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Optimal Real-Time Velocity Planner of a Battery Electric Vehicle in V2V Driving

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Abstract- **Autonomous driving systems are among the most interesting technologies in the transportation field nowadays, ensuring a high level of safety and comfort while also enhancing energy saving. For the following case study, a Battery Electric Vehicle (BEV) is considered able to communicate with other vehicles through vehicle-to-vehicle (V2V) technology by exchanging information on position and velocity. In this framework, an innovative real-time velocity planner has been developed aiming at maximizing the battery energy savings while improving the passenger comfort as well. This controller uses the principles of the equivalent consumption minimization strategy (ECMS) when the preceding vehicle is accelerating. Simulation results demonstrate improvements in comfort ranging from 26% to 42% ca. and in energy consumption (from 0.4% to 1.3%) when performing different drive cycles in V2V automated driving mode thanks to the proposed controller.**

I. INTRODUCTION

Advanced driver assistance systems (ADASs) appear to be well-established features in the automotive sector and new technologies are developed thanks to the several opportunities offered by these systems . In general, their diffusion is mainly due to the crucial need of increasing fuel economy, safety and comfort which can be achieved by ADASs. As an example of these technologies, cruise control fall into this category ranging from the basic definition to the adaptive one which allows the maintenance of a certain vehicle speed capable of satisfying the inter-vehicle distance constraints. This technology is highly affected by recent developments on self-driving vehicles such as direct vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication, as well as simpler information coming from GPS, such as route and traffic information [1][2][3].

The social impact of ADASs has been taken into consideration in several research works from literature. Indeed, their potential to reduce road accidents and widen the pool of road private transportation users (e.g. elder people, disabled people) is investigated and proved [4][5]. Regarding the improvement in terms of fuel economy and/or energy consumption, this is mainly achievable by the correct integration and exploitation of V2X information in the control policies implemented in the energy management system, the velocity planner and the trajectory planner.

Among the presented systems, the V2V scenario considers an automated vehicle traveling behind either a human-driven vehicle or an automated one and receiving from it information in terms of speed and acceleration. The vehicle behind (generally referred as ego vehicle) has been shown to potentially achieve significant benefits in terms of energy saving and comfort improvement by adjusting its driving pattern exploiting the information received.

The V2V connection might be used to provide immediate feedback to vehicles nearby, thus enhancing safety, or it may be used to develop an optimization strategy capable of processing a time window of information from the preceding vehicle (lead vehicle) as highlighted in the work by He et al. [6]. The fuel savings achievable through a vehicle control optimization strategy are significant, even though their values fall into a wide range when considering diverse vehicle topologies and driving scenarios [7].

Regarding existing studies where the V2X is used to improve the energy consumption, a lot of work can be found in the intersection approaches. In this field, diverse methods exploit the knowledge of the Signal Phase and Timing (SPaT) of the red lights due to V2I. The velocity profile is modified accordingly when approaching the intersection as in [8], where an energy consumption reduction was studied in this scenario and proved. Besides, [9] proposes that different powertrains may lead to diverse optimal ways of coming near an intersection. High-fidelity numerical models were embedded in this research activity as in [10], where an area in Chicago was analyzed due to its high number of red lights intersections. In [11], the pre-intersection speed profile of a bus is optimized using the V2I information for reducing the battery degradation costs and the one stemming from the energy consumption.

When it comes to V2V driving technologies, it has been shown how the Adaptive Cruise Control and its modifications (i.e., eco/cooperative or a mixed version) may lead to a higher energy efficient trip. Lopes and Evangelou [12] have studied a Nonlinear Model Predictive Control (NMPC) capable of enhancing the energy consumption mostly in urban and high-speed environments, also providing information on the influence of prediction horizon and trajectory preview for this type of control. Other rule-based strategies are found in literature: Glaser et Al [13, 14] have proposed a Smart And Green Autonomous (SAGA) control strategy suitable for electrified vehicles which provides the same safety of an ACC yet considering energy consumption reduction. Moreover, Lu et Al. [15] provided an Energy Efficient ACC in which multiple scenarios were taken into consideration retaining different levels of electric vehicle penetration in the market. The outcomes have shown how the highest benefits in energy reduction are obtained for a 20% penetration of this kind of cars. Indeed, when this percentage increases, the regenerative braking possibility decreases and the string stabilization is faster.

