Battery Electric Vehicles Platooning: Assessing Capability of Energy Saving and Passenger Comfort Improvement

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Matteo Spano
Department of Mechanical and Aerospace Engineering (DIMEAS)
Politecnico di Torino
Torino, Italy
matteo.spano@polito.it

Alessia Musa
Department of Energetic (DENERG)
Politecnico di Torino
Torino, Italy
alessia.musa@polito.it

Pier Giuseppe Anselma
Department of Mechanical and Aerospace Engineering (DIMEAS)
Politecnico di Torino
Torino, Italy
pier.anselma@polito.it

Daniela Anna Misul
Department of Energetic (DENERG)
Politecnico di Torino
Torino, Italy
daniela.misul@polito.it

Giovanni Belingardi
Department of Mechanical and Aerospace Engineering (DIMEAS)
Politecnico di Torino
Torino, Italy
giovanni.belingardi@polito.it

Abstract— **Techniques exploiting the communication between vehicles, infrastructure or anything capable of, are being developed in the recent years due to their effectiveness in improving energy efficiency, comfort and safety. The scenario analyzed in this paper is of four vehicles platooning, in which the leader (i.e. the first in the platoon) is set to travel through different drive cycles and is followed by three other vehicles. An optimization-based algorithm based on Dynamic Programming (DP) is implemented to find the benchmark optimal control solution for the speed trajectory of the three following Battery Electric Vehicles (BEVs). Optimal control targets for planning the three automated vehicle velocity profiles involve both reducing aggressive changes in velocity, thus enhancing passenger comfort, and decreasing energy consumption. Results show a potential range of 1.8 – 7.6 % energy reduction when comparing the energy consumptions of the lead and first follower vehicle, whereas the implemented optimization-based velocity planner predicts enhanced energy economy for the second and third follower BEVs. In general, the highest advantages both in energy consumption and comfort are predicted in the urban scenarios due to the high number of acceleration/deceleration phases.**

Keywords—Battery electric vehicle, platoon, optimal control strategy, energy consumption reduction, comfort improvement

I. Introduction

Nowadays connected and autonomous vehicles are widely discussed to achieve improvements in traffic flow management, safety, and comfort. These vehicles exploit different types of communication networks such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) or vehicle-to-everything (V2X) as example. In a V2V context, one-way or two-way communication might be implemented depending on the reference signal considered. On the other hand, accessing information related to the Signal Phase and Timing is enabled in V2I contexts. This allows changing the driving path near intersections and reducing propelling energy consumption. Finally, the V2X technology can be associated with the exchange of signals and information between vehicles and smartphones by exploiting LTI or 5G networks. Among these types of communication, V2V represents a trade-off technology between efficiency and ease of implementation when compared with V2I or V2X [1]. Exchanged data through the dedicated V2V short-range communication standard typically include speed, acceleration and position of the vehicles. The direction in which information is exchanged between vehicles in a platoon is called information flow topology (IFT). Different information flow topologies are possible [2-4], such as predecessor-following [5], bidirectional [6, 7], predecessor-leader following [8], two predecessor-following, two predecessor-leader following [9]. In these scenarios, cooperative adaptive cruise control (CACC) approaches applied to two vehicles or a platoon of vehicles are some of the most studied examples in literature. The platoon consists of a set of vehicles travelling in sequence in the same lane. A peculiar feature of the platoon is the reduced headway distance between the vehicles. The maintenance of a desired safety distance between the vehicles ensures platoon stability, while underestimating this aspect might cause the vehicles to collide [10]. Several research works focus on this aspect by assessing the percentage incidence of accidents. For example, based on analyses related to different distributions of inter-vehicular distances, Tian *et al.* [11] proposed a stochastic model for assessing the probability of collisions in the vehicle string for different levels of penetration of connected and autonomous vehicles. The maintenance of string stability indeed allows improving energy consumption as well as passenger comfort while enhancing road capacity [12]. The impact on energy saving is attributable both to the reduction of the drag coefficient (especially in driving scenarios with high speeds) and to the smoothing of the driving profiles [13]. Several authors have demonstrated the effectiveness of platooning when applied to trucks in motorway scenarios [14, 15]. This results in significant improvements in terms of fuel economy, comfort, and traffic congestion [13]. Based on the work presented by Anselma and Belingardi [16], this article focuses on the evaluation of energy saving capabilities of a platoon of four battery electric vehicles (BEVs). This can be achieved by optimizing off-line the velocity trajectory of the vehicles in the platoon using dynamic programming. The considered communication topology is of the predecessor-following

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type, i.e. each vehicle receives information from the preceding vehicle only. The obtained results show that it is possible to improve both energy consumption and passenger comfort for all the vehicles considered in several drive cycles. The article is composed as follows: in the first section, the BEV numerical model is presented. The next section defines the optimization problem for a platoon of four BEVs in a V2V scenario to evaluate energy performance and comfort. Finally, results are discussed and conclusions are drawn.

