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Gear management for fuel-efficient heavy-duty vehicle platooning

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Abstract— **Vehicle platooning has great potential for the reduction of greenhouse gas emissions and fuel consumption of heavy-duty vehicles. However, previous works on fuel-efficient platoon control largely ignore the effect of gear changes, even though experimental studies have shown that gear shifts have a large impact on the behavior and fuel consumption of vehicle platoons. In particular, the interruption in traction force during a gear shift can cause large deviations in the tracking of the reference speed and inter-vehicle distance and can result in the braking of the vehicles. In this paper, we discuss a control architecture that includes the management of gear shifts and we propose a method to select the gears that takes fuel-efficiency into account, but also targets the good behavior of the platoon. In detail, the proposed method is based on a dynamic programming formulation that computes the optimal sequence of gear shifts necessary for the fuel-efficient and smooth tracking of a given reference speed profile. The performance of the proposed approach is finally analyzed by means of simulations by comparing it with the performance of alternative solutions.**

I. INTRODUCTION

Vehicle platooning has been identified as a means to significantly decrease the energy consumption and the greenhouse gas emissions related to the freight transport sector. Heavy-duty vehicles are responsible for roughly 6 % of global greenhouse gas emissions [6], [9], and this percentage is expected to increase significantly if no action is taken [11]. This has been considered inadmissible and governments all over the world are taking action to drastically reduce these emissions. Experimental studies conducted in perfect environmental conditions have shown that, by letting heavy-duty vehicles drive at a short inter-vehicular distance (i.e., in a platoon formation), it is possible to achieve fuel savings of up to 10 % [2], [13]. However, the deployment of fuel-efficient truck platooning on public roads is not a trivial task due to, e.g., external traffic and varying topography. This has led to the creation of numerous governmental research programs [5], [15], [17], [18] aimed at making fuel-efficient truck platooning on public road possible.

Due to the large mass of heavy-duty vehicles, road altitude variation has a significant influence on the fuel consumption of truck platoons. The problem has been studied in [20], where the authors propose a two-layer control architecture to achieve fuel-efficient and safe platooning. The higher layer of such architecture, namely the platoon coordinator, generates a fuel-optimal speed trajectory for the platoon, while the lower layer, namely the vehicle control layer, distributively tracks it while guaranteeing the safety of the platoon operations. In this work the impact of gear shifts on the platoon dynamics has been ignored by assuming that trucks are equipped with a continuously varying transmission. However, commercial heavy-duty vehicles are typically equipped with gear boxes that have a finite number of gears. Moreover, changing gear introduces delays and a temporary interruption of the transferred force. In practice, such interruptions have shown to have a strong impact on the platoon behavior [1]. Gear shifts, in fact, typically take place in proximity of road altitude variations and due to the introduced delay, they can cause large deviations from the reference speed and inter-vehicular distance. To compensate for these deviations, the distance controller typically requires a maximum throttle phase followed by a braking phase. Due to the wasting nature of braking, this behavior is extremely inefficient.

In this paper we study how the gear selection in a vehicle platoon should be managed in order to achieve a high level of fuel-efficiency. We first propose and motivate a control architecture for fuel-efficient truck platooning that extends the control architecture presented in [20] by introducing an extra layer responsible for the gear selection for the platooning vehicles. Second, we propose a formulation for the gear management layer aimed at computing the optimal sequence of gear shifts for each vehicle on the basis of fuel-efficiency criteria. Finally, the proposed formulation is supported by a simulation study that compares the proposed control architecture to alternative solutions.

To the best knowledge of the authors, the gear management problem for vehicle platooning has not been studied. Extensive work has been conducted on the optimal gear management for a single vehicle, see e.g., [8], [4], [12] and [14]. In [8], a dynamic programming approach that optimizes the speed and the gear shifts of a single vehicle driving along a hilly road is proposed. While this method is well-suited for controlling single vehicles, due to the curse of dimensionality, it becomes prohibitive in the case of a platoon. In [4], the authors propose a hybrid model predictive control (MPC) approach to handle the gear shifts of a vehicle tracking a given speed profile. Due to the time burden of solving the corresponding mixed-integer optimization problem online, they derive the explicit MPC form of the problem. Although explicit MPC transforms the original MPC problem in the efficient exploration of look-up tables, this approach fails in supporting a large number of time-varying parameters as in the case of vehicles driving along a road with varying topography. In [12], a three-layer control

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architecture is proposed to handle the fuel-optimal control of a hybrid truck driving along a hilly road. The layers are responsible for the generation of the fuel-optimal speed profile, the scheduling of the gear and the powertrain mode, and the tracking of the optimal speed profile, respectively. Although this control architecture has been designed for a single vehicle, we believe that a similar control architecture can be suitable for the fuel-efficient control of platoons, as will be discussed in Section III. Finally we point out that in the majority of the works on gear management for single vehicles (see [4], [12] and [14]), the delay introduced by the gear shift is not taken into account. Due to the tracking of both speed and distance references typical of platooning control, this is a crucial aspect in the studied problem and, therefore, cannot be ignored.

The remainder of the paper is organized as follows. In Section II, we present the model of a truck driving in a platoon and the engine model used to estimate each vehicle's fuel consumption. In Section III, we analyze the gear management problem for vehicle platooning and we propose a control architecture to address it. Sections IV and V present the details of the two layers of this architecture, namely the gear management layer and the vehicle control layer. In Section VI, we present a simulation study that shows the performance of the proposed method compared to alternative solutions. Finally, Section VII concludes the paper.

II. VEHICLE MODEL

In this section we present the model of a vehicle driving along a road with a varying topography. The modeling is limited to the longitudinal dynamics and particular attention is paid to capturing the dynamics introduced by gear changes. Furthermore, we introduce a static model for estimating the fuel consumption of the platooning vehicles.