Concerning the present study, it builds on a previous work in which V2V technology was being investigated for optimal powertrain design and component sizing [16]. The optimization procedure for planning the Ego vehicle velocity was carried out off-line and based on an optimization algorithm, namely the Dynamic Programming (DP) [17]. The objective of the implemented DP was to minimize the overall battery energy usage and to improve comfort. Although a significant reduction in energy consumption was demonstrated, this controller cannot be applied to real-time procedure due to its computational cost and the requirement of the a priori knowledge of the drive cycle. Therefore, the study abovementioned is used as a starting point for the present research work which provides an innovative real-time controller capable of enhancing battery energy consumption while improving the comfort of the ride. Its design has been carried out by imitating the decisions taken by the off-line algorithm provided by Anselma and Belingardi [16], nonetheless opting for a computationally faster and real-time capable strategy such as the equivalent consumption minimization strategy (ECMS). The proposed ECMS based controller has been validated by benchmarking with global optimal results provided by DP and with results for the Lead vehicle in human operated driving.

The remaining part of the article is structured as follows: at first the main characteristics to model the vehicle are enlisted. Then, the retained automated driving scenario is presented followed by a deeper explanation of the control strategy. Finally, obtained results are discussed and conclusions are drawn together with ideas on future possible development.

II. METHODOLOGY

In this section, the retained vehicle is firstly introduced together with the modelling equations. Then in the second part, the V2V automated driving scenario is discussed in order to give an overview of the conditions in which this study has been developed. Finally, the implemented novel control strategy is presented along with the explanation of how the principles of ECMS have been adopted for this case study.

A. Vehicle Model

For the purpose of this study, the characteristics data of Fiat 500e Battery Electric Vehicle (BEV) are used for simulations and are enlisted in Table 1 [18][19] for sake of clarity. More precisely the road load coefficients RLs, the wheel radius, the final drive ratio and the curb weight are found from the US Environmental Protection Agency (EPA) database [18][19]. For what concerns the electric machine and the battery equipped, they have been modelled as efficiency tables derived in the software Siemens Amesim® using the main characteristics of the real elements [20][21], found also in Table 1. Furthermore, a quasi-static approach has been used in this study for representing the behavior of the vehicle, whose equations exploit the instantaneous knowledge of acceleration and velocity to compute the power request to the battery at every timestep while neglecting higher-order dynamics. Having this model a single-speed transmission, the torque requested at the electric machine T_{EM} in order to overcome the resistive load of the road and accelerate the vehicle is:

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

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

$$T_{RL} = (RL_A + RL_B \cdot v + RL_c \cdot v^2) \cdot r_{wheel} \quad (3)$$

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

In which T_{OUT} is the torque requested at the outlet of the transmission, τ_{fin} and η_{transm} are the final drive ratio of the vehicle and the transmission efficiency. T_{RL} and T_{slope} are the road load torque and the one due to the road slope; m and a are mass and acceleration of the vehicle, respectively. RL_A, RL_B and RL_C are the three road load coefficients which model the road resistance; v is the velocity of the vehicle; r_{wheel}, g and α are instead the wheel radius, the gravity acceleration and the inclination of the road. Once the torque requested to the electric machine is found, it is possible to compute the battery power request by including the EM losses L_{EM} and the electric power required by the auxiliaries P_{aux}, as follows:

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

Lastly, in order to represent the behavior of a battery the Rint model has been chosen, retaining the following equation to calculate the current flow through the battery and the instantaneous change in State of Charge (SOC):

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

$$S\dot{O}C = \frac{I_{batt}}{Q_{batt} \cdot \Delta t} \quad (7)$$

Where I_{batt} is the current flowing in the battery; V_{batt} and R_{batt} are the open circuit voltage and the internal resistance of the battery; Q_{batt} and Δt are the battery maximum capacity in ampere-seconds and the timestep.

