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Computation of eco-driving cycles for Hybrid Electric Vehicles: Comparative analysis

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A R T I C L E I N F O

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A B S T R A C T

In this paper, the calculation of eco-driving cycles for a Hybrid Electric Vehicle (HEV), using Dynamic Programming (DP), is investigated from the complexity-solving method viewpoint. The study is based on a comparative analysis of four optimal control problems formulated using distinct levels of modeling. Starting with three state dynamics (vehicle position and speed, battery state-of-charge) and three control variables (engine and electric machine torque, gear-box ratio), the number of state variables is reduced to two in a first simplification. The other two simplifications are based on decoupling the optimization of the control variables into two steps: an eco-driving cycle is calculated assuming that the vehicle is propelled only by the engine. Then, knowing that the vehicle follows the eco-driving cycle calculated in the first step, an off-line energy management strategy (torque split) for an HEV is calculated to split the requested power at the wheels between the electric source and the engine. As is shown, the decreased complexity and the decoupling optimization lead to a sub-optimality in fuel economy while the computation time is noticeably reduced. Quantitative results are provided to assess these observations.

1. Introduction

Spurred by environmental requirements, economic factors and energy-saving interests, eco-driving has attracted much attention from the scientific community in the last decade. It is now considered as a major solution to reduce the energy consumption linked to transportation. It can be seen as a multi-criteria optimization (fuel consumption, duration, drivability, etc.) of various tasks (navigation, guidance, stabilization) under safety constraints. In other words, the idea of eco-driving is to calculate the vehicle velocity trajectory that minimizes the vehicle energy consumption under constraints: speed limitations, final time and total traveled distance. This question can be solved using optimal control tools.

For conventional vehicles, fuel consumption, engine emissions or any combination of both over a fixed time window is the cost function to be minimized (Mensing, Bideaux, Trigui, Ribet, & Jeanneret, 2014; Mensing, Trigui, & Bideaux, 2011). For full electric cars, the cost function to be minimized is the electric power requested by the electric machine (Dib, Chasse, Moulin, Sciarretta, & Corde, 2014; Mensing, 2013; Miyatake, Kuriyama, & Takeda, 2011; Petit & Sciarretta, 2011; Sciarretta, Nunzio, & Ojeda, 2015). The duration of the trip can be considered as an additional degree of freedom in the optimization. A trade-off between the fuel consumption and the duration can be found. Two dynamics are usually considered: the position and the speed of the vehicle. For these two architectures (conventional and electric), two control variables are used: the engine or the electric machine torque and the gear-box ratio while the main constraints bear on speed limitations, vehicle stops and total traveled distance (Mensing, 2013; Sciarretta et al., 2015).

However, having an additional energy source increases the complexity of the models and thus the algorithms used to calculate eco-driving cycles as mentioned in van Keulen, de Jager, Foster, and Steinbuch (2010). In the case of hybrid electric vehicles, additional state and control variables have to be considered in the optimization: the battery State Of Charge (SOC) with a constraint on its final value and the electric machine torque.

The work in Kim, Manzie, and Sharma (2009) presents a strategy that optimizes both the speed profile and the torque split between the electric machine and the engine using a Gradient method. More recently, the

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algorithms in Mensing (2013) and Ngo, Hofman, Steinbuch, and Serrarens (2010) combine dynamic programming with the Energy Management System (EMS) design for a Hybrid Electric Vehicle (HEV) to calculate eco-driving cycles. A bi-level approach that reduces computation time was suggested in Ngo et al. (2010). The optimal control strategy is calculated by decoupling the optimization of the control variables. In a first step (an outer loop) the speed trajectory is optimized assuming that the vehicle is propelled only by the internal combustion engine or the electric machine. In a second step, the power split between the engine and the electric machine is optimized in an inner loop for a given vehicle speed, gear-box ratio and wheel torque. The missing point is the quantification of the sub-optimality induced by the method used. A similar approach was used in Sciarretta et al. (2015) where an overview of eco-driving problems for various architectures (electric, conventional and hybrid electric cars) was given. Analytical solutions were suggested in the case where the gear-box ratios are not optimized.

Later, in Heppeler, Sonntag, and Sawodny (2014), the authors worked on the direct optimization of the EMS for an HEV with a small deviation from the given desired vehicle velocity as an additional degree of freedom. It was shown that the additional degree of freedom for the velocity decreases fuel consumption by about 6.8% compared to a real-time power split strategy and by about 4.3% compared to an off-line power split algorithm with a *fixed* velocity trajectory. The work in Bouvier, Colin, & Chamaillard (2015) compared two approaches to calculate eco-driving cycles for a parallel HEV in terms of fuel saving. The study concluded that in order to generate the best speed trajectory in terms of fuel consumption, it is necessary to consider that the vehicle is an HEV: this consideration saves up to 3%. However, the comparison of the computation time of the two methods was not investigated.

