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Look-Ahead Cruise Control for Heavy Duty Vehicle Platooning

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Abstract— **Vehicle platooning has become important for the vehicle industry. Yet conclusive results with respect to the fuel reduction possibilities of platooning remain unclear, in particular when considering constraints imposed by the topography. The focus of this study is to establish whether it is more fuel-efficient to maintain or to split a platoon that is facing steep uphill and downhill segments. Two commercial controllers, an adaptive cruise controller and a look-ahead cruise controller, are evaluated and alternative novel control strategies are proposed. The results show that an improved fuel-efficiency can be obtained by maintaining the platoon throughout a hill. Hence, a cooperative control strategy based on preview information is presented, which initiates the change in velocity at a specific point in the road for all vehicles rather than simultaneously changing the velocity to maintain the spacing. A fuel reduction of up to 14 % can be obtained over a steep downhill segment and a more subtle benefit of 0.7 % improvement over an uphill segment with the proposed controller, compared to the combination of the commercially available cruise controller and adaptive cruise controller that could be used for platooning. The findings show that it is both fuel-efficient and desirable in practice to consider preview information of the topography in the control strategy.**

Fig. 1. Heavy duty vehicles traveling in a platoon can achieve significant fuel reduction. Preview information in hills should be taken into consideration for improved fuel-efficiency.

I. INTRODUCTION

The traffic intensity is escalating in many parts of the world, making traffic congestion a growing issue. In parallel, the demand for transportation services is increasing. Vehicle platooning, depicted in Fig. 1, has been widely recognized as a mean to reduce both harmful exhaust emission from the engine and fuel costs. By packing vehicles close to each other, the total road capacity can be increased and emissions can be reduced [1]. The concept of vehicle platooning is not new. The first investigation into control for heavy vehicle platooning was in the early 1960s [2]. Many experienced heavy duty vehicle (HDV) drivers know that driving at a short intermediate distance to a preceding HDV results in a lowered throttle action to propel the vehicle forward. The fuel reduction potential for HDV platooning was evaluated in [3], where it was shown that the fuel consumption can be reduced by 4–7 % on a typical Swedish highway for the follower vehicles. The saving is due to the reduced air drag between the HDVs. Thus, it is fuel-efficient to reduce the intermediate spacing as much as possible without endangering safety. In [4] it was shown that it can be reduced to approximately 2 m without endangering safety if the vehicles convey their control inputs through wireless communication. Operating at a short intermediate spacing requires tight control, which might lead to an increased control effort. Control for vehicle platooning with simplified system dynamics has been studied in [5]–[10], where maintaining a suitable relative distance, stability and robustness of the platoon have been identified to be among the main criteria to be considered. Research into more implementation-relevant aspects is only recently emerging due to the current advancements and maturity in applicable information and communication technologies for vehicles. A model-based control design approach, where a cooperative adaptive cruise control is proposed and experimentally evaluated, is presented in [11]. In [12] heterogeneous vehicle strings under simple decentralized control laws with a constant spacing control policy are analyzed. The considered vehicles do not need to have the same dynamics or the same controllers. In recent work [13]–[15] system architectures, wireless communication issues, and control for practical platooning applications were studied and evaluated through experiments in mixed traffic on a highway.

For HDV platooning it is essential to use realistic models and not just identical linear models, since mass and road gradient have a significant effect on the system dynamics [16]. Fuel optimal control for a single HDV based on preview information of the road topography, referred to as look-ahead cruise control (LAC), has been studied in [17] and [18]. They showed that the fuel consumption can be reduced by adjusting the velocity prior to an uphill or a downhill segment based on the vehicle parameters and the nonlinear dynamics of the HDV. However, to the best of our knowledge, control based on preview information of the road topography has not been studied for HDV platooning.

In this work, we are primarily concerned with what effect a varying road topography has on the fuel consumption for HDV platooning. We derive implementable and fuel-efficient

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controllers with low computational complexity, since it is generally not possible to implement complex control algorithms due to the limited computational power in the electronic control units. The focus within platooning so far has been on establishing optimal control policies based on linear models for maintaining a given spacing policy without considering the road topography. However, the topography might constrain an HDV traveling in a platoon so that the intermediate spacing cannot be maintained. For example, a large mass or weak engine might prohibit the HDV to maintain the set velocity in an uphill even though maximum torque is applied. Hence, the follower vehicles' velocities will be constrained and the preceding vehicles will increase the gap. In steep downhill segments the heaviest follower vehicles, in a heterogenous platoon, might have to brake and preceding vehicles might increase the gap when coasting. The former case in particular has been reported as an issue by professional HDV drivers, if no overtaking is possible, since constant braking can lead to brake failure due to excessive heating and it is not fuel-efficient.

The main contribution of this paper is to determine a fuel-efficient behavior for an HDV platoon when traversing a hill. We provide insight into practically implementable fuel-efficient control strategies for common uphill or downhill segments on Swedish highways. In this paper we show that it is most fuel-efficient to maintain a platoon when traversing a hill as opposed to splitting the platoon and resume it during or after the hill. It is shown that the commercially available adaptive cruise controller (ACC) is not fuel-efficient for a varying topography and that the LAC for a single HDV is not practical in HDV platooning. Hence, we present a practically feasible cooperative look-ahead controller for platooning (LAP). The results for for a heterogeneous HDV platoon of nine HDVs traveling over a 2 km road segment show that a fuel reduction of 12.1 % or 18.7 % can be achieved with the LAP controller when traversing a typical steep uphill or downhill segment of 240 m, respectively. The main conclusion is that it is desirable and fuel-efficient in practice to initiate control actions with respect to a point on the road rather than implementing each individual HDV's control action simultaneously to maintain a fixed spacing.

