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Eco-driving command for tram-driver system ⋆

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Abstract: In the transport domain, the aim of operators and manufacturers is not only to perform a route as quickly as possible but also to take into account the energy consumption. The scientific advances in the field of solving optimization problems challenge driving habits. Eco-driving assistance systems are then designed to reduce energy consumption. In this paper, achieving an energy efficient driving profile for a tram-driver system is presented. The optimization problem is to achieve inter-station distance in a time t, while respecting the constraints imposed by tram and route models, to minimize energy consumption.

Keywords: Human-Machine System, Minimization of energy consumption, Multi-model approach, Quadratic optimization.

1. INTRODUCTION

The work presented in this article is carried out in the context of the ECOVIGIDRIV project. Driving a tram involves the design of complex control panels that require from drivers more knowledge, performance and attention. On-time performance, passenger comfort and safety are the main tasks allocated to drivers. The operators want to increase traffic while reducing the energy consumption of the network. A major constraint is that the tram moves in an open world, *i.e.* it can be disturbed by pedestrians and cars. The tram driver must anticipate the behavior of drivers and pedestrians, while reducing its energy consumption. To date, the trams are not equipped with eco-driving assistance system. Our goal is to provide a support system for energy-efficient driving that should reduce energy consumption while maintaining the vigilance level of the driver (impacting the security level), respecting speed limits and time route, ensuring the arrival of the tram at intersections with throttle handle in neutral position (which is a safe operation procedure), and which must not be intrusive.

The aim of the article is therefore to provide the specifications of a system minimizing energy consumption and its impact on the driver vigilance with compliance to the network procedures. In the railway industry, support systems for energy-efficient driving have been developed. The ADAS (Advanced Driver Advisory Systems) optimize control of the passengers or freight train. They calculate a velocity profile based on timetable of the operator, on vehicle model and on characteristics of tracks to minimize energy consumption. A first system, Energymiser (Albrecht et al. (2011)), is used in the fast transportation of passengers over long distances. The energy-efficient information is displayed to the driver who must implement it. It is an acceleration control that the driver results in a position of the throttle handle. This manipulator has three zones: a positive acceleration zone; a "neutral" zone (traction control is zero with vehicle ahead by inertia); and a braking area. Whereas the train is running over long distances with a time route which allows the speed control, the tram travels shorter distances. Therefore, the slow dynamics of a speed control available in train domain is not suitable for the tram. It is then necessary to apply an acceleration command to suggest eco-driving for the driver . A second system, Freightmiser (Albrecht et al. (2006); Coleman et al. (2008)), is used in the freight transport. The special feature of this system is to calculate a sub-optimal control for a freight train whose engine may be electric, diesel or hybrid, while optimizing the management of the rail network. Freights are less constrained in time that trains carrying passengers. A third system, Metromiser (Howlett (1996)), is used in the metro but its complex interface makes it unusable for drivers in an open world. Finally, other systems dedicated to the management of the railway system (Howlett et al. (2009); Li-Xing et al. (2011)), the energy recovery (De Martinis and Gallo (2013)) and the speed constraints (Liu and Golovitcher (2003); Feng (2011)) can be considered in the optimization control problem. However, these systems are effective during an automated operation of the vehicle in a closed environment excluding the driver state in the stage of calculating the velocity profile to be followed. The driver should be considered as part of the system and he sometimes may not take into account information provided by the assistance system. Moreover, driver state changes over-

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the-time. Therefore, we must realize a predictive controller that will calculate in real time operational acceleration trajectory including the impact of human behavior during the calculation phase.
In this article, the eco-driving command for tram-driver system is presented. First, the dynamics are modeled for tram (motion and energy consumption) and a controller is designed. Then, the constraints of the tram model and the optimization problem to reduce energy consumption are discussed. The problem is then discretized to solve it numerically. The controller is then applied in a realistic simulation to test performances. Finally the perspectives for future work are proposed.