The longitudinal dynamics of a vehicle is derived by using Newton's second law, leading to

$$\begin{aligned} m_i\dot{v}_i &= F_{\mathrm{e},i}(T_{\mathrm{e,i}}, g_{\mathrm{e},i}) + F_{\mathrm{b},i} - m_i g \sin\alpha(s_i) \\ &\quad - m_i g c_{\mathrm{r},i} - \tfrac{1}{2}\rho A C_{\mathrm{d}}(d_i) v_i^2, \end{aligned} \tag{1a}$$

$$\dot{s}_i = v_i, \tag{1b}$$

where v_i, s_i and $g_{\mathrm{e},i}$ are the states of vehicle i and denote the vehicle speed, longitudinal position and engaged gear, respectively. The terms on the right hand side of equation (1a), from left to right, represent the engine force, the braking force, the gravitational force, the rolling resistance and the aerodynamic drag, respectively. The engine torque $T_{\mathrm{e},i}$ and the braking force $F_{\mathrm{b},i}$ are the control inputs of the system. The variable d_i denotes the distance to the preceding vehicle defined as $d_i = s_{i-1} - s_i - l_{i-1}$, where l_i is the length of vehicle i. The aerodynamic drag coefficient $C_{\mathrm{d}}(d_i)$ is defined as a function of the distance to the preceding vehicle as follows:

$$C_{\mathrm{d}}(d_i) = C_{\mathrm{d},0}\left(1 - \frac{C_{\mathrm{d},1}}{C_{\mathrm{d},2} + d_i}\right), \tag{2}$$

where $C_{\mathrm{d},0}$, $C_{\mathrm{d},1}$ and $C_{\mathrm{d},2}$ are parameters that have been estimated by regressing the experimental data presented in

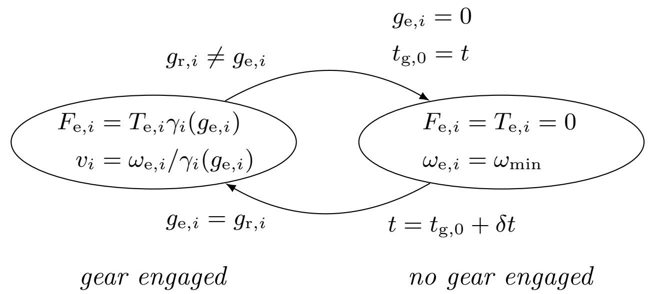

Fig. 1. Automaton modeling the vehicle powertrain.

[10] (see [20] for further details). The reduction of the aerodynamic drag with the decrease of the inter-vehicular distance is one of the main motivations for truck platooning. The variable $\alpha(s)$ represents the road slope at position s. Finally, the parameters m_i, g, $c_{\mathrm{r},i}$, ρ and A denote the vehicle mass, the gravitational acceleration, the roll coefficient, the air density and the cross-sectional area of the vehicle, respectively.

The longitudinal engine force $F_{\mathrm{e},i}$ is generated by the engine and transferred to the wheels through the transmission, which includes the clutch, the gear box and the final drive. Here, we use a simple model of the powertrain that is able to catch the dynamics introduced by the gear box. This model is represented by the automaton illustrated in Figure 1. The *gear engaged* state represents the relation between the engine and vehicle variables, when gear $g_{\mathrm{e},i}$ is engaged. The variables $T_{\mathrm{e},i}$ and $\omega_{\mathrm{e},i}$ are the torque and engine speed, respectively. For a correct operation of the engine, these variables are bounded by

$$\begin{aligned} T_{\mathrm{min},i} &\leq T_{\mathrm{e},i} \leq T_{\mathrm{max},i}, \\ \omega_{\mathrm{min},i} &\leq \omega_{\mathrm{e},i} \leq \omega_{\mathrm{max},i}. \end{aligned} \tag{3}$$

The parameter $\gamma_i(g_{\mathrm{e},i})$ denotes the transmission conversion rate from the vehicle longitudinal speed to the engine angular speed. It is a function of the final drive ratio, the wheel radius and the engaged gear $g_{\mathrm{e},i}$. The *no gear engaged* state models the transmission during a gear shift. In this state the clutch is open and, therefore, there is no torque generated nor force transferred to the wheels. The engine speed, furthermore, is assumed to be equal to ω_{min}. The required gear $g_{\mathrm{r},i}$ is the control input of the automaton and triggers the transition from the *gear engaged* to the *no gear engaged* state. The vehicle stays in the latter state for a time δt, before switching back to the *gear engaged* state.

A standard way to measure the fuel consumption is to use an affine map between the engine torque $T_{\mathrm{e},i}$ and speed $\omega_{\mathrm{e},i}$, and the consumed fuel per stroke [7], [8]. This affine map translates in the following quadratic relation between the fuel flow ψ_i and the engine variables:

$$\psi_i = \varphi_i(T_{\mathrm{e}}, \omega_{\mathrm{e}}) = a_{\psi,i} T_{\mathrm{e}} \omega_{\mathrm{e}} + b_{\psi,i}\omega_{\mathrm{e}}^2 + c_{\psi,i}\omega_{\mathrm{e}}, \tag{4}$$

where $a_{\psi,i}$, $b_{\psi,i}$ and $c_{\psi,i}$ are engine parameters. In order to run the simulation in Section VI, these parameters have

