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IFAC-PapersOnLine 49-11 (2016) 519–524

Compute Optimal Travel Duration in Eco-Driving applications

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***Abstract*— Considering a trip completed by a driver, in which the effects of infrastructure (roundabouts, intersections, traffic conditions) divide the trip in segments. An important problem in eco-driving is the energy minimization by optimizing one's driving style inside each segment while maintaining the trip's time duration. To this aim, this paper inherits principles of optimal off-line control problems with space and time boundary conditions. The novelty concerns the introduction of a multi-objective approach applied to the optimal control. The proposed optimization problem aims to find the best combination of segment's time durations without influencing the global final time and minimizing the trip's corresponding energy consumption. In order to solve this problem, a graph based approach is proposed and the optimal solution is obtained through the application of the Dijkstra's shortest path algorithm.**

***Index Terms*— Eco-driving, optimization, vehicle, energy reduction.**

I. INTRODUCTION

Fuel consumption in transport sector contributes to the emission of greenhouse gases in general and carbon dioxide (CO_2) in particular. Emission of CO_2 is a function of the state of the vehicle technology and the traffic state. Improvements in energy efficiency, the design of new-generations engines, and the introduction of more severe test procedures have reduced fuel efficiency of vehicles considerably over the last three decades. Meanwhile, number of vehicles has increased in different parts of the world in the period from 1980 to 2007 [11]. Each individual's actions result in trivial greenhouses gases emissions, but the results are hardly insignificant when viewed in the aggregate across the entire population [6]. Studies [8], [9], [10] have shown that important part of pollution are directly produced by individuals - i.e. personal transportation and household energy use - constitute anywhere from 32% to 41% of the total CO_2 emissions. Even if we take the low of this range, it roughly corresponds to the 8% of the world's total [6].

In order to ease conditions of local environment through the improvement of driving behaviour and local traffic flow, eco-driving strategies have been studied. The idea behind eco-driving is that there are different ways of driving a specific journey, but they are not equivalent from an energy point of view [14]. Eventually, the objective is to find the optimal one, that minimises CO_2 emissions, and consequently, maximises fuel cost savings. Initial studies focused on applications on highway with high velocity and varying road gradients [2], [3], [4], [5], then, attention regarding the application in an urban context [13], [14], [15]. In the latter, the optimal trajectory is constrained by urban traffic and boundary conditions imposed by the infrastructure (road signs, cross-roads).

Optimization problems can be solved in two ways [14]:

1) Off-line: in this case, known as *off-line assessment*, the speed profile of the vehicle is recorded during the trip (e.g. the GPS speed profile). Then, it is given as an input to the optimization problem in order to identify boundary conditions (distance and duration of the trip, initial and final speeds). Later, the optimization problem is solved to calculate the optimal speed profile that generates the minimum energy consumption over the trip under selected boundary conditions. Finally, the optimal energy is compared with measured one during the trip, in order to provide an eco-driving indicator. This score is given as feedback for the driver and allows him to improve his driving behaviour.

2) On line: in this case, it is possible to consider two different situations. In the first one, known as *on-line assessment*, the speed profile is recorded in real-time and the optimization is performed continuously in time. An eco-driving driving assistance is provided to the driver at each iteration of the algorithm.
In the second one, a prediction of the speed profile until a certain horizon of the trip is done, through the use of driver's trip planning, geo-localization and other infrastructure information. The optimal energy consumption is calculated based on this prediction and an *on-line assistance* is provided to the driver.

This paper inherits principles of off-line control problems and is based on the optimization results presented in [14]. In [14], the main idea is to divide a driver's trip in segments. Each segment is relied by events. Then for each one, an optimal speed profile in terms of energy is computed. These profiles respect the same boundary conditions (space and time) as the driver's. The algorithm ouput is a new trip composed by a set of new speed profiles that respects the same trip's global duration and traveled distance but less energetically expensive. This is the core of the eco-driving application [1].

The main novelty in this work concerns the idea of acting locally on each segment by additionally relaxing their boundary conditions, in particular their durations (mean speeds), without influencing the trip's global duration. The goal is to obtain an extra energy gain with respect to [14] by advising

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10.1016/j.ifacol.2016.08.076

the driver a different mean speed for each segment.