The outline of the paper is as follows. First we define the problem that we are considering in Section II. Then we present the system model in Section III, which serves as the basis for the controllers for typical uphill and downhill segments that are studied in Section IV. The results for the different controllers are presented in Section V. Finally, in Section VI we present a brief summary of the results in this paper and conclusions.

II. PROBLEM DESCRIPTION

We consider a platoon of N heterogeneous HDVs, as shown in Fig. 2, operating at close intermediate spacings and traversing a hill. The platooning HDVs are equipped with wireless transceivers. They are initially in steady state with a set velocity and spacing before traversing the hill. Velocity and spacing between the vehicles might vary during the hill, but are resumed afterward. The considered HDVs have different masses. We assume, without loss of generality, that each HDV in the platoon has the same powertrain configuration and equal maximum net torque available, since it is the power per unit mass that defines the constraints imposed on an HDV traveling in a hill.

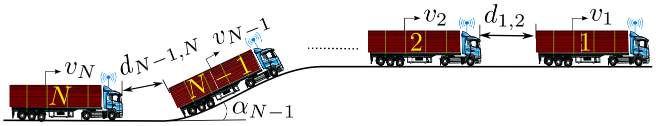

Fig. 2. A platoon of N HDVs travelling on a road with gradient α_i for vehicle i, intermediate spacing $d_{i-1,i}$, and velocity v_i.

The problem that we solve is to derive practically feasible fuel-efficient control strategies based on preview information. We investigate whether it is beneficial to utilize preview road gradient information with respect to fuel consumption and travel time. We determine if it is more fuel-efficient to maintain the platoon when traversing a hill or let the HDVs separate and then catch up, during or after the hill. The aim of this study is to find an implementable and fuel-efficient control strategy as well as the fuel reduction possibilities in HDV platooning when traversing steep uphill or downhill segments.

The LAC for a single vehicle is derived through model predictive control in [18]. The optimization is carried out with respect to minimizing fuel and time in the cost function, a nonlinear dynamics and fueling model, constraints on the control inputs, and constraints on the maximum absolute deviation from the road velocity of 5 km/h. For a steep uphill segment, the LAC increases the speed in advance and obtains a higher average velocity when traveling along the uphill segment and similarly the velocity is decreased before entering a steep downhill segment. The fuel saving LAC strategies for a single vehicle facing an uphill and downhill segment are shown in Fig. 3. The top plot shows road profiles that are traversed by a light, 20 t, and a heavier, 40 t, HDV[1]. The middle plot shows the corresponding optimal velocity trajectories. The bottom plot shows the intermediate spacing between the HDVs, had they traveled as a platoon with a desired short intermediate spacing of 5 m. It can be seen in Fig. 3 that a collision occurs if the HDVs strictly follow their individual LAC strategies when facing an uphill segment if the lead vehicle is lighter than the follower vehicle. Similarly, when facing a downhill segment, the vehicles collide with the order of the light HDV following the heavier HDV. Hence, when traveling in a platoon, scenarios can occur where it is not feasible to follow the individual fuel-optimal profiles.

III. SYSTEM MODEL

The state equation of a single HDV can be formulated as

$$\begin{aligned}\frac{\mathrm{d}d_{i-1,i}}{\mathrm{d}t} &= v_{i-1} - v_i \\ \mathrm{m}_{t_i}\frac{\mathrm{d}v_i}{\mathrm{d}t} &= F_{\text{engine}}(\delta_i, \omega_{e_i}) - F_{\text{brake}} - F_{\text{air drag}}(v_i, d_{i-1,i}) \\ &\qquad - F_{\text{roll}}(\alpha_i) - F_{\text{gravity}}(\alpha_i) \\ &= \mathrm{k}_i^{\mathrm{e}} T_e(\delta_i, \omega_{e_i}) - F_{\text{brake}} - \mathrm{k}_i^{d} v_i^2 f_i(d_{i-1,i}) \\ &\qquad - \mathrm{k}_i^{\mathrm{fr}} \cos\alpha_i - \mathrm{k}_i^{\mathrm{g}} \sin\alpha_i\end{aligned} \tag{1}$$

where $T_e(\delta_i, \omega_{e_i})$ denotes the net engine torque, δ is the engine fueling, ω_{e_i} denotes the angular velocity of the engine,

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[1] 40 t is the maximum allowed weight for long-haulage HDVs in Europe.