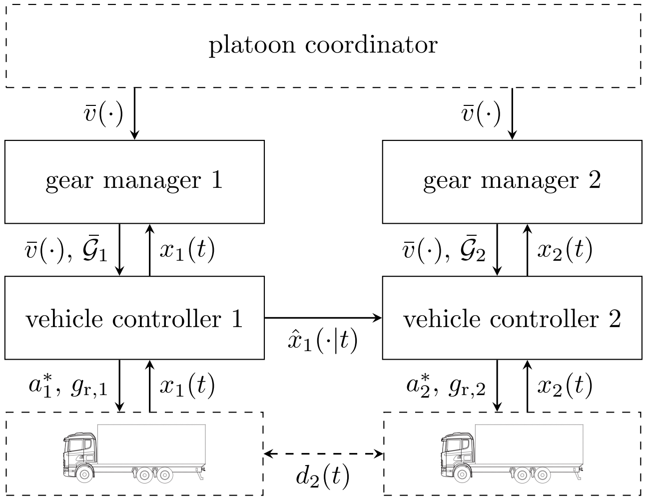

Fig. 2. Control architecture for a two-vehicle platoon.

been obtained by regressing the data from a real truck engine presented in [16].

III. CONTROL ARCHITECTURE

In this section we discuss the gear management problem for vehicle platooning and we propose a control architecture to handle it, see Figure 2. Here, we assume that the reference speed trajectory that the platoon should track is given. In particular, in this work the speed trajectory is computed by a platoon coordinator layer that, by exploiting road topography information, generates the fuel-optimal speed trajectory $\bar{v}(\cdot)$ for the whole platoon. Such trajectory is defined in space and is unique for the whole platoon, see [20] for a detailed discussion on the reference speed trajectory computation.

Gears have a strong impact on the vehicle's fuel consumption and on the reference speed and inter-vehicular distance tracking. The wrong gear can lead the engine to operate in a strongly inefficient region, while a gear shift taking place in the wrong moment, e.g., during an uphill stretch, can lead to a large deviation from the references that can be hard to compensate for. A gear management strategy for platooning should, therefore, take both aspects into account. To address these problems we suggest a two-layer control architecture as depicted in Figure 2.

The higher layer of such architecture, namely the gear management layer, is responsible for choosing the sequence of gear shifts $\bar{\mathcal{G}}_i$ for each vehicle in order to optimally track the reference speed trajectory $\bar{v}(\cdot)$. The gear shift sequence is, first of all, optimized according to fuel-efficiency criteria. Furthermore, due to the interruption of the transferred force during gear shifts, the gear managers also penalize the impact of gear shifts on the tracking of the speed and inter-vehicular distance. This is achieved by ensuring that the deviation from the references during gear shifts is small and that it can be compensated for in a limited time. As it will be shown in the simulation study of Section VI, these aspects are crucial for a smooth behavior of the platoon. The formulation and the implementation of the gear management layer are discussed in Section IV.

The lower layer of the control architecture, namely the vehicle control layer, tracks the speed reference $\bar{v}(\cdot)$ and the chosen spacing policy, while taking into account the requested sequence of gear shifts $\bar{\mathcal{G}}_i$. To be consistent with the space-defined reference speed, the vehicles track a spacing policy corresponding to a pure time gap, i.e., consecutive vehicles pass through the same points along the road with a constant time delay [20]. The vehicle control layer relies on a distributed MPC formulation where each vehicle shares its predicted state trajectory with the following vehicle. Furthermore, the knowledge of a future gear shift is exploited in the prediction of the vehicles state in order to guarantee the smooth tracking of the reference. Each vehicle controller computes the required engine torque and braking force, and triggers the gear shift. These requests are communicated to the engine, braking and gear management systems typically available in commercial trucks that execute them [19]. The formulation and the implementation of the vehicle control layer are discussed in Section V.

IV. GEAR MANAGEMENT LAYER

In this section we present the problem formulation and the implementation of the gear management layer.

The gear manager is a controller local to each vehicle that receives the space-defined reference speed profile $\bar{v}(\cdot)$ from the platoon coordinator and computes the optimal sequence of gear shifts for the current vehicle

$$\mathcal{G}_i = \{(g_{l,i}, s_{l,i})\}_{l=1}^{L_i}, \tag{5}$$

where $g_{l,i}$ and $s_{l,i}$ denote the l-th required gear and the longitudinal position where it should occur, respectively. For simplicity of notation, in the remainder of this section the index i corresponding to the current vehicle is dropped.

The gear manager is formulated as an optimization problem whose objective is to minimize the vehicle fuel consumption and the impact of the gear shift on the deviation from the reference speed profile and desired inter-vehicle gap. In detail, the cost that we aim to minimize is formulated as

$$J_{\text{fuel}}(\mathcal{G}) + \alpha J_{\text{shift}}(\mathcal{G}), \tag{6}$$

where $J_{\text{fuel}}(\mathcal{G})$ denotes the consumed fuel over the gear manager horizon H_{GM} and $J_{\text{shift}}(\mathcal{G})$ quantifies the energy lost during gear shifts (i.e., the energy that the engine would have transferred to the wheels if no gear shift takes place). The consumed fuel $J_{\text{fuel}}(\mathcal{G})$ is expressed as a function of the sequence of gear shifts $\mathcal{G}$, the reference speed $\bar{v}$ and the engine force needed to track $\bar{v}$ defined as

$$\begin{aligned} \bar{F}_{\mathrm{e}}(s) =& mv(s)\frac{d\bar{v}(s)}{ds} - F_{\mathrm{b}}(s) + mg\sin\alpha(s) \\ &+ mgc_{\mathrm{r}} + \tfrac{1}{2}\rho A C_{\mathrm{d}}(d)\bar{v}^2(s). \end{aligned} \tag{7}$$

