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-

⋆ Authors would like to thank ECOVIGIDRIV project members, the Fonds Unique Interministriel and the Nord Pas de Calais region.

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

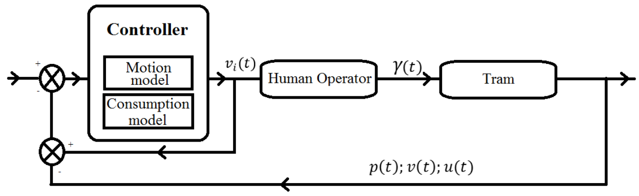

Fig. 1. Eco-driving command for a tram-driver system.

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).

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

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 $a_1 + b_1 v(t)$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 by its operating range (maximum traction/braking) which depends on the vehicle velocity. Furthermore, acceleration as well as its dynamics (jerk) are constraints. However, these constraints are linear and are not considered in this approach for simplification reasons. In the next section, tram model using constraints are developed.

3.1 Tram constraints

The tram performances are defined according to its engine but also by the requirements of operators. These constraints confine the range of use of the electric tram efforts. Therefore, they must be integrated into the controller. The constraints of the model are discussed in this section. The maximum traction and maximum electrical braking depend on the velocity in Fig. 2. The dotted path represents the traction force allowing the tram to accelerate for a throttle position equal to 1. If the velocity is lower than v_t, then the traction force is equal to u_{max}, else if the traction force is decreasing up to v_{max}. The curve represented by dashes corresponds to the force applied to brake function depending on the velocity of the tram with the throttle position equal to -1. The maximum electric braking force is constant between v_{f_1} and v_{f_2}. It is equal to u_{min} and is not compensated by a mechanical force. The electrical brake force decreases when velocity is lower than v_{f_1} or upper than v_{f_2}. During these two stages, the brake force is mechanically compensated. The method of least squares is used to partially linearize the curves of traction and brake forces (in Fig. 2). So tram operating range will be expressed in the following form:

$$\begin{cases} u(t) \leq u_{max}, v(t) \in [0; v_t[\\ kv(t) + u(t) \leq u_{max}, v(t) \in [v_t; v_{max}] \end{cases} \tag{6}$$

$$\begin{cases} k_1 v(t) - u(t) \geq 0 \quad , v(t) \in [0; v_{f_1}[\\ u(t) \geq u_{min} \; , v(t) \in [v_{f_1}; v_{f_2}[\\ k_2 v(t) \geq u_{min} \; , v(t) \in [v_{f_2}; v_{max}] \end{cases} \tag{7}$$

Where k, k_1, k_2 are constants. In equation (6) are represented the operating range of the tram traction and in equation (7) tram operating range when braking. The tram is also limited by its velocity in equation (8) which is between v_{min} and v_{max}.

$$v_{min} \leq v(t) \leq v_{max} \tag{8}$$

In the following, the tram operating range $(u(t); v(t))$ is denoted D. In next section is given the method for minimizing energy consumption.

3.2 Tram control optimization

The objective is to minimize the energy consumption of the tram. The cost function in equation (4) is minimized within the constraints in equations (3,6,7,8) and those defined by the route. Either the notation in equations (9,10,11):

$$\dot{x}(t) = Ax(t) + Bu(t) + d \tag{9}$$

$$x(t) = \begin{bmatrix} p(t) \\ v(t) \end{bmatrix} \tag{10}$$

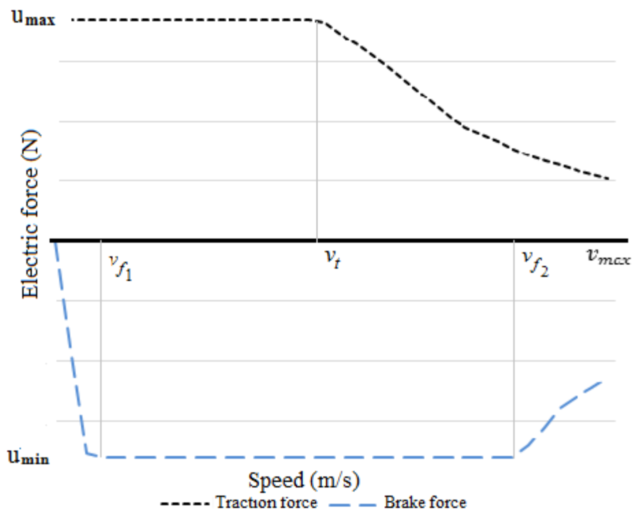

Fig. 2. Total force depending on velocity.