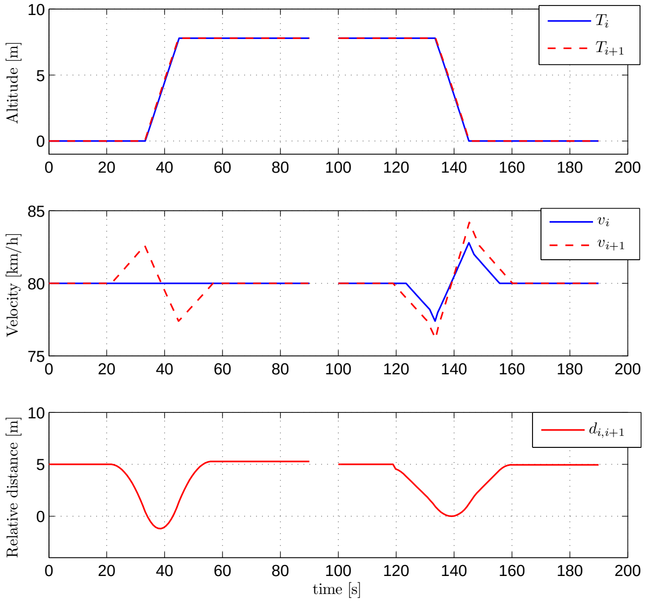

Fig. 3. Fuel optimal trajectories for a single HDV. The top plot shows the topography of the roads, where the uphill climb has a road gradient of 3 % and the downhill segment has a gradient of -3 %. Each vehicle experiences the hills at different times, since they are traveling at different velocities. The experienced topography is denoted by T_i and T_{i+1} for the corresponding 20 t and 40 t HDV. Note that when traveling over the uphill the light HDV has the lead position, whereas it has the follower position over the downhill segment. The middle plot shows the velocity trajectories for the light HDV produced by the LAC, denoted by v_i, and the heavy HDV, which is denoted by v_{i+1}. The bottom plot shows the intermediate spacing between the vehicles.

m_{t_i} denotes the accelerated mass and $i = 1, \ldots, N$ denotes the vehicle index. $\mathrm{k}_i^{\mathrm{e}}, \mathrm{k}_i^{d}, \mathrm{k}_i^{\mathrm{fr}}$, and $\mathrm{k}_i^{\mathrm{g}}$ denote the characteristic vehicle and environment coefficients for the engine, air drag, road friction, and gravitation respectively. The state variables v_i and $d_{i-1,i}$ denote the velocity for vehicle i and the intermediate spacing to the preceding vehicle, as shown in Fig. 2. α_i denotes the road gradient and the function $f_i(d_{i-1,i})$ is a nonlinear mapping of the air drag reduction with respect to the position in the platoon (for a more detailed description see [16]). The dynamic model is accurate for high velocities: at low velocities the internal dynamics of the vehicle has a larger impact on the longitudinal dynamics. Braking is not fuel-efficient, since energy produced by the engine is lost through frictional heating of the brakes during braking. Therefore, only the net engine torque is considered as a control input in this study.

The engine is modeled after a six cylinder 420 hp Scania engine, where the engine torque during fueling for a single HDV is given as [18],

$$T_e(\delta, \omega_e) = a_e\omega_e + b_e\delta + c_e. \tag{2}$$

a_e, b_e, c_e are characteristic coefficients, which are derived empirically from engine map data. When there is no fueling, $\delta = 0$, the vehicle is said to be coasting. In this case the engine produces a small braking torque, which is given as

$$T_c(\omega_e) = a_c\omega_e + c_c < 0, \tag{3}$$

where a_c and b_c are empirically derived constants. The fueling is also derived empirically and given as

$$\delta(\omega_e) = P\delta_{\max},$$

where $P \in [0, 1]$ is the normalized fueling quantity, $\delta_{\max} = a_\delta\omega_e^2 + b_\delta\omega_e + c_\delta$ is the maximum fueling, and $a_\delta, b_\delta, c_\delta$ are constants. Hence, the complete engine torque model during all modes of operation is given by

$$T_e(\omega_e, P) = \begin{cases} a_e\omega_e + b_eP\delta_{\max} + c_e, & \text{if } P > 0, \\ a_c\omega_e + c_c, & \text{if } P = 0. \end{cases} \tag{4}$$

Finally, the fuel consumption is given by

$$\gamma(\omega_e, P) = c_f \int \omega_e\delta(\omega_e)dt, \tag{5}$$

where c_f is the number of cylinders that ignite during a full revolution of the crankshaft. The torque model (4) and fuel consumption model (5) are simplifications. However, since this paper focuses on comparing different driving strategies with respect to relative fuel consumption it is deemed to be adequate and give realistic results [19].

We constrain the allowed velocity range to $v_{\text{road}} \pm 5$ km/h, where v_{road} is the nominal road speed. The limits are set based on legislation and driver acceptance constraints. We consider the HDVs in the platoon to travel at a small intermediate spacing of 5 m and do not allow it to drop more than 1 m due to safety constraints.

IV. CONTROL STRATEGIES BASED ON PREVIEW INFORMATION

In this section we introduce five different control strategies. We present the controllers' behaviors for typical steep Swedish uphill and downhill segments, for which a precise definition is given. For clarity and relevance, two neighboring HDVs of different masses, 20 t and 40 t are considered throughout this section. HDVs of equal mass would be able to maintain the same velocity with respect to any topography, hence platooning control strategies based on preview information are not necessary in such cases. The controllers that we consider are denoted

- CC: Cruise controller, which aims to maintain a set speed.
- ACC: Adaptive cruise controller, which aims to maintain a set spacing to the preceding HDV, [16].
- LAC: Look-Ahead cruise controller, which utilizes preview road topography information and calculates an optimal velocity trajectory for a single HDV, [18].
- PLAC: Preemptive look-ahead cruise controller for platooning, which aims to adjust the LAC velocity profile such that a collision is avoided and for fuel-efficiency.
- LAP: New cooperative look-ahead platooning cruise controller for HDVs utilizing preview topography information.