Then, it can be formulated as

$$J_{\text{fuel}}(\mathcal{G}) = \int_{s_0}^{s_0+H_{\text{GM}}} \varphi\big(\bar{F}_{\mathrm{e}}/\gamma(g_{\mathrm{r}}(s)), \bar{v}(s)\gamma(g_{\mathrm{r}}(s))\big)\, ds, \tag{8}$$

where $\varphi(\cdot,\cdot)$ represents the fuel model defined in (4) and s_0 the initial vehicle position. Here we remark that $\gamma(g_\text{r})$ is the transmission ratio that relates the velocity/force at the wheels to the required engine speed/torque. It depends on the required gear $g_\text{r}(s)$ that is defined as a function of the gear shift sequence $\mathcal{G}$ as

$$g_\text{r}(s) = \begin{cases} g_l, & \text{if } s_l \le s < s_{l+1}, \\ g_L, & \text{if } s_L \le s < s_0 + H_\text{GM}, \end{cases} \tag{9}$$

where $(g_0,\, s_0)$ is a parameter of the optimization and represents the initial engaged gear and position pair. The term $J_\text{shift}(\mathcal{G})$, representing the lost energy during the gear shifts, is expressed as a function of the required engine force $\bar{F}_\text{e}(s)$ in (7) as

$$J_\text{shift}(\mathcal{G}) = \sum_{l=1}^{L} \int_{s_l}^{s_l+2\delta s} \bar{F}_\text{e}(s)\, ds, \tag{10}$$

where $2\delta s$ represents an upper bound on the space that a gear shift takes. A small energy loss during the gear shift results in a small deviation from the speed and distance references and therefore in the smooth behavior of the platoon.

The minimization of the presented cost function should take place while certain constraints are fulfilled. First of all, we require that the gear shift sequence $\mathcal{G}$ is able to generate the required force $\bar{F}_\text{e}$ while driving at the reference speed $\bar{v}$ and the engine operates in a bounded region. This is ensured by introducing the following two constraints:

$$\bar{F}_\text{e}(s) \le F_\text{max}(g_l), \tag{11a}$$

$$v_\text{min}(g_l) \le \bar{v}(s) \le v_\text{max}(g_l), \tag{11b}$$

for all $s \in [s_l, s_{l+1})$. Here, $F_\text{max}(g) = T_\text{max}\gamma(g)$ denotes the maximum engine force (at the wheel) that can be generated by the engine while gear g is engaged. The variables $v_\text{min}(g) = \omega_\text{min}/\gamma(g)$ and $v_\text{max}(g) = \omega_\text{max}/\gamma(g)$ denote the minimum and maximum speeds, respectively, that the vehicle can drive, while gear g is engaged. Second, we require that the gear shifts are not happening too often. By assuming that the vehicle is not allowed to drive faster than a certain speed, the latter requirement is relaxed by requiring that consecutive gear shifts are spaced by a minimum interval Δs_shift, i.e.,

$$s_{l+1} \ge s_l + \Delta s_\text{shift}. \tag{12}$$

Finally we wish to guarantee that deviations from the reference speed profile and desired inter-vehicle gap, caused by the interruption of traction force during the gear shifts, can be compensated for in a bounded space span. By choosing this span such that it is covered by the prediction horizon of the vehicle control layer (under certain assumption on the minimum vehicles speed), we provide the basis for a good reference tracking of the vehicle control layer. This requirement is enforced by demanding that the energy lost during the gear shift (that is assumed to take place on a space interval shorter than $2\delta s$) can be compensated in the space intervals Δs before and after the gear shift. Let us first introduce the energy quantities $E_{\delta 1}(l)$, $E_{\delta 2}(l)$, $E_{\Delta 1}(l)$ and $E_{\Delta 2}(l)$ displayed in Figure 3. These represent the energies lost during the first and second half of the l-th gear shift and the extra energy available in the space intervals Δs before and after the gear shift, i.e.,

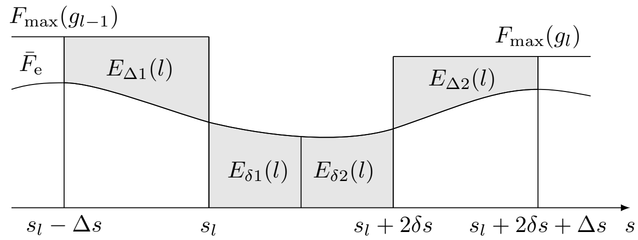

Fig. 3. Illustration representing the small deviation constraint in the formulation of the gear manager as expressed in (14).

$$\begin{aligned} E_{\delta 1}(l) &= \int_{s_l}^{s_l+\delta s} \bar{F}_\text{e}(s)\, ds, \\ E_{\delta 2}(l) &= \int_{s_l+\delta s}^{s_l+2\delta s} \bar{F}_\text{e}(s)\, ds, \\ E_{\Delta 1}(l) &= \int_{s_l-\Delta s}^{s_l} F_\text{max}(g_{l-1}) - \bar{F}_\text{e}(s)\, ds, \\ E_{\Delta 2}(l) &= \int_{s_l+2\delta_s}^{s_l+2\delta_s+\Delta s} F_\text{max}(g_l) - \bar{F}_\text{e}(s)\, ds. \end{aligned} \tag{13}$$

The discussed requirement can be now formalized by the inequalities

$$\begin{aligned} E_{\delta 1}(l) &\le E_{\Delta 1}(l), \\ E_{\delta 2}(l) &\le E_{\Delta 2}(l). \end{aligned} \tag{14}$$

To summarize, the task of each gear manager is to solve the following optimal control problem:

$$\begin{aligned} \underset{\mathcal{G}}{\text{minimize}} \quad & J_\text{fuel}(\mathcal{G}) + \alpha J_\text{shift}(\mathcal{G}) \\ \text{subj. to} \quad & \bar{F}_\text{e} \le F_\text{max}(g_l),\ \forall s \in [s_l, s_{l+1}), \\ & v_\text{min}(g_l) \le \bar{v}(s) \le v_\text{max}(g_l),\ \forall s \in [s_l, s_{l+1}), \\ & s_{l+1} \ge s_l + \Delta s_\text{shift}, \\ & E_{\delta 1}(l) \le E_{\Delta 1}(l), \\ & E_{\delta 2}(l) \le E_{\Delta 2}(l), \end{aligned}$$

for $l = 0, ..., L$. Thanks to the discrete nature of gears, the optimization problem can be efficiently solved by using dynamic programming [3]. This is achieved by introducing a discretization of the spatial domain s. The optimal gear shift sequence $\bar{\mathcal{G}}_i$ is finally communicated to the corresponding vehicle controller.