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{b_1}{m} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \quad \& \quad d = \begin{bmatrix} 0 \\ -\frac{a_1}{m} + gi' \end{bmatrix} \tag{11}$$

with d a matrix that represents the disturbances caused by the track profile which are slopes, bends, etc. The current cost function does not solve a linear quadratic control problem because it is not convex nor quadratic. We must change the model in order to calculate the command to be applied by the driver. To do this, simply to express the criterion to be minimized so as to solve a convex quadratic linear problem. For this purpose, $Ru^2(t)$, $x^T(t)Qx(t)$ are added to equation (4) where Q and R are symmetrical weighting matrices in equation (12) defined to obtain the convex quadratic objective function in equation (13). R is defined positive and Q is defined not negative (Anderson and Moore (2007)). Thus, it is possible to determine the solution to consume less energy along the tram route. Criterion (13) is then:

$$0 < R, \quad 0 \leq Q \quad \& \quad S = \begin{bmatrix} 0 \\ \frac{1}{2} \end{bmatrix} \tag{12}$$

$$J = 2x^T(t)Su(t) + Ru^2(t) + x^T(t)Qx(t) \tag{13}$$

The term $v(t)$ is replaced by $2x^T(t)S$ where S is a weighting matrix. The transpose of $x(t)$, here $x^T(t)$, is the set of solutions of the problem on his condition and $u(t)$ the set of solutions on the command. Now, for a convex quadratic linear problem the cost function is written in equation (14):

$$\begin{aligned} J = (u(t) + R^{-1}S^T x(t))^T R(u(t) + R^{-1}S^T x(t)) \\ + x^T(t)(Q - SR^{-1}S^T)x(t) \end{aligned} \tag{14}$$

The expression of our modified tram model in equation (15) is denoted as follows:

$$\begin{cases} \dot{x}(t) = (A - BR^{-1}S^T)x(t) + B\tilde{u}(t) + d \\ \tilde{u}(t) = u(t) + R^{-1}S^T x(t) \end{cases} \tag{15}$$

It is now possible to calculate the command to minimize the cost function of the convex quadratic linear problem in equation (16):

$$J = \min_{\tilde{u},p,v} \int_{T_A}^{T_B} x^T(t)(Q - SR^{-1}S^T)x(t) + R\tilde{u}^2(t) \quad (16)$$

The cost function is quadratic if and only if $(Q-SR^{-1}S) \geq 0$ according to (Borne et al. (1990)). The equation (13) allows to obtain the equation (17).

$$SR^{-1}S^T = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{1}{4R} \end{bmatrix} \quad (17)$$

The terms Q and R previously added are used to obtain a convex cost, it is necessary that these terms are as small as possible. However, in order to avoid any penalty on the tram position, the Q matrix is defined in equation (18).

$$Q = \begin{bmatrix} 0 & 0 \\ 0 & q_2 \end{bmatrix} \quad (18)$$

To ensure the condition $(Q - SR^{-1}S^T) \geq 0$, we must have $q_2 > 0$ and $4q_2R \geq 1$. To obtain a convex cost, traction or brake force and velocity of the tram can not be heavily penalized. The criterion is defined to calculate the command of our tram to minimize energy consumption. The discretization of the model permits the solving of optimization problem numerically.

3.3 Model discretization

To solve the optimization problem numerically, it must be discrete. The sampling period to avoid any data loss during the route should be determined. It must be chosen depending on the speed of the dynamic of the tram on the route. In this study, the data considered are those of Valenciennes tramway. Sampling period T_s is one second, the mass m of $50000kg$ is used with R equal to 0.1, $q_2 = 2.5$ and $4q_2R = 1$ and where $\tilde{A} = A - BR^{-1}S^T$ and $\tilde{B} = B$. The tram model given in equation (15) becomes (equation (19):

$$\begin{cases} x(t) = \tilde{A}x(t) + \tilde{B}\tilde{u}(t) + d \\ \tilde{u}(t) = u(t) + R^{-1}S^T x(t) \end{cases} \quad (19)$$

The discrete state model in equation (20) is obtained for a sampling interval of one second for the model in equation (19):

$$\begin{cases} x(k+1) = A_d x(k) + B_d \tilde{u}(k) + d_d \\ \tilde{u}(k) = u(k) + R^{-1}S^T x(k) \end{cases} \quad (20)$$

The cost function J in equation (16) is also discretized in equation (21) and T the number of steps in equation (22) were calculated according to predefined constraints:

$$J = \sum_{k=0}^{T} R\tilde{u}(k)^2 \quad (21)$$

$$T = \frac{T_B - T_A}{T_S} \quad (22)$$

Which constraints are expressed by equation (5,8). The control problem is a convex quadratic problem. Thus, the resolution time to set the driving profile is faster than the expected refreshing time for the information given to the driver. In addition, it is used in real time to calculate a new driving profile as the constraints and used models may not be accurate enough. This is why the optimization calculation is restarted every second. In this case, the interior point method is used to determine the optimum that reduces the energy consumption according to the constraints applied both on the vehicle and on the environment, and that need to be updated during the route.