The ACC does not need to be aware of the constraints for the preceding or follower vehicle. However, if wireless communication is utilized, a cooperative control strategy can be established, where a vehicle in the platoon can receive information regarding the intended velocity profiles of its neighboring vehicles within radio range. The novel PLAC is based on model predictive control and utilizes the intended velocity profile of the preceding vehicle. Thereby, it adjusts the LAC profile with respect to fuel-efficiency such that the minimum spacing constraint is not violated. The LAP is derived through dynamic programming, where the LAC strategy is calculated for each vehicle in the platoon and the profile that requires the largest adjustment in velocity to address the constraint imposed by the steep hill segment is set to be the common velocity profile for all vehicles. The velocity profile is tracked from the same point on the road. Hence, the follower vehicles defers their control action until they reach the point where the lead vehicle started to change its speed and cooperatively allow for small changes in intermediate spacing. Note that the computational cost for solving the dynamic programming is exponential in the state dimension. Thus, a centralized solution is computationally too expensive for online applications and in general hard to solve for an arbitrary number of vehicles.

The fuel optimal control for a single vehicle on a flat road is to maintain a constant velocity, under the presumption that the travel time is fixed [17]. Any deviations in acceleration or deceleration result in an increased fuel consumption. Therefore, a change in reference speed is only required for steep hills, where the extensive mass of the HDVs do not allow them to maintain the speed limit. We define small road gradients using small angle approximation as

$$\alpha_l < \alpha < \alpha_u \tag{6}$$

where

$$\alpha_u = \frac{k_i^e T_e(\delta_{max}, \omega_e) - k_i^d v_i^2 f(d_{i-1,i}) - k_i^{fr}}{k_i^g} > 0,$$

$$\alpha_l = \frac{k_i^e T_c(\omega_e) - k_i^d v_i^2 f(d_{i-1,I}) - k_i^{fr}}{k_i^g} < 0.$$

α_u is the steepest road gradient for which the velocity can be maintained in an uphill climb with maximum net engine torque and α_l is the steepest road gradient for which an HDV can maintain a constant velocity by coasting and not having to brake. Steep hills are thereby defined as road segments with gradients outside the range in (6).

A. *Control Strategies for Steep Uphill Segments*

We consider three alternative fuel-efficient control strategies to avoid a collision. Fig. 4 shows the trajectories produced by the different controllers.[2] Five velocity trajectories are shown in the middle plot for two neighboring vehicles in a platoon, where the preceding HDV, with subindex i, has a mass of 20 t and the follower vehicle, with subindex $i+1$, has a mass of 40 t. Two of the trajectories correspond to the original LAC strategy and the other velocity trajectories correspond to the ACC, the PLAC strategy, and the proposed LAP. The top plot shows the experienced road topography for each velocity profile and the bottom plot shows the intermediate spacing with respect to each velocity profile. As can be seen in Fig. 4, the lead vehicle does not experience the uphill climb as steep due to its smaller mass and therefore maintains a constant speed.

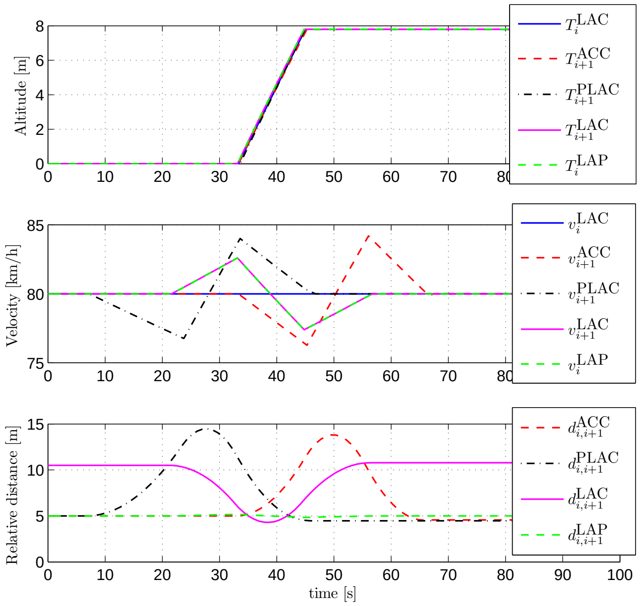

Fig. 4. Trajectories for different control strategies that governs neighboring HDVs in a platoon during a 240 m long uphill segment, with road grade 3 %. The total road length is 2 km. The top plot shows the experienced road topography with respect to each control strategy. The experienced topography for the preceding vehicle is denoted by T_i^z and the experienced topography for the follower vehicle is denoted by T_{i+1}^z, where $z \in \{\text{LAC, ACC, PLAC, LAP}\}$ denotes the corresponding control strategy. The velocity trajectories for the preceding vehicle is denoted by v_i^z and v_{i+1}^z for the follower vehicle. The bottom plot shows the corresponding intermediate spacing, which is denoted by $d_{i,i+1}^z$.

The simplest control strategy for a steep uphill segment is to maintain the individual LAC strategies and increase the spacing between the vehicles in advance such that the smallest reduction in intermediate spacing is slightly less than 5 m. The velocity trajectories in this case is given by the solid (blue, LAC) line, denoted by v_i^{LAC}, for the preceding vehicle and the solid (magneta, LAC), denoted by v_{i+1}^{LAC}, line for the follower vehicle. The corresponding intermediate spacing is given by the solid (magneta, LAC) line, denoted as $d_{i,i+1}^{\text{LAC}}$ in the bottom plot of Fig. 4. To allow for an initial intermediate spacing of 5 m shortly before the uphill climb, three control strategies are given. The dashed (red, ACC) curves display the velocity and intermediate spacing profile for the first control strategy, when the follower vehicle's controller is trying to maintain the set intermediate spacing. This corresponds to a control strategy that is based on local state information such as the ACC. When entering the steep uphill segment the follower vehicle starts to drop in velocity even though maximum net engine torque is applied, whereas the preceding vehicle can maintain its velocity. Therefore, the intermediate spacing increases initially and the controller for the follower vehicle strives to correct the error in desired intermediate spacing by increasing the velocity after the hill to catch up as fast and fuel-efficiently as possible. When