V. VEHICLE CONTROL LAYER

In this section we discuss the problem formulation for the vehicle control layer. Each vehicle controller receives the reference speed $\bar{v}(\cdot)$ and the requested sequence of gear shifts $\bar{\mathcal{G}}_i$ from the higher layers, and the optimal state trajectory $\hat{x}_{i-1}(\cdot|t)$ from the preceding vehicle. By solving an MPC problem aimed at safely tracking the reference speed and the time gap, it computes the required acceleration a_i^* and triggers the gear shifts.

The state prediction of the MPC problem is based on the vehicle model

$$\begin{aligned}\dot{v}_i(\tau|t) &= a_i(\tau|t),\\ \dot{s}_i(\tau|t) &= v_i(\tau|t),\end{aligned} \tag{15}$$

where $v_i(\tau|t)$ and $s_i(\tau|t)$ denote the predicted speed and position of vehicle i at time $\tau \geq t$ computed at time t, respectively, while the control input $a_i(\tau|t)$ denotes the predicted vehicle acceleration. For simplicity of notation, we introduce the state vector $x_i = [v_i\, s_i]^{\mathrm{T}}$. The tracking of the speed reference and the time gap t_{gap} is achieved by introducing the cost function

$$\begin{aligned}J_{\text{MPC}}(a_i(\cdot|t)) = \int_t^{t+H_{\text{MPC}}} &||x_i(\tau|t) - \hat{x}_{i-1}(\tau - t_{\text{gap}}|t)||^2_{\zeta_i Q}\\ &+||x_i(\tau|t) - \bar{x}_i(t)||^2_{(1-\zeta_i)Q}\\ &+||a_i(\tau|t) - \bar{a}_i(t)||^2_R\\ &+||\xi_i(\tau|t)||^2_P \, d\tau,\end{aligned}$$

where H_{MPC} is the MPC horizon and $||\cdot||_Q$ represents the weighted norm operator defined as $||x||^2_Q = x^{\mathrm{T}}Qx$. Here, the first term penalizes the state deviation from the time gap, the second one the state deviation from the speed reference, the third one input deviation from the reference, while the forth one penalizes the slack variable related to the no-braking constraints that will be discussed later. The parameters $Q > 0$, $R > 0$ and $P > 0$ denote the weights on the aforementioned terms, while $\zeta_i \in [0, 1]$ is the trade-off between the time gap and the speed reference tracking. The references $\bar{x}_i(t)$ and $\bar{a}_i(t)$ are obtained from the reference speed $\bar{v}(s)$ and their computation is discussed in [20]. In order to account for the vehicle dynamics defined by the vehicle model (1), we introduce the minimum and maximum allowed accelerations, $a_{\text{min},i}$ and $a_{\text{max},i}$, respectively, and the coasting acceleration $a_{\text{coast},i}$ (i.e., the vehicle acceleration when no fuel is injected in the engine) defined as follows:

$$\begin{aligned}a_{\text{min},i}(\tau|t) &= \frac{1}{m_i}(F_{\text{b,min},i} + F_{\text{ext},i}(\tau|t)),\\ a_{\text{max},i}(\tau|t) &= \frac{1}{m_i}(T_{\max}\gamma_i(g_{\text{e},i}(\tau|t)) + F_{\text{ext},i}(\tau|t)),\\ a_{\text{coast},i}(\tau|t) &= \frac{1}{m_i}(T_{\min}\gamma_i(g_{\text{e},i}(\tau|t)) + F_{\text{ext},i}(\tau|t)),\end{aligned}$$

where $F_{\text{b,min},i}$ represents the minimum force that can be generated by the braking system and $F_{\text{ext},i}(x_i)$ denotes the summation of the external forces acting on the vehicle defined as

$$\begin{aligned}F_{\text{ext},i}(\tau|t) = &- m_i g \sin\alpha(s_i(\tau|t)) - c_r m_i g\\ &- \tfrac{1}{2}\rho A_v C_{\text{d}}\big(\hat{s}_{i-1}(\tau|t) - s_i(\tau|t) - l_{i-1}\big)v_i^2(\tau|t).\end{aligned}$$

Note that the engaged gear $g_{\text{e},i}(\tau|t)$ is a parameter of the optimization problem and is computed according to the automaton displayed in Figure 1, where the input variable $g_{\text{r},i}$ is driven according to gear shift sequence $\bar{\mathcal{G}}_i$. Here we assume that the transmission ratio γ_i is equal to 0 when the engaged gear $g_{\text{e},i}$ is 0 (i.e., when the powertrain is in the *no gear engaged* state). As a result, during a gear shift the maximum acceleration $a_{\max}$ and the coasting acceleration a_{coast} will coincide. The vehicle acceleration a_i can be now bounded by the hard constraint

$$a_{\text{min},i}(\tau|t) \leq a_i(\tau|t) \leq a_{\text{max},i}(\tau|t)$$

and the soft constraint

$$a_i(\tau|t) + \xi_i(\tau|t) \geq a_{\text{coast},i}(\tau|t), \quad \epsilon_i(\tau|t) \geq 0.$$

By strongly penalizing the slack variable ξ_i in the cost function, we are requiring that the braking is taking place only if one of the hard constraints is activated. Furthermore, the prediction horizon H_{MPC} is chosen such that, by assuming a minimum speed allowed, always covers a space longer than $2(\delta s + \Delta s)$, i.e., the space that a gear shift and its compensation takes in the gear management layer. This, combined with the inclusion of the engaged gear in the acceleration bounds in (16), guarantees the smooth tracking of the reference speed and time gap.