4. CONTROLLER APPLICATION

The optimization algorithm is used in real time. Thus, at each iteration a new driving profile for solving the minimization of energy consumption for the route of the tram driving simulator is defined. The advantage of operating in real time is to adapt to the situation, to update the constraints and the model that may be wrong (for instance changing the maximum velocity on the section due to work in progress). In addition, changing the profile of the route corresponds to a disturbance of the command that is considered by changing the value of the matrix d of the equation (9) and is corrected during the next step. In this section the environment and the route of the tram are described. The presented data are resulting from the tram driving simulator "OKSimRail" developed by Oktal society and is particularly used to coach tram drivers. The tram travels a total distance of $1842.58m$ for a time of $357s$ not considering stops that the tram is respecting in stations. In this route, there are four sub-routes that correspond to the inter-station distances. The first sub-route, $P1$, is the distance made to go from the starting point to the station 1. This sub-route is a straight line of $167m$ to be performed in $43s$. The second sub-route, $P2$, with a distance of $625m$ is to be performed in $140s$ from station 1 to station 2. It consists of one intersection, four speed changes and two bends. The distance of $600m$ between station 2 and station 3 is to be completed in $110s$. This is the third sub-route, $P3$, where trams must cross two intersections, two speed changes and one turn. The last sub-route, $P4$, is to complete the distance between the station 3 and the station 4 separated by $450m$ in $64s$. The driver must regulate the velocity of the tram three times and addresses two intersections and end on a turn before arriving at final station. During the experiment the traffic lights are not included. route is presented in Fig. 3.

The command from the controller is calculated on this route. The resolution model calculates a velocity profile that meets the velocity limits, the crossing of intersections and stop at stations in Fig. 4.

Initially, the command is determined by not taking into account the impact of bends on the tram and then, in a second time, bends of the track were included to assess their impact on energy consumption. The position of the throttle is rarely above 50% when the tram accelerates

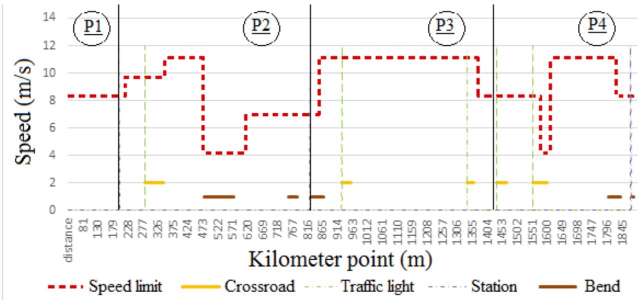

Fig. 3. Simulated route.

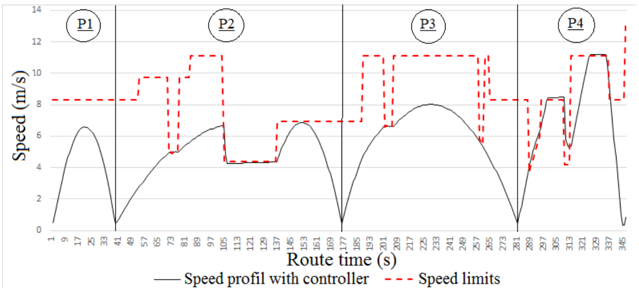

Fig. 4. Control optimization for a given schedule considering bends

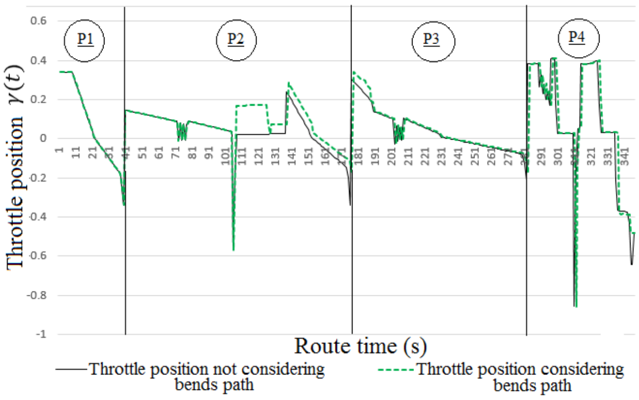

Fig. 5. Comparison between throttle positions.

in Fig. 5, and to maintain velocity, throttle position is very close to the neutral position (= 0). Finally, the only route with strong variations of the command is $P4$, where the route time is barely small regarding the large distance. However, the command the driver has to follow in order to carry out $P2$ and $P3$ sub-routes is really different when considering or not the impact of bends in Fig. 5. The tram requires greater acceleration when traveling on a turn. This "over-acceleration" corrects the error that is produced by interference from the track bends and implies a position of throttle away from neutral.