This paper follows the path described above and pursues the analysis further. A parallel HEV equipped with a Diesel engine is considered. This choice is not restrictive, as the methodology presented here could be easily transposed to other cases of interest. The objective is to calculate, within a reasonable time, an eco-driving cycle for an HEV under final time, distance and SOC constraints while fulfilling the speed limits. We wish to find a trade-off between the accuracy of the DP solution and the complexity of the algorithms used to obtain this solution (an accuracy/complexity balance). For this purpose, four methods to calculate eco-driving cycles are considered:

- The first method is based on solving directly the optimal control problem associated to eco-driving for HEVs.
- The second method is based on reducing the number of state variables by introducing a tuning parameter to satisfy the SOC final constraint.
- The third method is based on decoupling the optimization of the control variables into two steps. In a first step, an eco-driving cycle is calculated assuming that the vehicle is propelled only by the engine. In the second step, to follow the calculated eco-driving cycle, an off-line energy management strategy is designed to optimize the torque split and the gear-box ratios.
- The last method is similar to the previous one except that only the torque split is optimized in the second step.

These methods are compared in terms of fuel consumption, state trajectories, computation time of the DP and memory (RAM) use. Based on the numerical results, a conclusion about the chosen trade-off between accuracy/complexity is drawn.

The paper is organized as follows. In Section 2, the vehicle model is described. The calculation of eco-driving cycles is detailed in Section 3. Section 4 details the proposed numerical methods to calculate eco-driving cycles for an HEV. Numerical and simulation results are discussed in Section 5. In light of the results, some conclusions on the most convenient method to be used are drawn based on a trade-off between optimality/complexity.

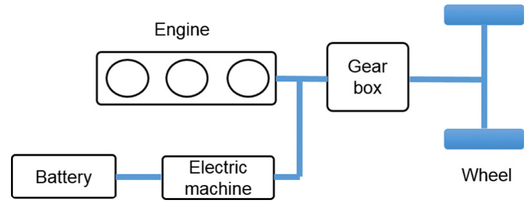

Fig. 1. Parallel mild-hybrid architecture.

2. Vehicle modeling

The system considered here is a dual shaft parallel mild hybrid with an electric machine (*EM*) connected to the engine by a belt (Fig. 1). The gearbox is between the power-train and the wheel. This architecture allows regenerative braking (the electric machine works as a generator during braking phases), hybrid and zero-emission vehicle (ZEV) modes. Due to the architecture choice, during the ZEV mode, the engine injection is cut off and the electric machine produces power, keeping the engine rotating. This system was used in Michel et al. (2015) and Simon, Michel, Nelson-Gruel, and Chamaillard (2015).

2.1. Motion equations

The vehicle is modeled in a vertical plane. According to Newton's law of motion, the vehicle speed v satisfies the following differential equation

$$m \cdot \frac{dv(t)}{dt} = F_t(t) - F_r(t), \tag{1}$$

where F_t is the traction force to be provided by the engine, F_r is the sum of resistance forces and m is the total vehicle mass including the rotating parts. The force F_r comprises the rolling resistance force, the aerodynamic drag force. Its expression is given by

$$F_r(t) = c_0 + c_1 \cdot v(t) + c_2 \cdot v(t)^2, \tag{2}$$

where c_i, $i = \{0, 1, 2\}$ are the constant coefficients of the road load equation. To take the road grade α into account, the coefficient c_0 will not be constant and its expression will be

$$c_0 = c_0^a + m \cdot g \cdot sin(\alpha), \tag{3}$$

where g is the acceleration of gravity, c_0^a is the road load coefficient. This model considers only the forces in the longitudinal direction. In this study, the road grade is null.

2.2. Internal Combustion Engine (ICE)

The ICE under consideration is a Diesel engine. The fuel consumption $\dot{m}_f$ (g/s) is computed through a look-up table as a function of the engine rotational speed (ω_{eng}) and the effective engine torque (T_{eng}) (see Fig. 2)

$$\dot{m}_f = \dot{m}_f(\omega_{eng}, T_{eng}). \tag{4}$$

2.3. Electric machine model

The electric machine is modeled by a quasi-static map describing its electric power. The electric power P_m consumed (in traction mode) or supplied to the battery (in recuperation mode) is of the form

$$P_m = P_m(\omega_{el}, T_{el}), \tag{5}$$

where T_{el} is the electric machine torque and w_{el} is the electric machine rotational speed. This map includes the losses in the electric machine