Finally, in order to guarantee the safe operation of the platoon we introduce the safety constraints

$$\begin{aligned}s_i(t_{\text{n}}|t) - \frac{v_i^2(t_{\text{n}}|t)}{2\overline{a}_{\text{min},i}} &\leq \hat{s}_{i-1}(t_{\text{n}}) - \frac{\hat{v}_{i-1}^2(t_{\text{n}})}{2\underline{a}_{\text{min},i}} - l_{i-1},\\ s_i(t_{\text{n}}|t) &\leq \hat{s}_{i-1}(t_{\text{n}}) - l_{i-1},\end{aligned} \tag{16}$$

where $\underline{a}_{\text{min},i}$ and $\overline{a}_{\text{min},i}$ represent conservative lower and upper bounds on $a_{\text{min},i}$, respectively and the time t_{n} represents when the next MPC instance will be solved. A discussion on the introduced safety constraints is presented in [20].

To summarize, the MPC problem solved in each vehicle controller is formulated as follows:

$$\begin{aligned}\underset{a_i(\cdot|t)}{\text{minimize}} \quad & J_{\text{MPC}}(a_i(\cdot|t))\\ \text{subj. to} \quad & \dot{v}_i(\tau|t) = a_i(\tau|t),\\ & \dot{s}_i(\tau|t) = v_i(\tau|t),\\ & a_{\text{min},i}(\tau|t) \leq a_i(\tau|t) \leq a_{\text{max},i}(\tau|t),\\ & a_i(\tau|t) + \epsilon_i(\tau|t) \geq a_{\text{coast},i}(\tau|t),\ \epsilon_i(\tau|t) \geq 0,\\ & f_{\text{safe}}(x(t_{\text{n}}|t)) \leq 0,\end{aligned}$$

for $\tau \in [t,\, t + H_{\text{MPC}}]$, where $f_{\text{safe}}(x(t_{\text{n}}|t)) \leq 0$ denotes the safety constraints (16). The resulting optimal state trajectory $\hat{x}_i(\cdot|t)$ is communicated to the follower vehicle. The problem has been solved by discretizing the vehicle dynamics, relaxing the problem to a linear MPC problem and recasting it in a quadratic programming problem, similarly to the approach used in [20].

VI. SIMULATION RESULTS

In this section we study the performance of the proposed approach by means of simulations. We consider a heterogeneous platoon of four vehicles with mass of 25, 40, 25 and 40 tons, respectively, and with the same powertrain characteristics. In detail, each vehicle is equipped with a 400 hp engine and a 14-gear gear box (a gear shift is assumed to produce a interruption of transferred force of $\delta t = 2\,\text{s}$). The gear management uses a prediction horizon H_{GM} of 4 km, while the vehicle control layer has a prediction horizon H_{MPC} of 8 s. The altitude profile has been artificially

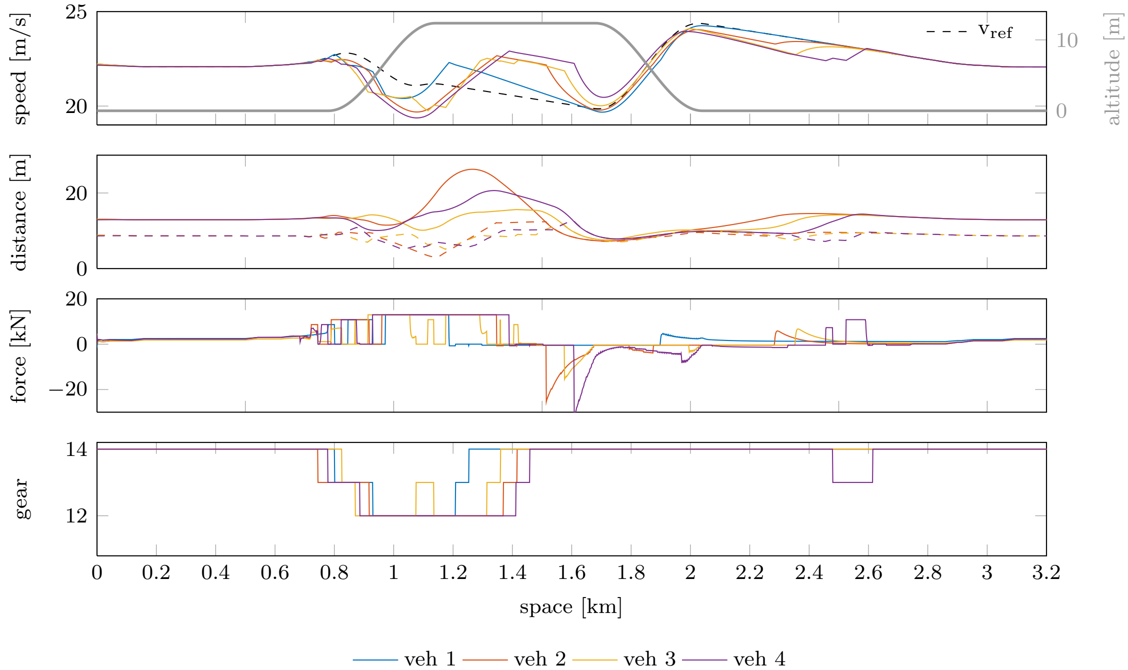

Fig. 4. Simulation of a four-vehicle platoon driving over a hill, when the *reference gear management* is deployed. The first plot displays the road altitude in gray color and the speed of the vehicles. The second plot shows the inter-vehicular distance with solid lines and the safe distance computed according to (16) with dashed line. The third plot shows the control force, defined as the summation of the engine and braking forces. Finally, the fourth plot displays the gear selected by the gear management. Note that all the variables are plotted as a function of the longitudinal position along the road.