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[2] Note that each controller produces a different average velocity before arriving at the hill. Thus, the hill is entered at different times, as seen in the slightly varying time position of the uphill segment plots.

the distance is reduced to a certain extent, the follower vehicle starts to coast, cutting off the fuel injection, and resumes platooning with lowered air drag at the point of matching the set spacing. The (black, PLAC) dashed-dotted velocity trajectory that is lowered prior to the uphill climb in Fig. 4 shows the second strategy, where the follower vehicle uses a preemptive control strategy to avoid a collision. The controller reduces the speed by coasting and thereby increases the intermediate spacing before the uphill segment. Hence, the follower is eventually able to increase its speed and follow a similar LAC profile for a single vehicle over the uphill segment. The controller calculates how much the speed needs to be decreased prior to the uphill segment and then increased in order to match the set spacing at the end of the hill. The (green, LAP) dashed trajectories show the velocity profile and slight variation in spacing that occurs with the LAP. Here, the preceding vehicle cooperatively adjusts its velocity profile to match the constrained LAC profile for the follower vehicle.

B. Control Strategies for Steep Downhill Segments

For steep uphill segments, the follower vehicle is constrained to the preceding vehicle's velocity profile if the preceding vehicle is heavier. Therefore, only the case when a lighter vehicle precedes a heavier vehicle is considered. However, for steep downhill segments, both cases of having a lighter or heavier preceding vehicle compared to the follower vehicle can be addressed.

The trajectories for facing a downhill segment when the heavier HDV is preceding the lighter HDV are shown in Fig. 5. They are subindexed by i for the preceding vehicle and by $i+1$ for the follower vehicle. The top plot shows the experienced road topography, the middle plot shows the velocity trajectories based on the corresponding control strategy, and the bottom plot shows the intermediate spacing with respect to each velocity profile. Four different control strategies are illustrated in Fig. 5. The trajectories with superindex LAC shows the simplest case when the LAC strategy is utilized by both vehicles and the intermediate spacing is increased to 8.7 m in advance, so that the lower boundary of 4 m is not breached. The dashed (red, CC) lines display the trajectories for when the preceding vehicle is governed by the commercial CC and the follower vehicle is governed by the ACC. The corresponding intermediate spacing, which is kept constant with the ACC, is given in the bottom plot. The CC has no information regarding the oncoming topography. Thus, the velocity increases when entering the downhill segment and it is forced to brake when it exceeds the allowed velocity limit. The follower vehicle tracks the velocity and spacing to the preceding vehicle with its ACC and is also forced to brake eventually. The solid (magneta, PLAC) trajectories displays the PLAC for when the follower vehicle receives information through wireless communication regarding the preceding HDV's LAC velocity profile. Thereby, it can preemptively avoid a collision by initially reducing its speed to increase the intermediate spacing and then compensate by maintaining the gained speed over the downhill segment a while afterward. When the spacing is increased, the follower vehicle finally reduces its velocity by coasting to match the desired spacing and speed of the preceding vehicle. The final control strategy, LAP, is displayed by the dashed (green, LAP) trajectories. The controller operates cooperatively by comparing the intended LAC velocity profiles for both vehicles. The heavier preceding vehicle needs to deviate its velocity the most from the nominal road speed, hence both vehicles agree to follow that profile.

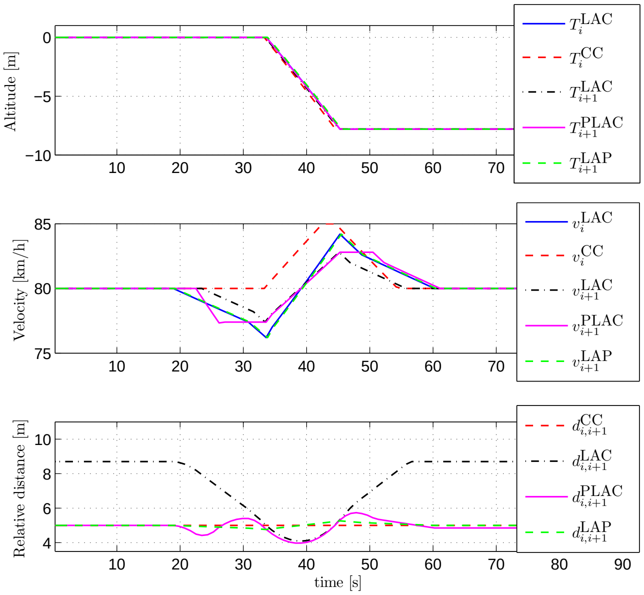

Fig. 5. Trajectories for different control strategies governing neighboring HDVs in a platoon during a 240 m long downhill segment with road grade -3 %. The total road length is 2 km. The top plot shows the experienced road topography with respect to each control strategy. The experienced topography for the heavier preceding vehicle, i, is denoted by T_i^z and the experienced topography for the lighter follower vehicle, $i+1$, is denoted by T_{i+1}^z, where $z \in \{\mathrm{CC}, \mathrm{LAC}, \mathrm{PLAC}, \mathrm{LAP}\}$ denotes the corresponding control strategy. The velocity trajectories for the preceding vehicle is denoted by v_i^z and by v_{i+1}^z for the follower vehicle. The bottom plot shows the corresponding intermediate spacing, which is denoted by $d_{i,i+1}^z$.

