehicles With Different Destinations: Consider the scenario in Fig. 11 where each vehicle has different destinations denoted by their numbers and with $k_1, k_2 > 0$. Let us assume that $d_s = 10$ km, $d_f = 200$ km, $k_1 = k_2 = 2$, $v_{\min} = 70$ km/h, $v_{\max} = 90$ km/h, and $v = 80$ km/h. Looking at the distance ratio between the vehicles, we have that distance ratio of $200/10 = 20$ between vehicle 1 and 2, $210/20 = 10.5$ between vehicle 2 and 3, and $600/30 = 20$ between vehicle 1 and 3. We know from Fig. 6 that, given the conditions with speed limits, the break-even ratio is 10.5, which is exactly what the distance ratio between vehicle 2 and 3. This means that the potential fuel savings are 0%. So vehicle 3's candidate is vehicle 1, however, vehicle 1 will check the neighboring vehicles first (i.e., vehicle 2) where a coordination will be fuel efficient and therefore vehicle 1

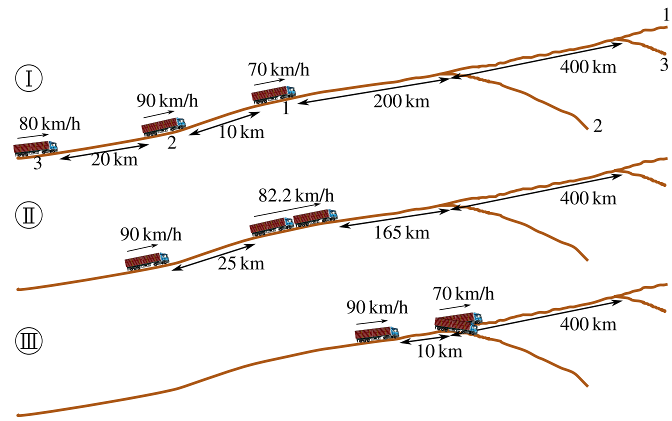

Fig. 12. A sequence of each moment where the coordination algorithm makes a decision for the scenario depicted in Fig. 11.

will not consider vehicle 3 at all. Vehicle 2 has only vehicle 1 as a candidate, and therefore in this step, vehicle 1 and 2 will form a platoon while vehicle 3 maintains its speed (see sequence I in Fig. 12). While vehicle 1 and 2 are merging, they are not considered in the algorithm until the platoon has been formed. Once vehicle 1 and 2 have merged into a platoon, the platoon will have 165 km (new d_f) before they split and vehicle 3 will be 25 km (new d_s) behind the platoon. Hence the distance ratio between the platoon and vehicle 3 is $165/25 =$ 6.6, there will be no fuel savings coordinating vehicle 3 with the platoon to the split point. However, vehicle 3 is not a platoon, therefore the algorithm will calculate if there are any fuel savings by coordinating with any of the vehicles within the platoon. Since vehicle 1 will travel the same road as vehicle 3 for a long stretch, there will be potential fuel savings even without adjusting the platoon's speed and only vehicle 3 acts. Therefore, vehicle 3 will drive faster to catch up with the platoon while the platoon maintains its speed, see sequence II in Fig. 12. Once the platoon splits at the splitting point, vehicle 1 will assist with the coordination by slowing down so the platoon can be formed faster, see sequence III in Fig. 12. With these actions, the algorithm allowed the vehicles to totally save 5.52% compared to if no coordination were executed at all. If we look closer, vehicle 3 could have actually started catching up while vehicle 1 and 2 where merging to form a platoon. So instead of vehicle 3 maintaining its speed (80 km/h), it could have driven faster (90 km/h) to not increase the gap between the vehicles and then merge even earlier than our suggested actions. With this action, the vehicles could have saved up to 5.81%. Our proposed algorithm is close the optimal saving despite just considering pairwise coordination compared to a global coordination that is required to reach that saving.

VI. Simulation Evaluation

In this section, we will validate our approach with cooperative formation using an advanced vehicle model used at Scania.