constructed and is composed by an uphill stretch followed by a downhill stretch, as depicted in gray color in the first plot of Figure 4. The proposed controller is compared to two alternative solutions:

- *reference gear management*: this is the standard gear management common in commercial heavy-duty vehicles. The gear shift takes place when the engine speed reaches certain thresholds. These thresholds are increased when the required normalized torque is higher than 80 % for more than 1 s. This allows the engine to operate in a higher power range when this is needed;
- *fuel-based gear management*: this is an alternative formulation of the proposed gear manager where only the consumed fuel and the number of gear shifts are minimized, while the constrains on the lost energy during the gear shift (i.e., inequalities in (14)) are not included. The number of gear shifts has been included in the cost function in order to avoid that it becomes unnecessary too large.

The three controllers have been compared on the basis of the platoon fuel consumption computed according to the fuel model in (4) as

$$F = \sum_{i=1}^{N_\text{v}} \int_0^{T_\text{sim}} \varphi_i(T_{\text{e},i}(t), \omega_{\text{e},i}(t))dt \tag{17}$$

TABLE I

Normalized fuel consumption and reference tracking deviation (in %) of the platoon for three gear management strategies, namely the reference, the fuel-based and the proposed gear managements.

	reference	*fuel-based*	*proposed*
Consumed fuel (F)	100	90	89
Tracking deviation (D)	100	12	5

and the reference tracking deviation computed as

$$D = \sum_{i=1}^{N_\text{v}} \int_0^{T_\text{sim}} ||x_i(t) - \hat{x}_{i-1}(t - t_\text{gap})||^2_{\zeta_i Q} \\ + ||x_i(t) - \bar{x}_i(t)||^2_{(\zeta_i - 1)Q}\, dt,$$

where N_v and T_sim represent the number of vehicles in the platoon and the simulation time, respectively. The normalized platoon fuel consumption and the reference tracking deviation for the three gear management strategies are summarized in Table I. Let now proceed to the analysis of the three simulations.

Figure 4 displays the platoon behavior when the *reference gear management* is used. The deployed gear management does not exploit any information on the road ahead and requires gear shifts only on the basis of the engine variables. We can notice that all four trucks asynchronously downshift two times at the beginning of the uphill. The delays introduced by the gear shifts and the fact that the vehicle control layer cannot take them into account (because with such gear management formulation future gear shifts

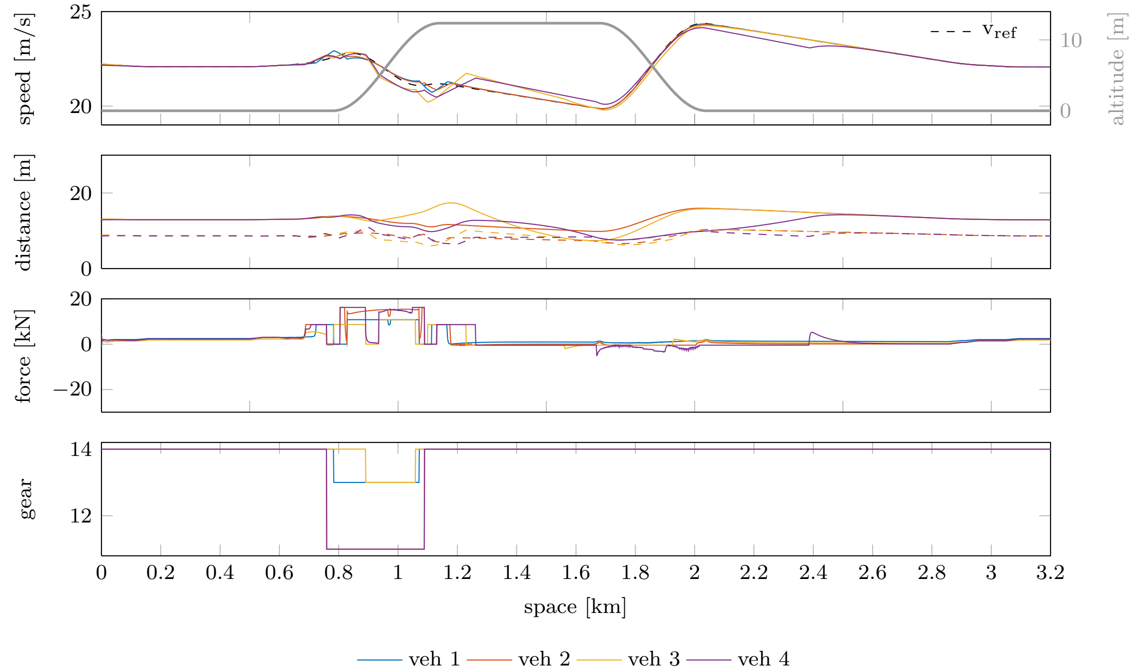

Fig. 5. Simulation of a four-vehicle platoon driving over a hill, when the *fuel-based gear management* is deployed. Refer to the caption of Figure 4 for the plots explanation.

are unknown) result in a large deviation from the reference speed and time gap for all follower vehicles. To compensate for such deviation the vehicle controllers require the engines to generate the maximum torque after the gear shifts take place. Due to the limited prediction horizon, the vehicle control layer does not see far enough to understand that it is counter-productive to require such a large amount of energy from the engine. This behavior leads in fact to the vehicles coasting and finally braking in order to avoid collision with the preceding vehicles. Since the reference speed trajectory computed by the platoon coordinator requires the heaviest trucks to coast after the uphill, only an extremely long prediction horizon would have avoided the braking of the vehicles. A similar behavior has been also experienced in the experiments with real vehicles presented in [1] where a three-vehicle platoon drives along a hilly road.