For instance, the same route $P2$, $625m$ in $140s$, performed considering bends implies energy over-consumption increase of 55% in table 1.

Table 1. Energy over consumption considering bends

Route	P1	P2	P3	P4	Total
Distance (m)	167	625	600	450	1842
Duration (s)	43	140	110	64	357
Over consumption (%)		55	8	3	16

So bends can not be neglected in the optimization problem. In this study, the energy consumption for driving "Pulse & Glide" ($P\&G$ which is to move as fast as possible to the speed limit and then let the vehicle advance by its own inertia) performed automatically is compared with an optimized driving calculated by the controller. The route time is of route identical in both cases. Table 2 shows the saved energy between the two driving modes.

Table 2. Energy consumption comparison between P&G and controller

Route	P1	P2	P3	P4	Total
Distance (m)	167	625	600	450	1842
Saved energy (%)	-12	12	5	10	7

The controller can reduce energy consumption, up to 12% in $P2$, on the entire route in Table 2. The slight over-consumption in $P1$ is explained by the high precision of the controller that gives an energy consumption value for a throttle position range where it is normally zero. This does not prevent to reduce energy consumption by 7% for the entire route. The controller and its performance were presented in this section and some improvements are already considered and will be discussed as perspectives in next section.

5. CONCLUSION

In this paper, a method to calculate a driving profile for minimizing energy consumption is presented. The controller calculates the eco-driving command to apply. It allows, in the studied case, to reduce energy consumption up to 12%. To include changes in speed and slopes and bends in the controller, the study of a hybrid Model Predictive Controller (MPC) is considered. If the computation time becomes too important, a controller that includes both the advantages of a hybrid MPC and the current algorithm will be studied. The integration of the driver model in the controller is a perspective that we want to explore. The driving task can not be automatic because the driver main task is to ensure security and safety during route. The driver should apply the calculated driving profile but his response time and his ability to respect instructions can vary and is not stable over-the-time, for instance for security reasons if an object can be found on the tram tracks. Therefore, it is proposed to incorporate into the controller a model of Human Operator in Fig. 6. The measured variables of the driver may be incorrect or not observable. Thus, the estimation of the driver will set the model parameters and information mode that drivers will have to follow to minimize energy consumption. Some driver model can be found and developed based on literature review as for example in (Cacciabue et al. (2013)). The refresh time of the eco-driving instruction to be displayed to the driver will be defined in later studies. To assist the driver in eco-driving, it is possible to achieve a cooperative eco-driving system (Vanderhaegen (1997); Lemoine et al. (1996)) where the human operator allocates a task to the controller (followed by eco-driving route) and performs a parallel task (security management) (Millot and Boy (2012); Soualmi et al. (2014)). Another controller can support the driver in its movement (Masikos et al. (2011); Marouf et al. (2011); Sentouh et al. (2013)) to help implement eco-driving instruction. External events (passing pedestrians,

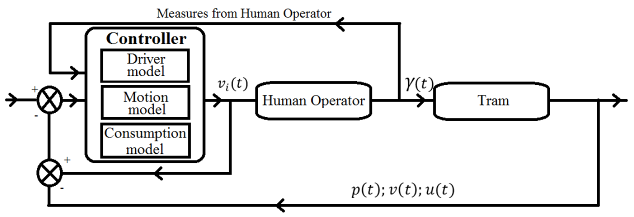

Fig. 6. Multi-model approach including Human in the controller.

road vehicles on tracks, etc.) can disturb the following of driving profile and thus causing delay. The controller will then adjust to the new traffic conditions. If the route is no longer feasible in the originally allocated time, and in order not to jeopardize the safety and the comfort of passengers (overspeed, sudden acceleration, etc.), the controller must be able to relax the time constraint to ensure solving the optimization problem. The driver behavior can be considered as a perturbation which need to be minimized regarding energy consumption. Indicators focusing on time and distance traveled respecting the application of eco-driving command should be developed to demonstrate the impact of driver on the tram system.

ACKNOWLEDGEMENTS

The present research work has been supported by:
The Nord-Pas-de-Calais Region,
The European Community,
The Regional Delegation for Research and Technology,
The Ministry of Higher Education and Research,
The International Research Network HAMASYTI (Human-Machine Systems in Transportation and Industry), And the National Center for Scientific Research.
The authors gratefully acknowledge the support of these institutions.

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