A. Simulation Setup

In order to verify our results, we need some experimental data to compare with. The setup is to coordinate two HDVs,

Fig. 13. A tractor-semitrailer vehicle with a 480 hp engine and 6 × 2 configuration.

Fig. 14. The highway from Södertälje to Jönköping in Sweden.

each with a 6 × 2 configuration and 480 hp engine with a 12 speed gearbox (see Fig. 13), to form a platoon driving from Södertälje to Jönköping in Sweden (see Fig. 14) and compare the fuel cost to if the vehicles were driving alone. The road is approximately 280 km long. The altitude and the slope of the road are depicted in Fig. 15. This is considered as a moderately hilly road.

We decided to evaluate for the distance ratio $d_f/d_s = 22$, which corresponds to an initial distance of 12.2 km between the vehicles. According to our theoretical results (with $v_{\min} =$ 70 km/h, $v_{\max} = 90$, and $v = 80$ km/h), we would yield a 8.4% air drag reduction in average compared to if the vehicles were driving alone. The vehicles should merge approximately after the first vehicle has driven 44.7 km (56.9 km for the second vehicle). Note that our fuel-optimal speed (obtained from the platoon formation problem) indicates the average speed the vehicle should drive in order to form a platoon. However, such a CC (to maintain an average speed) has not been implemented, we simply set the CC set speed as the fuel-optimal speed.

B. Simulation Model

To evaluate the experiment, we simulate the scenario using a validated simulation model from Scania that produces reliable results and replicates real-life behavior of an HDV [35]. The simulation model considers individual parts in the powertrain such as engine, clutch, gearbox, auxiliary systems, axles, etc., which are modeled in detail. The model also includes the full braking system, taking into account the nonlinear behavior of the system and the complex model of roll resistance, which depends on the dynamics of the tires, such as tire temperature, vehicle speed, and wheel radius. The air drag reduction is modeled as a constant, 0% reduction when driving alone and 32% reduction when driving behind another HDV without any transient phase. The gear shifting logic behind the gearbox is controlled by software used in real-life HDVs. A controller area network (CAN) system is also modeled, which describes the interaction between electronic control units (ECU), actuators, and physical properties of the HDV. The model consists in total of 4482 variables, 943 equations, and 441 states describing a single HDV.

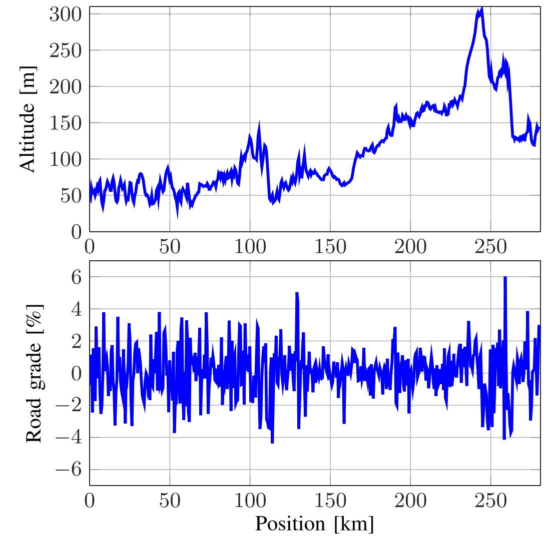

Fig. 15. The road profile with altitude (top) and road grade (bottom) of Södertälje-Jönköping.

C. Södertälje-Jönköping Road Profile

We set both vehicles to the same weight, and simulated for three different vehicle masses; 20 t, 40 t, and 60 t. For each weight we simulated twice, with and without platoon formation, in order to see the savings that we obtain. The speed profiles of a cooperative formation for two 40 t HDVs are depicted in Fig. 16. We see that both vehicles start at 80 km/h then the lead vehicle slows down to 70 km/h while the trailing vehicle drives faster at 90 km/h. At position 57 km, we see that the trailing vehicle slows down to match the speed of the lead vehicle before they accelerate and drive at 82.5 km/h to ensure that the lead vehicle is not delayed. The merging maneuver can be seen for all vehicle masses in Fig. 17. For this particular road, if an HDV were to drive exactly at 80 km/h throughout the whole stretch, the air drag would constitute of 59%, 42%, and 32% of the total force for 20 t, 40 t, and 60 t vehicle mass, respectively, giving us our estimated energy savings of 4.9%, 3.5%, and 2.7%, respectively.