The trajectories for the reverse order, when the preceding HDV weighs 20 t and the follower HDV weighs 40 t, are given in Fig. 6. For this ordering, both vehicles can use their LAC and maintain the short intermediate spacing of 5 m before the downhill segment, since the follower will initiate its speed reduction before the preceding lighter HDV. This is displayed by the solid (blue, LAC) trajectory for the preceding vehicle and the (red, LAC) dashed trajectory for the follower vehicle. The corresponding increase in intermediate spacing is given in the bottom plot by the (red, LAC) dashed curve. The dashed (blue, CC) trajectories display the scenario when the preceding vehicle is governed by the CC and the follower vehicle is governed by the ACC. The preceding HDV does not reach the maximum speed constraint and can resume its set speed by cutting off the fuel injection throughout the downhill segment and afterward. However, the follower vehicle must brake all the way during that stretch to maintain a constant spacing due to its heavier mass. The trajectories for the cooperative LAP controller is given by the solid (green, LAP) curves. In this case the preceding vehicle agrees to track the trajectory of the follower vehicle,

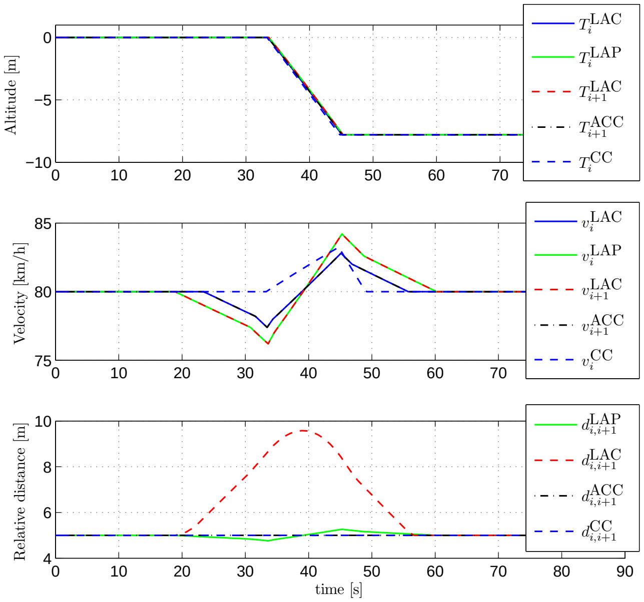

Fig. 6. Trajectories for different control strategies governing neighboring HDVs in a platoon during a 240 m long downhill segment with road grade -3 %. The total road length is 2 km. The top plot shows the experienced road topography with respect to each control strategy. The experienced topography for lighter preceding vehicle, i, is denoted by T_i^z and the experienced topography for the heavier follower vehicle, $i+1$, is denoted by T_{i+1}^z, where $z \in \{\text{CC, LAC, LAP}\}$ denotes the corresponding control strategy. The velocity trajectories for the preceding vehicle is denoted by v_i^z and by v_{i+1}^z for the follower vehicle. The bottom plot shows the corresponding intermediate spacing, which is denoted by $d_{i,i+1}^z$.

since it requires the largest velocity changes when facing the downhill segment.

V. EVALUATION OVER TYPICAL ROAD PROFILES

In this section we evaluate the fuel-efficiency of the proposed controller strategies, which are based on preview information of the topography. The total fuel consumption is considered for two neighboring HDVs that travel over a 2 km long road with a 240 m or 320 m hill. We determine which controller is most fuel-efficient and practically feasible. Finally, we apply the proposed LAP controller on an $N = 9$ HDV platoon of masses ranging between 20 t to 40 t and evaluate the performance for two hills.

The relative fuel consumption for the sum of two HDVs of masses 20 t and 40 t traveling as a platoon facing an uphill segment are given in Table I. Table II lists the relative fuel consumption when facing a downhill segment with the preceding HDV being heavier and Table III lists the results when facing a downhill segment with the preceding HDV being lighter. The relative fuel consumption is given in comparison with the total fuel consumption of two HDVs traversing the hills alone with their individual LAC, which is denoted as Nominal in the tables. The Hypothetic controller gives the scenario when both HDVs are governed by the optimal LAC for a single HDV and hypothetically obtain the air drag reduction for having a constant intermediate spacing of 5 m to the neighboring vehicle. It is not practically feasible, but gives the theoretically highest obtainable fuel reduction. The first column lists the controllers that are considered in the order {preceding, follower}, the second column gives the relative fuel consumption obtained for a 240 m long hill, and the third column gives the relative fuel consumption obtained for a 80 m longer hill. The average velocity for all the control strategies, except for the {CC, ACC} combination when traveling downhill, is 80 km/h.

TABLE I

TABLE OF RELATIVE FUEL CONSUMPTION FOR DIFFERENT UPHILL CONTROL STRATEGIES WITH A LIGHTER PRECEDING HDV.

Controllers: $\{\text{HDV}_i, \text{HDV}_{i+1}\}$	Fuel Consumption [%] (240 m uphill)	Fuel Consumption [%] (320 m uphill)
Nominal	100	100
{LAC, LAC}∗	93.00	94.29
{LAC, ACC}∗	93.50	95.34
{LAC, ACC}	92.50	93.45
{LAC, PLAC}	92.54	93.20
{LAP, LAP}	92.24	92.81
Hypothetic	92.23	92.76

* Results obtained for initial intermediate spacing of 10.5 m for the 240 m segment and 15.5 m for the 320 m segment.