II. Methodology

In this section, the equations implemented to model the BEVs will be shown at first along with the main characteristics of the vehicle. Then, the adopted control strategy will be explained.

A. Vehicle Modelling

This work considers a platoon of four BEVs and investigates the possible benefits in terms of comfort and energy reduction thanks to V2V communication. All the four vehicles in the platoon are assumed identical. Related mass and road resistance data are extracted from the U.S. Environmental Protection Agency database considering a passenger car [17, 18]. The battery and electric machine (EM) are modelled as efficiency tables derived using Siemens Amesim® software [19, 20]. A direct drive transmission is considered being embedded in each BEV. For the sake of clarity, Table I summarizes principal vehicle data such as: the curb weight m; the wheel radius r_{wheel}; the three road load coefficients A, B and C [21], the final drive ratio τ_{fin}; the battery pack energy E_{batt} and the peak power of the electric machine $EM_{max,pow}$.

TABLE I. VEHICLE, EM AND BATTERY MAIN DATA

Parameter	Value	Parameter	Value
m	1248 kg	C	0.44 N/(m/s)^2
r_{wheel}	0.27 m	τ_{fin}	7.82
A	143 N	E_{batt}	42 kWh
B	0.90 N/(m/s)	$EM_{max,pow}$	83 kW

To model the vehicle behavior, a quasi – static approach [22, 23] is used. This method is widely used in the literature to compute the energy consumption of a vehicle, especially at early development stages when the computational effort must be reduced. Although higher–order dynamics are not used, the accuracy of this approach can be considered adequate for this kind of assessments. As far as this study is concerned, the implemented equations exploit the knowledge of the drive cycle (i.e. time series of vehicle acceleration and velocity) to compute the battery power request and the variation in battery State of Charge (SOC). At each time instant t, the EM torque T_{EM} requested to overcome the resistive road load and to provide the required acceleration is calculated as follows:

$$T_{EM}(t) = \frac{T_{OUT}(t)\ /\tau_{fin}}{\eta_{transm}^{sign(T_{OUT}(t))}} \tag{1}$$

$$T_{OUT}(t) = (T_{RL}(t) + T_{slope}(t) + m \cdot a(t)) \tag{2}$$

$$T_{RL}(t) = (A + B \cdot v(t) + C \cdot v(t)^2) \cdot r_{wheel} \tag{3}$$

$$T_{slope}(t) = [m\ \cdot g \cdot \sin(\alpha(t))] \cdot r_{wheel} \tag{4}$$

In which T_{OUT}, T_{RL} and T_{slope} are, respectively, the outlet transmission torque, the road load torque and the torque contribution required to overcome the road inclination. η_{transm} is the transmission efficiency (i.e. 95% in this study); m, a and v are curb weight, acceleration and velocity of the vehicle, respectively; g and α are the gravity acceleration and the road slope. The knowledge of the EM torque can then be exploited to compute the battery power request P_{batt} as in eq. (5):

$$P_{batt}(t) = (T_{EM}(t) \cdot \omega_{EM}(t)) + L_{EM}(t) + P_{aux} \tag{5}$$

where ω_{EM} is the EM rotational speed. L_{EM} is the EM power loss in watts which depends on both the torque and the angular speed of the electric machine. P_{aux} is the power requested to run the auxiliaries (e.g. lighting, lubrication) and its value is set to 500 watts. Finally, the open-circuit voltage V_{batt} and the internal resistance R_{batt} can be calculated by interpolating in one-dimensional look-up tables with battery SOC as independent variable. Then, V_{batt} and R_{batt} are exploited to compute the current flow in the battery I_{batt} and the instantaneous change in SOC as follows:

in which Q_{batt} is the battery maximum capacity in ampere-

$$I_{batt}(t) = \frac{\left(V_{batt}(t) - \sqrt{V_{batt}^2(t) - 4R_{batt}(t)P_{batt}(t)}\right)}{2R_{batt}(t)} \tag{6}$$

$$SOC(t + \Delta t) = SOC(t) - \frac{I_{batt}(t)}{Q_{batt}}\Delta t \tag{7}$$

seconds; Δt is the simulation time-step. The whole introduced procedure is iterated at each simulation timestep until the drive cycle is completed.