Table II shows the simulation results for the three different vehicle masses. We note that the mergence point deviated from our theoretical expectations for all three setups. This is due to the road topography causing the vehicles not being able to maintain

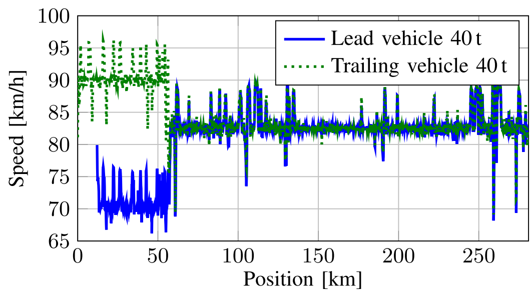

Fig. 16. Speed profiles when executing a cooperative formation on the Södertälje-Jönköping road when $d_f/d_s = 22$.

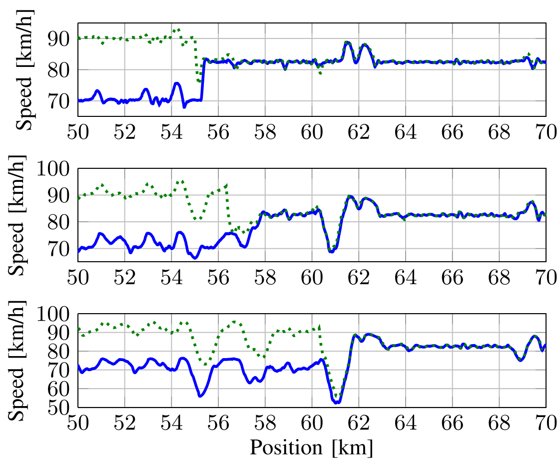

Fig. 17. The merging maneuver for 20 t (top), 40 t (middle), and 60 t (bottom) vehicles when executing a cooperative formation. The merging point differs between the vehicle masses due to the variation of road slope that affected the speed of the vehicles.

TABLE II
THE RESULTS FROM MAKING A PLATOON FORMATION COMPARED TO THE NOMINAL CASE OF NOT COORDINATING FOR $d_f/d_s = 22$

Södertälje–Jönköping	20 t	40 t	60 t
$\bar{v}_1$ [km/h]	70.6	71.2	70.9
$\bar{v}_2$ [km/h]	90.2	90.3	88.7
$\bar{v}_p$ [km/h]	82.8	82.8	82.1
Mergence point [km]	56.6	58.0	61.7
Energy savings [%]	3.8	2.2	1.7

its set speed, which can be noted in the average speeds. The average speeds in general for almost all cases were higher than recommended, which leads to a later mergence point except for the 20 t case. That is because we assumed that once the trailing vehicle starts to slow down to match the speed of the lead vehicle, the coordination phase is over which occurred when the vehicles are approximately 100 m away from each other. In our theoretical results, the merging point is when the vehicles are on the same position. For the 60 t case, the road was too hilly for the trailing vehicle to be able to maintain 90 km/h. We note that all three setups saved energy when executing a platoon formation. The energy savings might be a little bit less than we anticipated and this is due to two reasons. One is that the vehicles were not driving at 80 km/h the whole stretch, but varied in speed, which adds to the energy. Secondly, the merging occurred later than expected, which meant less platooning time.