Figure 5 shows the platoon behavior when the *fuel-based gear management* is used. Here, topography information of the road ahead is exploited in the computation of the gear shift sequence. The optimization is based only on the fuel consumption and the number of gear shifts, while the impact of the gear shift on reference tracking is ignored. As a result, even if the number of gear shifts during the uphill stretch is reduced to one, the vehicle control layer has trouble to compensate for the generated deviation from the reference. This is due to the fact that the gear shifts take place in sections where the required force $\bar{F}_{e,i}$ necessary to track the reference speed is close to the maximum. Consequently, the third and forth vehicles full-throttle for a certain amount of time and, in order not to collide with the preceding vehicle, they finally brake.

Figure 6 displays the platoon behavior when the *proposed gear management* is used. With respect to the previous case, the gear shift optimization also targets the impact of the gear shifts on the deviation from the reference. In particular, by choosing the parameter Δs equal to $30\,\mathrm{m}$ and assuming that the vehicle speed is bounded in a certain interval, we can guarantee that the deviation from the references due to the gear shift can be compensated for over the prediction horizon $H_{\mathrm{MPC}} = 8\,\mathrm{s}$ of the vehicle control layer. By analyzing the simulation results, we can notice that the gear management requires the gear shifts to take place before the start and the end of the uphill section. In such regions, in fact, the energy lost during the gear shifts is small enough to be compensated for in a sufficiently short horizon. As a result, the deviations generated by the gear shifts are promptly compensated and the vehicles smoothly track the reference speed and time gap without engaging the brakes. Besides the good tracking of the reference speed and time gap, the absence of braking leads to an additional fuel saving of the platoon compared to the fuel-based gear management as displayed in Table I.

VII. CONCLUSIONS

In this paper we studied the gear management problem for fuel-efficient heavy-duty vehicle platooning. We discussed a control architecture that includes the management of the gear shifts and we proposed a method based on dynamic programming to choose the sequence of gear shifts. In particular the gear shift sequence is optimized according to fuel-efficiency criteria and in order to have a limited impact on reference tracking. We finally presented a simulation study where the performance of the proposed controller is

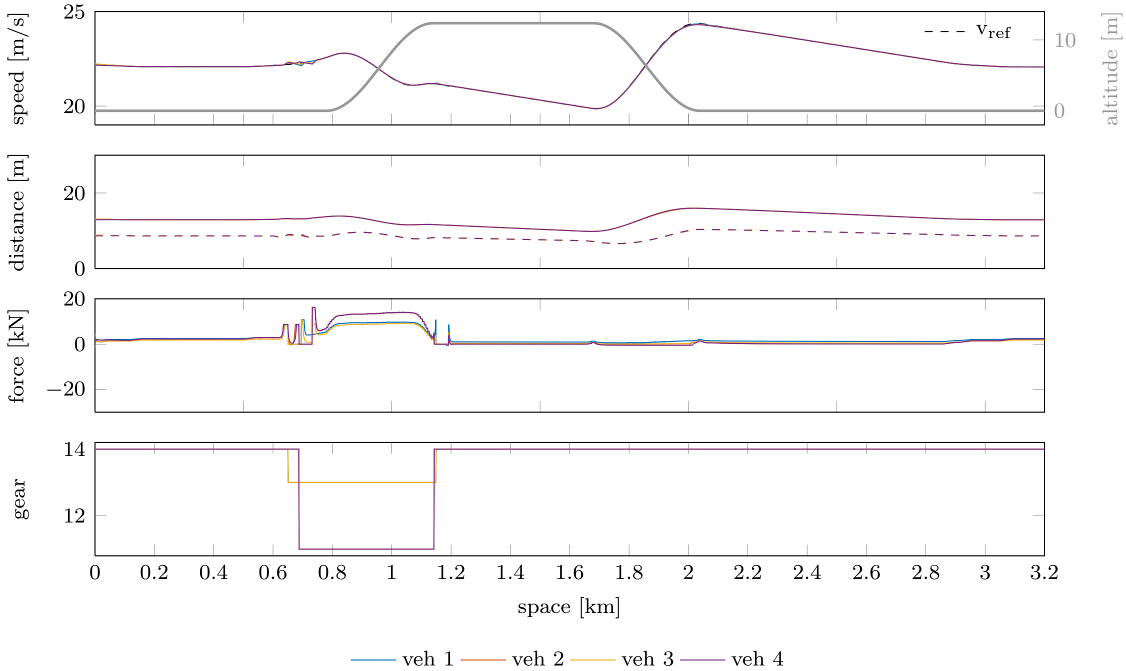

Fig. 6. Simulation of a four-vehicle platoon driving over a hill, when the *proposed gear management* is deployed. Refer to the caption of Figure 4 for the plots explanation.

compared to alternative solutions. Future works will investigate the possible benefits of adding communication between the vehicle gear managers (this would for example enable the synchronization of the gear shifts) and the performance of the controlled platoon while driving over more realistic topography profiles.

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