2. CONTROLLER DESIGN

The aim of the work is to achieve energy-efficient control of a tram-driver model. For this, a multi-model approach is proposed in Fig. 1 to take into account all the components and characteristics. Three components are modeled: the controller, the driver and the tram. The tram model input variable is the throttle handle position denoted $\gamma(t)$ and the output variables are the position $p(t)$, the velocity $v(t)$ and the traction force $u(t)$. The total mass m of the tram with passengers is a parameter that is updated at every stop station. The controller model calculates the instruction $v_i(t)$, the intended velocity, that the driver must reach to reduce the consumption of the tram from the remaining time route, the tram output variables, and controller internal models that are tram and vehicle consumption models. In this article, the controller permitting energy consumption reduction during a route integrating the tram model is presented. The motion model of the tram is given by the equation (1) to optimize the control.

$$\begin{cases} \dot{p}(t) = v(t) \\ \dot{v}(t) = \dfrac{1}{m}u(t) - \dfrac{1}{m}(A + Bv(t) + Cv^2(t)) - gi' \\ \quad with \;\; i' = i + \dfrac{k_e}{r_c} \;\; \& \;\; i = sin(\alpha) \end{cases} \tag{1}$$

The terms A, B and C are constants defined by the manufacturer and correspond to mechanical and aerodynamic characteristics of the tram. The term $A+Bv(t)$ represents the resistance due to bearings and mechanical frictions and $Cv^2(t)$ the aerodynamic drag term with C that characterizes its coefficient of air penetration. The term gi' represents the resistive force produced by the slope and the passage of a tram in turn, with the gravitational acceleration g and i' the intensity of the turn added to the slope, and $u(t)$ the traction or braking force applied at time t. The tram model is controlled by a throttle which, according to its $\gamma(t)$ position, provides an entry into traction or braking effort $u(t)$. Tram engine dynamics is not considered in this study. As the dynamics of the electric motor and the transmission are faster than the dynamics of the tram, only the mechanical dynamics will be considered. In addition, the traction or braking force is proportional to the throttle position as mentionned in (Vial (2012); Howlett et al. (1994). The traction force is proportional to the fuel supply rate in the engine, *i.e.* the position of the throttle through a train diesel engine and/or hybrid. The position of the throttle $\gamma(t)$ is bounded

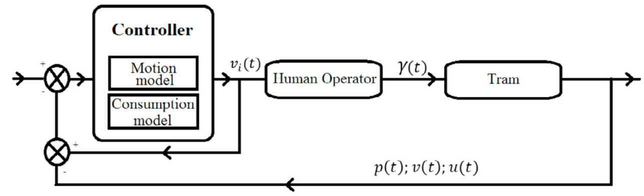

Fig. 1. Eco-driving command for a tram-driver system.

between −1 and 1 and $u(t)$ the traction or braking force is limited between u_{min} and u_{max} are based on the velocity of the tram in equation (2).

$$\forall\gamma(t) \in [-1; 1], \quad u_{min} \le u(t) \le u_{max}, \quad \gamma(t) = \frac{u(t)}{u_{max}} \tag{2}$$

The resistive force against tram move can be simplified into a linear function $v(t)$ in the velocity range $[v_{min}; v_{max}]$. In addition, the constant C is very low and the velocity of the tram is relatively low. In this velocity range, the term $A + Bv(t) + Cv^2(t)$ is approximated in $a_1 + b_1v(t)$by using the least squares method that gives in equation (3):

$$\begin{bmatrix} \dot{p}(t) \\ \dot{v}(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{b_1}{m} \end{bmatrix} \begin{bmatrix} p(t) \\ v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{m} \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ -\dfrac{a_1}{m} + gi' \end{bmatrix} \tag{3}$$

The controller model is now presented and the problem must be formulated in order to be optimized.

3. OPTIMIZATION PROBLEM

The objective is to minimize power consumption of a tram in equation (4), during its displacement from a station A to station B in a time route T which is defined by the equation (5). The tram starts from the station A to the position p_A with a velocity equal to zero and arrives at the station B at the position p_B with zero velocity. It starts at time T_A and it arrives at the station B at the time T_B. Either the expression of mechanical power confirmed by the operator and in the literature (Vial (2012)) which corresponds to the force multiplied by the velocity of the tram in equation (4):

$$E = \min_{u,p,v} \left\{ \int_{T_A}^{T_B} u(t)v(t) \right\} \tag{4}$$

i.e.:

$$\begin{cases} p(T_A) = p_A \;\; , \; p(T_B) = p_B \\ v(T_A) = 0 \quad\; , \; v(T_B) = 0 \end{cases} \tag{5}$$

The influence of braking or jerking when driving as well as energy recovery, are not considered in this study. Nevertheless, we know that, according to De Martinis (De Martinis and Gallo (2013)), these factors included in the problem could be solved. Several authors consider tram control optimization as the basis for eco-driving efficiently (Howlett et al. (1994); Monastyrsky and Golownykh (1993); Delprat et al. (2004); Rousseau (2008)) *i.e.* minimizing traction effort or braking $u(t)$, which corresponds to the input of the dynamic model of the tram. But the tram is constrained