TABLE I
VEHICLE, BATTERY AND EM CHARACTERISTICS

Parameter	Value	Parameter	Value
Curb weight	1474 kg	RL_C	0.40 N/(m/s)^2
r_{wheel}	0.28 m	τ_{fin}	9.59
RL_A	110.8 N	Battery Pack Energy	42 kWh
RL_B	2.35 N/(m/s)	EM Peak Power	83 kW

A. *Driving Scenario*

Regarding the driving scenario considered in this research, it involves a single-lane road in which two vehicles are travelling in the same direction, as depicted in Fig. 1. In general, the vehicle in front is here referred to as lead vehicle whereas the succeding one is called ego vehicle. In this scenario, the two are able to communicate to each other via V2V technologies installed on-board, in which for sake of simplicity no delay in data exchange is considered. More precisely, the ego automated vehicle has the knowledge on the lead vehicle instantaneous values of acceleration and velocity together with the inter-vehicle distance (IVD). Therefore, these data are exploited by the ego vehicle to avoid irregular changes in acceleration, hence smoothing the overall speed profile and resulting in a more efficient energy consumption and an enhancement in passenger comfort.

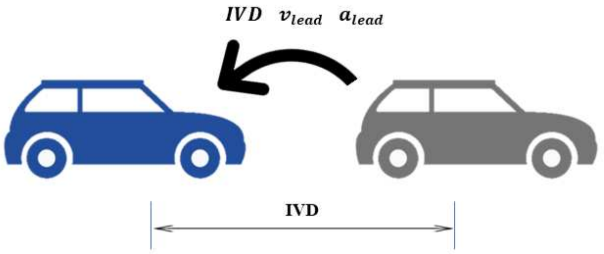


Fig. 1. Flow of information between the lead vehicle (grey) and the ego vehicle (blue), represented with their inter-vehicular distance IVD.

A. *Control Strategy*

Hereafter, the control strategy designed to drive the ego vehicle exploiting the information exchanged through the V2V system is presented. In general, the controller receives the instantaneous acceleration and velocity of the lead vehicle together with the IVD and sets the ego vehicle acceleration taking into account the power request at the battery and the current IVD. Anselma and Belingardi [16] have already demonstrated that this technology may lead to interesting savings in terms of energy consumption and better comfort-related conditions, yet they implemented a control strategy which cannot be used in real-time applications due to remarkable computational cost associated to the use of DP. Hence, a diverse control strategy is developed using the operating principle of the Equivalent Consumption Minimization Strategy (ECMS) [22], for which an instantaneous cost function J is defined coherently to the problem hereby presented as expressed in eq. (8). Namely, two parts constitute the cost function which are the power demanded to the battery P_{batt} (expressed in kW) and a term related to the instantaneous change in inter-vehicle distance $\dot{IVD}$. The latter is multiplied by a constant equivalence factor s, which is expressed in kW/(m/s) to adjust the dimensionality of the equation and plays a crucial role for assessing the optimal trajectory of the ego vehicle. Indeed, its tuning has been performed offline by means of trial and error in order to satisfy the constraints chosen for this study (that can be found in the next sections) and to enhance comfort and energy consumption.

$$J_{cost}(IVD, v_{lead}, a_{lead}, a_{ego}) = P_{batt}(a_{ego}) + s(IVD) \cdot \dot{IVD}(IVD, v_{lead}, a_{lead}, a_{ego}) \tag{8}$$

In which: v_{lead}, a_{lead} and a_{ego} are the lead vehicle velocity, lead acceleration and ego acceleration. Moreover, this term is computed at each time instant based on the values of speed and acceleration for both the lead vehicle (obtained through V2V communication) and the ego vehicle (according to the current speed and the possible acceleration control values). Therefore, the controller at each timestep computes the J_{cost} of all the possible different trajectories and selects the strategy that would minimize this term.

Furthermore, once all the tests were done using a constant value for the equivalence factor it has been noted as this setting was far from being optimal when compared to the results obtained by the DP in [16]. Therefore, in order to achieve an improved version of the proposed strategy, it has been adopted an adaptive equivalence factor [23] whose value depends on the IVD itself and it has again been tuned for the different drive cycles. Basically, the idea lies upon the fact that when the IVD is high the control strategy should penalize more the increase in the distance by preferring higher accelerations. Viceversa, when the IVD is low, the ego vehicle is approaching the lead one and therefore the strategy should prefer lower acceleration or even deceleration. This control could be achieved by attributing an increasing value to the equivalence factor as the IVD grows. In Fig. 2 the trend of s used for all the driving cycle is found as a function of the distance between vehicles.