B. Driving Scenario

To offer an exhaustive overview of the driving scenario considered for this study, Fig. 1 illustrates the vehicles platoon. This entails a single–lane road in which the four BEVs travel in the same direction. The first vehicle in the platoon is referred to as lead, whereas the others (represented in blue) are the followers. The vehicles can communicate between each other via V2V so as to exchange information regarding their own velocity and acceleration. Then, the relative distance between each predecessor–follower, here referred as inter-vehicular distance or IVD, can be computed by exploiting the exchanged information. For the sake of simplicity, communication delay or missing packages have not been retained in this work, i.e. the V2V communication is supposed ideal. Moreover, no changes in vehicle drag resistance based on the IVD with the preceding vehicle are considered since this is beyond the scope of this research.

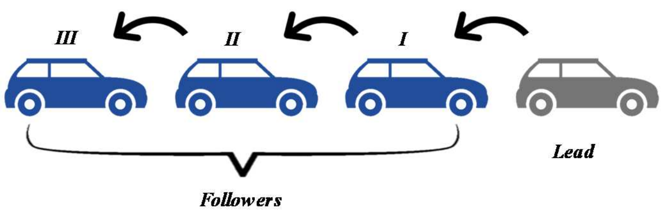


Fig. 1. Platooning scenario showing the lead vehicle along with the three followers. The arrows represent the flow and direction of communications (V2V)

C. Control Strategy

As aforementioned, the objective of this research is to assess the ideal energy consumption reduction and passenger comfort improvement in a platoon of four vehicles. To this aim, each of the controlled automated BEVs (i.e., Follower I, Follower II and Follower III) regulates its longitudinal acceleration upon the driving style of the preceding vehicle. Indeed, each BEV can measure the IVD with the preceding vehicle. This information can be exploited to derive an energy-efficient acceleration of the following vehicle. When determining the longitudinal acceleration, the IVD between the following and the preceding vehicles is constrained to remain in a predefined window. The controller hereby developed is a dynamic programming (DP) based algorithm which outputs the optimal acceleration for reaching a customized goal [24]. More in detail, the optimizer runs backwardly the drive mission and at each time instant it calculates an user-defined cost function for each discretized control value at each discretized state value. Then, the optimal control trajectory is found as the one that minimizes the cost function throughout the entire drive cycle.

It is therefore worth clarifying the control and the state variables along with the cost function implemented in the DP algorithm as in equations (8-9). Here, X is the state vector composed of the velocity of the i-th BEV and the distance between the i-th and (i+1)–th vehicles; U is the control variable and it is namely the acceleration of the i-th BEV (the one which is currently controlled); J_{cost} is instead the cost function. Particular attention has to be put on this term, since the optimization is strictly related to the formulation of the cost function. As it is illustrated in eq. (9), this parameter is composed of two terms, i.e. the battery energy request and the multiplication between a constant weight μ_{jerk}, (whose value has been extrapolated from [25]) and the module of the i-th vehicle acceleration. Owing to this second term in the cost function, the control strategy does not only minimize the i-th BEV energy consumption, but it also improves passenger comfort by minimizing its vehicle velocity change rate.