The results in Table I show that there is a vast fuel saving potential in platooning when traversing an uphill segment compared to the nominal case. Increasing the intermediate spacing to 10.5 m so that both vehicles can maintain their individual LAC strategies without violating the minimum spacing constraint is more fuel-efficient compared to governing the preceding HDV with the LAC and the follower vehicle with the ACC at the same spacing setting. It is more fuel-efficient to govern the preceding vehicle with the LAC and the follower vehicle with the ACC at a smaller spacing setting of 5 m. The PLAC strategy that aims to increase the spacing before the uphill climb is not as fuel-efficient in comparison for this case. The maximum fuel reduction of 7.8 % is obtained with the cooperative LAP strategy, when the lighter vehicle refrains from its own LAC and complies with the constrained follower vehicle profile. Note that if the order of the HDVs were reversed the fuel reduction would be the same for the LAP, since the air drag is not mass dependent. The third column of Table I shows that an improved fuel reduction of 0.7 % can be obtained with the LAP compared to the commercially available {LAC, ACC} combination, where the LAC for the lighter preceding HDV, shown in Fig. 4, behaves like a CC in this case. It can also be seen that the fuel saving potential is decreased for a longer uphill segment. Increasing the length of the uphill segment forces the HDVs who cannot maintain their velocity to reduce their speed in the uphill more in comparison with the shorter uphill segment. This is equivalent to the behavior for a steeper uphill segment. For very steep uphill segments, where the HDV reaches its speed boundary, no fuel saving can be obtained.

Table II shows that it is more fuel-efficient to govern the preceding vehicle with the CC and the follower vehicle with the ACC for an intermediate spacing of 5 m compared to the nominal case of traveling alone with the LAC. The fuel consumption is reduced further by increasing the intermediate spacing so that both HDVs can be governed by their individual LAC without violating the minimum spacing constraint. The fuel-efficiency is further improved by governing the follower vehicle with the ACC at the same

TABLE II

TABLE OF RELATIVE FUEL CONSUMPTION FOR DIFFERENT DOWNHILL CONTROL STRATEGIES WITH A HEAVIER PRECEDING HDV.

Controllers: $\{\mathrm{HDV}_i, \mathrm{HDV}_{i+1}\}$	Fuel Consumption [%] (240 m downhill)	Fuel Consumption [%] (320 m downhill)
Nominal	100	100
{CC, ACC}	91.97	96.07
{LAC, LAC}$*$	88.12	87.80
{LAC, ACC}$*$	88.10	88.47
{LAC, PLAC}	87.88	87.04
{LAC, ACC}	87.17	86.04
{LAP, LAP}	87.15	86.03
Hypothetic	87.65	86.76

* Results obtained for initial intermediate spacing of 8.7 m for the 240 m segment and 12 m for the 320 m segment.

TABLE III

TABLE OF RELATIVE FUEL CONSUMPTION FOR DIFFERENT DOWNHILL CONTROL STRATEGIES WITH A LIGHTER PRECEDING HDV.

Controllers: $\{\mathrm{HDV}_i, \mathrm{HDV}_{i+1}\}$	Fuel Consumption [%] (240 m downhill)	Fuel Consumption [%] (320 m downhill)
Nominal	100	100
{CC, ACC}	97.80	100.77
{LAC, ACC}	91.15	91.91
{LAC, LAC}	87.83	87.52
{LAP, LAP}	87.50	86.65
Hypothetic	87.65	86.76

initial spacing. Using the PLAC further reduces the fuel consumption. However, governing the lead vehicle with the LAC and the follower vehicle with the ACC at a spacing of 5 m is more fuel-efficient. The maximum fuel reduction is obtained with the cooperative LAP controller. For a downhill segment this controller has a higher fuel reduction than the hypothetic case. As opposed to traveling in an uphill, when traveling in a downhill the air drag has a larger effect on the required engine torque input to handle the imposed constraints. Therefore, the LAC is no longer optimal in a downhill due to the lowered air drag. Hence a slightly higher fuel saving is obtained for the LAP strategy.

Table III shows it is still more fuel-efficient to platoon by governing the preceding 20 t vehicle with the CC and the follower 40 t vehicle with the ACC in the 240 m long downhill segment, compared to the nominal case. However, for the 320 m long downhill segment it would have been more fuel-efficient for the vehicles to travel alone with their individual LAC. During the longer downhill segment a larger amount of energy is wasted, since the follower HDV is forced to brake when they are governed by the CC and ACC respectively. The same result can be observed in Table II, with the reverse ordering of the HDVs. Governing the preceding vehicle with the LAC and the follower vehicle with the ACC improves the fuel-efficiency, but the same issue of braking arises for a longer downhill segment. Both individual LAC can be used for the given vehicle order without endangering safety, which further reduces the fuel consumption. The highest fuel reduction is obtained for the LAP strategy. An improved fuel reduction of 14 % can be obtained in this case with the LAP compared to the {CC, ACC} combination that can be used for platooning. A longer downhill segment enables an increased fuel saving irrespective of vehicle order with the LAP. Note that the fuel reduction is slightly different for the LAP in Table II and Table III. This is due to a varying engine efficiency at different engine speeds in the engine model (4). The air drag reduction experienced by each HDV will be different based on the vehicle order. Hence, the required engine torque to facilitate the decelerations will differ, which results in the differences in fuel reduction. However, the energy required at the wheels to propel the HDVs forward is the same irrespective of vehicle order.