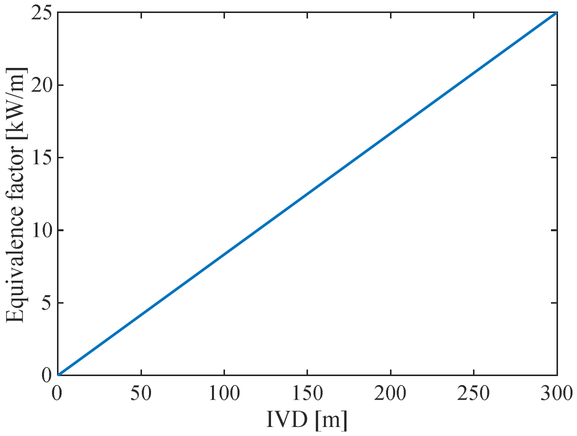
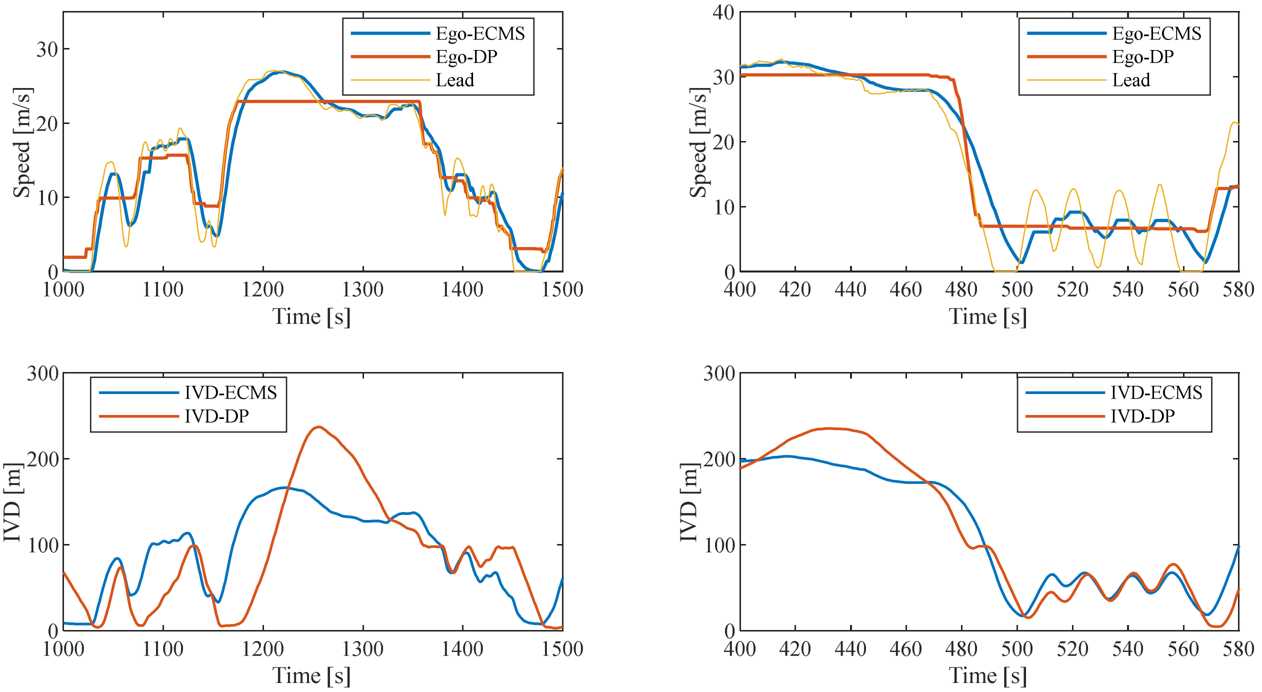


Fig. 2. Trend ot the equivalence factor as a function of the inter-vehicular distance IVD.