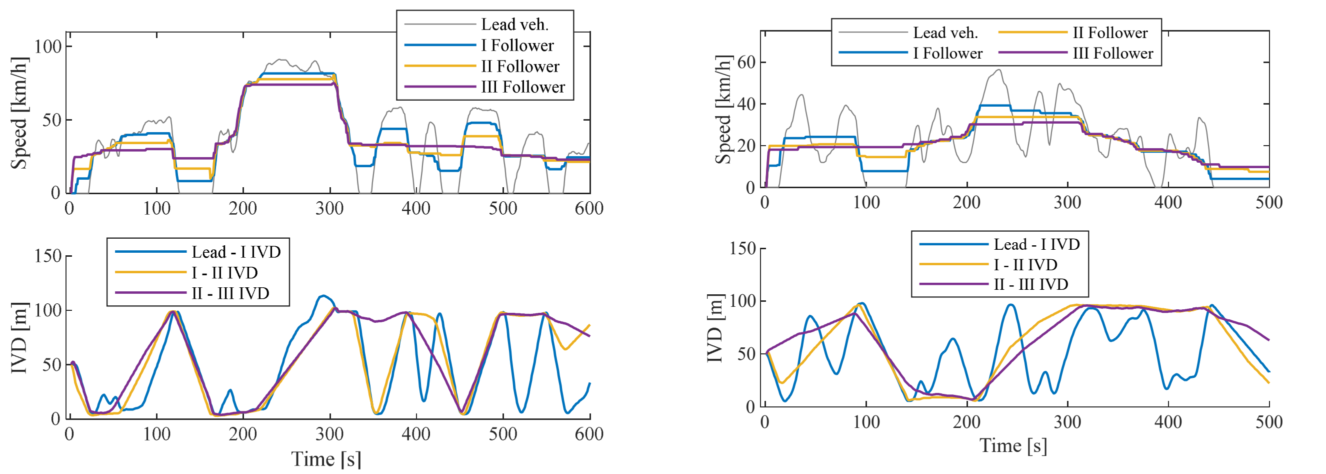
$$X = \begin{Bmatrix} v_i \\ IVD \end{Bmatrix}, \quad U = \{ a_i \} , \tag{8}$$

$$J_{cost,i} = \int_{t_o}^{t_f} [(1 - \mu_{jerk})\, E_{batt_i}(t, v_i, a_i) + \mu_{jerk} \cdot |a_i|]\, dt \tag{9}$$

Moreover, constraints have been set regarding the maximum and the minimum value of IVD. The former has been chosen after considering road occupancy and limitations on V2V communication. Its precise value is either 100 m if driving in a urban environment, or 300 m when travelling through an extra-urban/highway scenario. Regarding the minimum value instead, it stems from consideration on safety distance to be ensured and it depends on relative velocity between preceding vehicle and following vehicle and on the following vehicle speed [26].

III. Results

In the this section, the preliminary results obtained from the proposed longitudinal velocity controller for the BEVs platooning are shown. Energy saving capabilities and potential for comfort improvements yielded by the proposed approach will be discussed. Here, passenger comfort is evaluated by assessing the root mean square (rms) value of the vehicle longitudinal acceleration throughout the whole drive cycle. Fig. 2 illustrates the results of the implemented control strategy in terms of speed profile (top diagrams) and inter-vehicular distance (bottom diagrams) over time in urban and extra-urban drive cycles, namely (a) Urban Dynamometer Driving Schedule (UDDS) and (b) Worldwide harmonized Light vehicles Test Procedure (WLTP). In Fig. 3, the same type of results are displayed for aggressive and highway driving missions, i.e. according to (a) the Supplemental Federal Test Procedure (US06) and (b) the Highway Fuel Economy Test (HWFET) cycles. According to the results shown in these figures, the proposed control strategy achieved the predefined objectives by maintaining a constant speed as much as possible and by remarkably smoothing the velocity profile compared with the preceding vehicle. Indeed, no evident ramps of acceleration and deceleration are found when examining the trends shown in Fig. 2 and in Fig. 3.



(a) UDDS

(b) WLTP

Fig. 2. Velocity profile and inter-vehicular distance IVD of the BEVs platooning in a partial time window while riding according to the urban/extra-urban drive cycles: (a) UDDS and (b) WLTP