By varying t_f (segments' final time) and computing a new optimal energy we introduce an extra degree of freedom to the problem for each segment. Therefore, a compromise has to be done. Such a compromise, well known in economy, game theory and engineering, is also called the Pareto optimality. As an example, in Fig. 1, we show a Pareto diagram of the optimal energy as a function of the corresponding final time. We observe that until 200 s, small changes in the final time have an important impact on the energy (up to 50% in energy reduction), while after that time the change is almost neglectable. Transposing this notion to the eco-driving implies that the segment's energy level $E(t_f)$ cannot be improved (diminished) without reducing (increasing) the segment's final time t_f. The problem of having several segments and several choices of their final times, can be numerically solved by applying Dijkstra algorithm on an energy graph, where each vertex corresponds to a possible time duration to accomplish the segment's distance and each edge corresponds to the associated optimal energy cost.

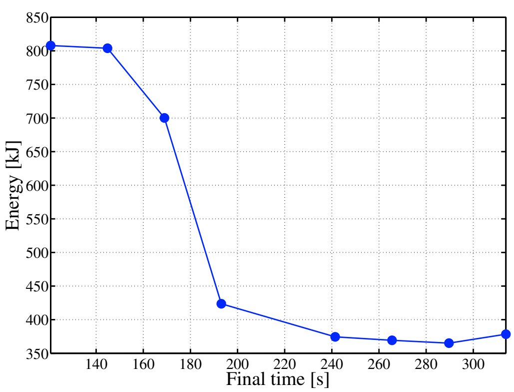

Fig. 1. Optimal energy cost as function of the final time

The rest of the paper is organized as follows: in Section II we introduce mathematical models to estimate the consumption of the vehicle and the optimization problem to obtain the corresponding optimal energy. In Section III, we introduce the proposed method to modulate segments' mean speeds and the numerical resolution. Paper ends with simulation results in Section IV and concluding remarks.

II. PROBLEM FORMULATION

The proposed method is based on the solution of an off-line, constrained optimization problem. The aim is to find speed profiles that minimize the energy consumption over a trip horizon, subject to the vehicle dynamic model, with state constraints at the times where external perturbations are encountered (traffic or infrastructure).

A. Vehicle model

Let us consider an Internal Combustion Engine powered Vehicle (ICEV) and let us make the hypothesis that it is possible to measure the speed $v(t)$ of the vehicle during a trip.

Using the input speed $v(t)$ and the vehicle's longitudinal dynamics, it is possible to write the vehicle model, as follows

$$\begin{cases} \dot{x}(t) &= v(t) \\ m\dot{v}(t) &= F_t(t) - F_{res}(t) - F_{bra}(t) \end{cases} \quad (1)$$

where m, $F_t(t)$, $F_{res}(t)$, and $F_{bra}(t)$ are the mass of the vehicle, the traction force, the resistance force (sum of all resistive forces acting on the vehicle), and the braking force respectively.

The resistance force is given from the contribution of the aerodynamic force $F_a(t)$, the rolling force $F_r(t)$, and the gravity force $F_g(t)$,

$$F_{res}(t) = F_a(t) + F_r(t) + F_g(t) \quad (2)$$

and each can be expressed as follows,

$$F_a(t) = \frac{1}{2} S C_x v(t)^2 \quad (3)$$

$$F_r(t) = c_r m g \quad (4)$$

$$F_g(t) = mgsin(\sigma(t)) \quad (5)$$

with S, the frontal surface of the vehicle, C_x, the aerodynamic drag coefficient, c_r, the rolling resistance coefficient, g, the gravity acceleration and $\sigma(t)$, the road slope angle.
If we substitute the contribution of each resistive force in Eq. (1) and we explicit the traction force, we get

$$F_t(t) = m\dot{v}(t) + \frac{1}{2} S C_x v(t)^2 + c_r m g + mgsin(\gamma(t)) + F_{bra}(t) \quad (6)$$

Traction force $F_t(t)$ can be used to calculate the engine torque as follows

$$T_{eng} = \frac{F_t(t) r_w}{\gamma_t(t)} \quad (7)$$

where $\gamma_t(t)$ and r_w are, respectively, the transmission ratio and the wheel ratio. For the sake of simplicity, the transmission ratio is estimated as the output of the map

$$\gamma_t(t) = \Gamma(v(t), T_{eng}(t)). \quad (8)$$

The speed of the vehicle $v(t)$ can also be used to calculate the engine speed $\omega_{eng}(t)$, as follows

$$\omega_{eng}(t) = \frac{\gamma_t(t)}{r_w} v(t) \quad (9)$$

Finally, fuel power consumed by the engine $P_f(t)$ can be modelled under a steady-state approximation using the following engine map

$$P_f(t) = \Pi(T_{eng}(t), \omega_{eng}(t)) \quad (10)$$