(a) (b)

Fig. 3. Comparison of the results obtained using the novel control strategy based on ECMS (blue line) and the ones of the DP (red line), considered as a referece, for two zoomed time windows of (a) WLTP and (b) US06 drive missions. For both the graphs, in the upper part is found the velocity of the vehicles whereas in the lower part is indicated the trend over time of the inter vehicle distance (IVD)

Moreover, after further examining the results obtained in [16] to understand the choices of the DP when dealing with a similar problem, it has been noted as the strategy often opts to diminish the IVD when the lead vehicle is decelerating. Therefore, in order to mimic this behavior, the control strategy has been modified as follows:

- If the lead vehicle is accelerating or coasting, the ECMS is used to determine the optimal trajectory;
- If the lead vehicle is decelerating, an Adaptive Cruise Control (ACC) similar strategy [24] is performed having as objective to reach a predefined IVD while travelling at a similar lead vehicle velocity to replicate the optimal behavior predicted by the DP.

III. RESULTS

In this section, the results obtained by the ECMS based control strategy designed in this study are presented as figures comparing the different behaviors of the two vehicles and a summarized table.

For what concerns the comfort, it is assessed using as main indicator the root mean square (rms) of the acceleration throughout the cycles, comparing the values obtained by the lead and ego vehicles to show potential benefits stemming from the novel control strategy. Moreover, before presenting the results, it is worth describing the constraints used for the IVD that are mainly on a minimum and a maximum distance. The former has been chosen to ensure the safety and it depends on the relative speed of the two vehicles and on the speed of the ego one [25]. The latter stems from considering both road occupancy and limitations in the wireless inter-vehicular communication. The maximum IVD has thus been chosen to be 100 m in urban environment (i.e. when the ego vehicle speed is lower than 50 km/h) and 300 m in extra-urban/highway scenarios.

The results obtained using the designed velocity planner are presented in Fig. 3 for the (a) Worldwide Harmonised Light Vehicles Test Procedure WLTP and (b) the Supplemental Federal Test Procedures US06 cycle, together with the outcomes of the DP which are considered as reference in this research. As it can be noted from the velocity graphs, both the ECMS and the DP control strategies smooth the accelerations and decelerations of the ego vehicle, thus resulting in an enhancement of the passenger comfort and in an energy consumption reduction. Obviously, the a priori knowledge of the drive cycle allows the DP to have longer constant-speed phases, nonetheless the real time strategy presents interesting results as well. Indeed, focusing on the IVD graphs for both cycles, it can be noted as the two curves respectively referred to DP and ECMS have similar trend, hence reflecting the quality of the implemented strategy and its tuning operations. Besides, it is mentionworthy to point out the fact that the equivalence factor has been kept constant in every drive cycle to ease the related calibration process.

TABLE II
CONTROL STRATEGY OUTCOMES IN ENERGY CONSUMPTION AND COMFORT

Drive Mission	E_{lead} *[kWh/100km]*	$E_{ECMS/ACC}$ *[kWh/100km]*	E_{DP} *[kWh/100km]*	ΔE *[%]*	$rms(\ddot{x})_{lead}$ *[m/s^2]*	$rms(\ddot{x})_{ECMS/ACC}$ *[m/s^2]*	$rms(\ddot{x})_{DP}$ *[m/s^2]*	$\Delta\, rms(\ddot{x})$ *[%]*
WLTP	17.46	17.23 (-1.3%)	16.53 (-5.3%)	+4.1	0.52	0.34 (-34.6%)	0.34 (-34.6%)	-0.0
UDDS	12.97	12.80 (-1.3%)	11.94 (-7.9%)	+6.7	0.63	0.43 (-31.2%)	0.45 (-28.6%)	-3.7
HWFET	17.05	16.99 (-0.4%)	16.74 (-1.8%)	+1.5	0.30	0.22 (-26.4%)	0.26 (-12.3%)	-19.1
US06	21.31	21.06 (-1.2%)	20.28 (-4.8%)	+3.7	0.99	0.57 (-41.8%)	0.63 (-36.5%)	-9.7