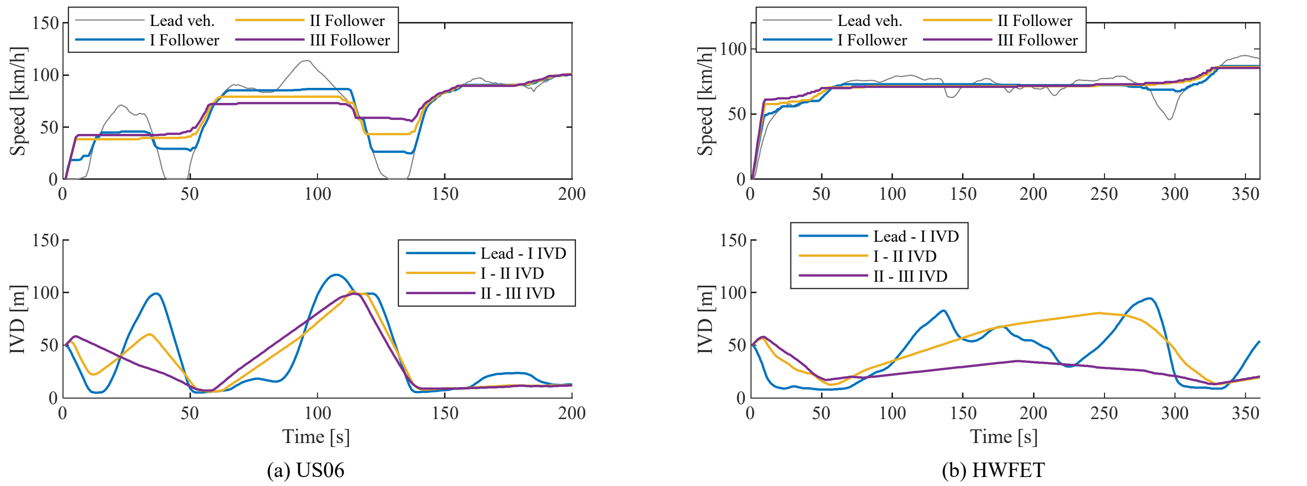


Fig. 3. Velocity profile and inter-vehicular distance IVD of the BEVs platooning in a partial time window while riding according to the aggressive and highway drive cycles: (a) US06 and (b) HWFET

Focusing on the speed profiles of the follower vehicles (i.e. the vehicle controlled by the DP-based algorithm), the constant speed phases are shifted towards lower values while accelerating and vice versa while braking. Table II reports obtained results in terms of energy consumption and rms of the longitudinal acceleration (that has been assumed representative of the passenger's comfort) for all the vehicles in the platoon and all the considered drive cycles. For both the considered evaluation metrics, the percentage of improvement compared with the preceding vehicle is included as well in Table II. In general, higher improvements can be reached in urban driving scenarios, as it can be seen from the relative percentages expressed in Table II regarding the UDDS and WLTP. This behavior stems from the substantial reduction in acceleration/deceleration ramps that are frequent in these cycles. Furthermore, enhanced results can be achieved for the Follower I compared with Follower II and Follower III both in terms of energy saving and passenger comfort improvement. This can be explained by the fact that, when moving progressively towards the vehicles in the back of the platoon, the longitudinal speed is already significantly smoothed with respect to the preceding vehicle one and further enhancements are therefore limited. Regarding the inter-vehicular distance profiles, it can be seen how the Follower I noticeably exploits the whole range of possible gaps by frequently shifting from the safety distance to the maximum allowed. On the contrary, the IVD of the Follower II and the Follower III vehicles is more relaxed since the longitudinal speed of the corresponding preceding vehicles has already been smoothed. A graphical comparison between Leader and Follower vehicles in terms of energy consumption and passenger comfort is illustrated in Fig. 4a and in Fig. 4b, respectively. Related numerical values are reported in Table II along with the percentage of improvement compared with the corresponding preceding vehicle. This comparison further highlights how remarkable improvements can be achieved by the Follower I compared with the Lead vehicle thanks to V2V communication. On the other hand, less improvement can be achieved by Follower II and Follower III compared with Follower I. This is visible when referring both to the ideal energy consumption and to the rms of the acceleration. A possible explanation relates to the velocity of the Follower I BEV being already optimized by the DP-based controller, thus reducing the margin for improvement of Follower II and Follower III. This trend is particularly detectable in the highway scenario since the energy saving improvement of Follower II falls below 1% and the corresponding passenger comfort becomes even worse comparing the Lead vehicle and the Follower I in the platoon. Even though it might be considered as an unexpected results, this can be attributed to the speed profile of the HWFET cycle being already smoothed.