VII. CONCLUSION

In this paper, we have investigated how to form platoons of two or more HDVs with respect to fuel efficiency through coordinations on the fly and not considering rerouting without delaying the transport. For a two vehicle case, we formulate the problem as an optimization problem based on speeds (current speed, coordination speed, and platooning speed) as well as air drag reduction the HDVs experience once the platoon is formed. The optimal speeds are for both vehicles to act (lead vehicle slows down and trailing vehicle drives faster) in order to execute a fuel-efficient platoon formation and once the platoon has been formed, adjust the speed to match the delivery time accordingly. In practice, where there are traffic and physical constraints (that can be modeled as speed constraints), the resulting optimal merging speeds are in most cases on the boundaries, with a platoon speed that matches the time constraint. When considering platoon formation of several vehicles, a pairwise coordination (which is to coordinate with the closest fuel-saving neighbor) is a sufficiently good strategy that yields noticeable fuel savings. Once the paired vehicles have formed a platoon, one can then consider making a new pairwise coordination if more potential fuel savings exist. In this way, the platoon formation algorithm is scalable. Lastly, we compared our coordination approach with an advanced model used in Scania, which suggested that our results are in the right direction.

The obtained results have assumed no traffic. However, in reality, traffic is commonly a significant factor in coordination decisions since it will affect the possibilities to form platoons and the potential fuel savings. Therefore, it is of interest to make a sensitivity analysis to study when it is still beneficial to make a coordination despite deviating from the optimal speed due to road or traffic conditions. Furthermore, a driver has to follow the driving and resting time regulations—in Europe, a driver cannot drive longer than 4.5 hours without taking a break. This can affect the possibilities for platoon formation as well as fuel-saving potentials. Further investigation is also required in order to improve and extend the algorithm to a network of vehicles and for more fuel savings. Investigating these is left for future work.

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

Jonas Mårtensson (M'15) received the M.Sc. degree in vehicle engineering and the Ph.D. degree in automatic control from KTH Royal Institute of Technology, Stockholm, Sweden, in 2002 and 2007, respectively. The topic of his Ph.D. thesis was geometric analysis of stochastic model errors in system identification. He holds a tenure-track position as an Assistant Professor with the Department of Automatic Control, KTH Royal Institute of Technology. He is also engaged as a Program Leader in the Integrated Transport Research Laboratory and is a Thematic Leader for the area Transport in the Information Age within the KTH Transport Platform. Between 2008 and 2012, he worked on modeling, control, and optimization of the transient torque response in combustion engines, utilizing variable geometry turbines and variable valve timings. Since 2011, his main research has been within cooperative and autonomous transport systems, in particular related to heavy-duty vehicle platooning. He is involved in several collaboration projects with Scania CV AB, Södertälje, Sweden, dealing with collaborative adaptive cruise control, look-ahead platooning, route optimization and coordination for platooning, path planning and predictive control of autonomous heavy vehicles, and related topics. In 2012, he was one of the main creators of the KTH Smart Mobility Lab, which is a model-based platform for implementation and demonstration of intelligent transport solutions.

Karl H. Johansson (S'92–M'98–SM'08–F'13) received the M.Sc. and Ph.D. degrees in electrical engineering from Lund University, Lund, Sweden. He held visiting positions at the University of California, Berkeley, from 1998 to 2000 and at the California Institute of Technology from 2006 to 2007. He is the Director of the ACCESS Linnaeus Centre and Professor at the School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. He is a Wallenberg Scholar and Director of the Stockholm Strategic Research Area ICT The Next Generation. His research interests are in networked control systems, hybrid and embedded systems, and applications in smart transportation, energy, and automation systems.

Prof. Johansson has been a member of the IEEE Control Systems Society Board of Governors and the Chair of the IFAC Technical Committee on Networked Systems. He has been on the Editorial Boards of several journals, including *Automatica*, IEEE TRANSACTIONS ON AUTOMATIC CONTROL, and *IET Control Theory and Applications*. He is currently on the Editorial Board of the IEEE TRANSACTIONS ON CONTROL OF NETWORK SYSTEMS and the *European Journal of Control*. He was a recipient of many awards, including the triennial Young Author Prize from the International Federation of Automatic Control.