When facing both the uphill or a downhill segments the results show that the LAP is the most fuel efficient control strategy. However, there is only a slight difference in fuel saving obtained from the LAP compared to letting the preceding HDV be governed by the LAC profile that requires the largest changes in velocity and the follower vehicle by the ACC. Using the ACC implies that the HDVs simultaneously change their velocity. The lead HDV accelerates to resume the road speed after exiting the uphill segment. The follower vehicles in a platoon would then have to accelerate in the uphill climb, which is not always feasible. Similarly, the lead HDV decelerates after exiting a downhill segment. The follower vehicles, still traveling along the downhill segment, would then have to brake with the ACC, which is fuel-inefficient. Thus, it is both fuel-efficient and desirable in practice to implement the LAP control strategy, which initiates the change in velocity at a specific point in the road for all HDVs, as opposed to simultaneously changing the velocity to maintain the spacing. Fig 7 shows the trajectories for an $N = 9$ heterogeneous HDV platoon traversing an uphill and a downhill segment with the cooperative LAP strategy. It can be observed from the offset in the velocity trajectories given in the middle plot, that each vehicle defers its control action to track the agreed velocity profile until it reaches the same point. The top plot shows that the uphill segment is entered when each HDV in the platoon reaches the maximum velocity and equivalently for the downhill segment. The bottom plot shows that there is an equally slight change in the intermediate spacing between all HDVs. A fuel reduction of 12.1 % over the 2 km long road with the uphill segment and a fuel reduction of 18.7 % over the road of same length with a downhill segment is achieved for the whole platoon in total compared to if each HDV would have traveled the same road profile alone with their individual LAC.

VI. CONCLUSION

It is both fuel-efficient and desirable for practical reasons to consider the topography in HDV platooning due to physical constraints that are imposed on the system. Existing control strategies with respect to preview information for a single HDV is not always applicable to heterogeneous platooning. Several controllers, based on preview information, have been introduced and evaluated to provide intuition for how to tackle steep uphill and downhill segments with respect to fuel reduction. For fuel-efficiency the platoon should be maintained when traversing a hill, as opposed to letting the HDVs separate due to imposed constraints and then resume platooning by catching up after the hill. Thus, it is favorable to have a cooperative LAP control strategy, which initiates the change in velocity at a specific point in the

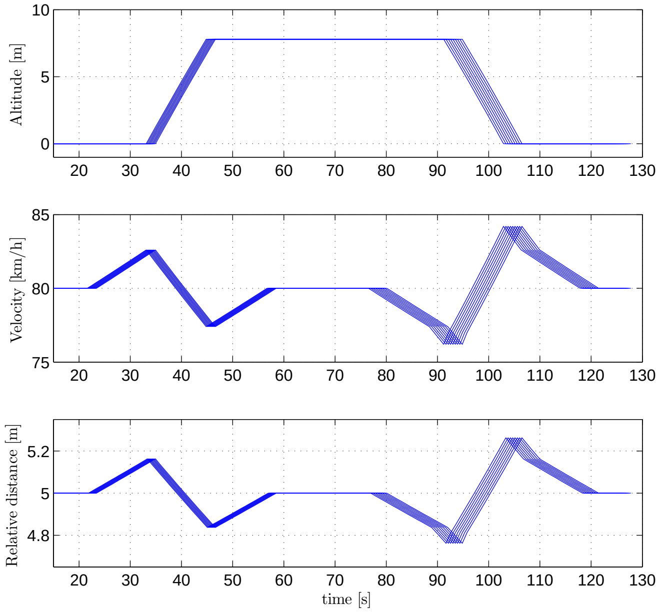

Fig. 7. Trajectories produced by the LAP strategy for an $N = 9$ HDV platoon traveling over a 4 km long road with uphill and downhill segments of 240 m. The lead HDV's trajectories are the ones that change earliest. The mass configuration of the platoon is $[m_1, \dots, m_9] = [20, 25, 30, 35, 40, 35, 30, 25, 20]$ tons, which are common for long-haulage HDVs in Europe. The top plot shows the experienced topography for each HDV. The middle plot shows their velocity trajectory and the bottom plot shows the corresponding intermediate spacing between neighboring vehicles.

road for all HDVs, as opposed to simultaneously changing the velocity to maintain the spacing. The presented LAP controller is practically feasible, since each HDV's intended velocity profile given by the commercially available LAC system can be transmitted. It is then simple to compare the profiles so that the profile that requires the largest changes in velocity can be agreed upon. The LAP controller can reduce the fuel consumption for two neighboring HDVs up to 14 % over a road with a downhill segment compared to the commercially available CC and ACC that could currently be utilized for platooning in practice. For an uphill climb, it can be observed that a more subtle benefit of 0.7 % improvement can be obtained with the proposed controller.

The LAP does not require knowledge of the specific vehicle parameters such as mass or maximum available engine torque. Nor any information regarding the dynamics of the surrounding vehicles. However, several system uncertainties exist in practice. Even though the most varying intended velocity profile is agreed upon, some HDVs in the platoon might still not be able to track it, for example, due to errors in mass estimation or maximum available engine torque. It has been argued in [20] that in such circumstances it is most beneficial to reach the desired maximum or minimum speed before reaching an uphill or downhill segment respectively. However, in the presence of uncertainties the fuel-efficient action for HDVs traveling in a platoon is still unclear. Further investigation into sensitivity to system uncertainties is left for future work.

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