The whole outcomes for the different driving missions are found in Table 2, in which it is possible to find: the energy consumption of the lead vehicle E_{lead}; the energy consumption of the ego vehicle for both the proposed strategy and the reference one ($E_{ECMS/ACC}$ and E_{DP} respectively) along with the relative difference with respect to the energy consumption of the lead vehicle; the rms of the accelerations for the lead vehicle over all the cycles, referred to as $rms(\ddot{x})_{lead}$; the comfort results for both strategies together with the percentage variation with regards to the lead vehicle; finally, in the 5th and 9th columns are found the comparisons for both performances between the novel velocity – planner hereby proposed and the reference one (i.e., the DP based one). Besides, it is worth mentioning that no aerodynamic drag force reduction has been considered due to platooning of the vehicles (i.e., two or more vehicles travelling closely through the same path), due to the often high IVD that would have resulted in a negligible decrease in consumption for the ego vehicle.

Starting the discussion focusing on the results obtained by the proposed controller, it can be seen that the Highway Fuel Economy Test HWFET resulted in the lowest improvements in energy reduction of about 0.4%. This relates to the HWFET being composed of a low amount of decelerating phases and therefore the control policy struggles to diminish the IVD, thus closely following the velocity of the lead to not exceed the maximum threshold. On the other hand, all the other cycles obtained a reduction in energy consumption of about 1.2 – 1.3 %. Concerning the retained cycles including urban driving (i.e., WLTP and the Urban Dynamometer Driving Schedule UDDS), this improvement is mostly due to the high number of accelerating and decelerating phases, which allows the strategy to further smooth the accelerations in the ego vehicle and to exploit the decelerating zones for recovering the IVD. Regarding to the aggressive cycle US06, the more efficient energy consumption can be attributed to a mix of hills and smooth accelerations , as it can be also noted from Fig 3(b).

Furthermore, looking at the outcomes in terms of comfort, it is seen that the ego vehicle is capable of decreasing substantially the accelerations with respect to the preceding car. The corresponding improvement, denoted by the decrease in the rms of the vehicle acceleration, ranges from 26% to 42% ca. in the four drive cycles considered. Likewise the outcomes in energy consumption, the lowest improvements is here obtained in the HWFET, stemming from the fact that the base cycle does not entail already aggressive changes in velocity.

Moreover, shifting the attention on the comparison between the overall results of the control strategy hereby proposed and the ones of the reference (DP), the latter results in better improvements in energy consumption for all the drive cycles. Nevertheless, these outcomes are expected due to the a priori knowledge of the mission for the DP algorithm, which often brings the ego vehicle to high distances from the lead one when a decelerating zone is closeby (i.e., the IVD can be recovered by slowing down at a lower rate than the preceding vehicle). Even though, when it comes to comfort it can be noted that the proposed velocity planner attains better results than the ones of the reference in all the missions considered (or the results are equal as it happens for the WLTP cycle). It is worth mentioning that the objective function of the reference algorithm has the primary aim of reducing the energy consumption and only partly to lead to better comfort. Therefore, the global optimal results have to be considered as such only for a precise objective function and might be outperformed in comfort by a different strategy, as it happens for the proposed one.

IV. CONCLUSIONS AND FUTURE WORKS

This paper proposes a novel velocity planner which, exploiting the information exchanged through V2V communication, may lead to improvements in terms of energy consumption and comfort enhancement. The control strategy implemented is based upon the principles of the ECMS and the ones of the Adaptive Cruise Control, and aims at mimic the behavior of a DP controller already developed yet making it possible to be used in real time operations. The quality of this velocity planner has been tested in four different conventional drive cycles, resulting in a reduction in energy consumption with respect to the lead vehicle of about 0.4%-1.3% and a passenger comfort improvement of about 26% to 42% (here assessed using the rms of the acceleration throughout the entire cycle). Moreover, improved performance has been suggested for the proposed control strategy in urban driving where the number of stops is high, or more in general where long deceleration events are found.

Regarding possible future works, it could be interesting searching for a different trend of the equivalence factor depending on the IVD, which was here considered as linear. For this purpose, an Evolutionary Algorithm (EA) might be implemented in the offline tuning operation. Moreover, it could be worth developing a machine learning algorithm which might train on the DP results to see how it performs and if it is suitable of being implemented in real time.

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