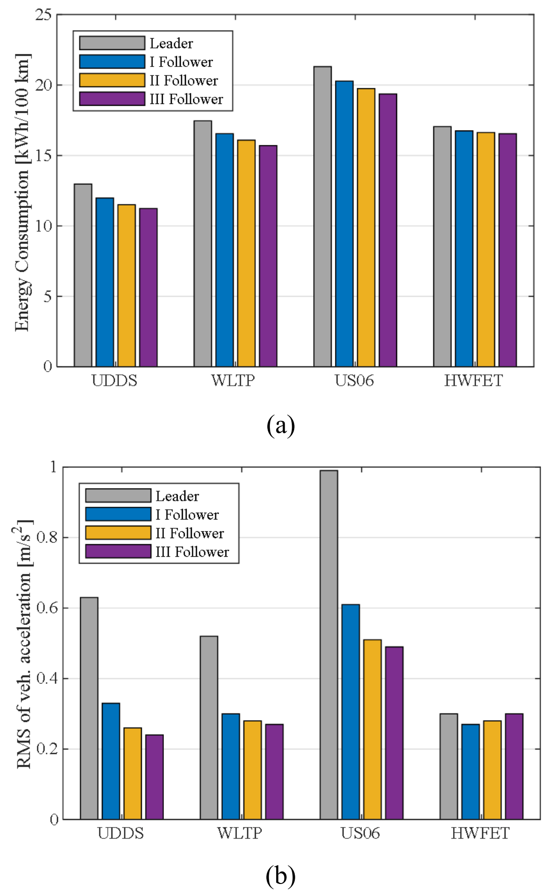


Fig. 4. Energy consumption and rms of the longitudinal acceleration of the four BEVs in the platoon as predicted by the implemented DP-based longitudinal velocity control algorithm in UDDS, WLTP, US06 and HWFET

TABLE II. SUMMARY OF THE RESULTS OBTAINED IN THE DIVERSE DRIVE MISSIONS

Drive Mission	E_{lead} ***[kWh/100km]***	$E_{foll,I}$ ***[kWh/100km]***	$E_{foll,II}$ ***[kWh/100km]***	$E_{foll,III}$ ***[kWh/100km]***	$rms(\ddot{x})_{lead}$ ***[m/s²]***	$rms(\ddot{x})_{foll,I}$ ***[m/s²]***	$rms(\ddot{x})_{foll,II}$ ***[m/s²]***	$rms(\ddot{x})_{foll,III}$ ***[m/s²]***
UDDS	12.97	11.98 (7.6%)	11.51 (3.9%)	11.24 (2.3%)	0.63	0.33 (48.2%)	0.26 (20.9%)	0.24 (8.3%)
WLTP	17.46	16.55 (5.2%)	16.09 (2.8%)	15.70 (2.4%)	0.52	0.30 (41.6%)	0.28 (8.7%)	0.27 (3.0%)
US06	21.31	20.28 (4.8%)	19.75 (2.6%)	19.36 (2.0%)	0.99	0.61 (38.4%)	0.51 (17.0%)	0.49 (4.3%)
HWFET	17.05	16.75 (1.8%)	16.63 (0.7%)	16.54 (0.6%)	0.30	0.27 (10.0%)	0.28 (-3.7%)	0.30 (-7.1%)

IV. CONCLUSIONS

This paper proposes a DP-based control algorithm that is applied to the platooning of four Battery Electric Vehicles. The inter-vehicular communication is exploited to optimally control the longitudinal vehicle acceleration of the following vehicles in the platoon. Reducing energy consumption while enhancing passenger comfort are the main objectives of the implemented algorithm. The aforementioned controller is inherited from a previous study of the authors [16], nonetheless the scenario hereby proposed has been extended to a platoon of four vehicles in different driving missions.

Results show that significant improvements can be achieved both in terms of energy consumption and in terms of passenger's comfort, for the first following vehicle, whose longitudinal dynamics is controlled by the proposed strategy. On the other hand, limited further relative improvements can be attained by the subsequent vehicles in the platoon stemming from the adoption of the controller. Indeed, the relative variations endure a minor change when considering the energy savings between Follower II and Follower III. Results in a urban scenario show a relevant improved behavior, both in energy saving and comfort, and the controller is capable of achieving interesting improvements even considering the last vehicle in the platoon. Hence, the implemented control strategy can effectively be applied to driving scenarios where frequent accelerations and decelerations are found such as in urban areas.

Although the DP can achieve the global optimal solution, it cannot be used in real -time controllers. Thus, future works should investigate diverse strategies whose computational efforts are lower, e.g. Equivalent Consumption Minimization Strategy (ECMS) [27], Model Predictive Control (MPC) [28] and others.

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