Fuel Consumption Optimization for a City Bus

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Abstract: This paper deals with the optimization of the fuel consumption for a city bus of the city of Rouen, in France. This work takes part from the ANGO project, a french PREDIT-ANR project. The aim consists in modelling the bus and its fuel consumption in order to formulate a problem of optimmization of the consumption (criterium definition, constraints, initialized variables, ...). Some simulation results are shown under an advisory system to the bus driver and experimental works are presented.

1. INTRODUCTION

The eco-driving style and rules (how to drive economically and ecologically) is usually well-known in the professional automotive areas. But very few drivers adopt such economical and ecological driving style everyday, either with cars or trucks. It is shown that a fuel reduction of 15 percents could be reached if drivers could pay attention to their way of driving. At the scope of a whole country, this potential gain represents several tons of CO2 which would not be emitted every day. So, the point is to induce normal and professional drivers to a more economico-ecological driving style, in any driving condition: in cities, roads or highways, in normal or dense traffic situations and under any weather condition. More and more institute now propose some eco-driving trainings.

Siemens VDO developed an "electronic co-pilot" named GERICO dedicated to eco-driving assistance which provides information, advices and alerts to the driver in real-time while driving, it is based on a specific HMI [3].

LCPC-LIVIC developed an integrated system to prevent drivers from approaching a curve at a dangerous velocity. This system features three functions. The first function consists in knowing the geometry characteristics of the upcoming road. The second function has to compute a safe speed according to the road section, the state of the vehicle and the driver. The last function must impose the speed control of the vehicle in order to achieve a safe speed in the case that the driver does not achieve a safe velocity.

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One of the objectives of the current ANGO (TEOR+) project is the optimization of the fuel consumption of a city bus, considering the geometrical longitudinal profile of the bus lane, its charge, etc. An advisory system for the driver is studied in order to optimize the consumption among an advisory speed profile.

In the following, Section 2 gives a detailed description of the bus used in the ANGO project and its modelling under several hypothesis. An improvement of the bus modelling is presented by adding the torque converter. Section 3 deals with some fuel consumption aspects and section 4 formulates the optimizing problem under constraints. In section 5 some simulation results are described and the last part presents the beginning of experimental works about the advisor system for the fuel consumption optimization.

2. VEHICLE DESCRIPTION AND MODELLING

The vehicle used in the ANGO project is a CITELIS city bus, a jointed bus, with four doors and a Diesel engine using some diester.

2.1 Vehicle description

It contains thirty-six sitting places and one hundred and thirty-eight standing ones. The length of the bus is 18 m with a weight that can vary between 17000 kg and 29000 kg.

The engine is a four-stroke engine with six cylinders and a direct injection supercharged by a turbo-compressor. The ANGO bus is equipped with an automatic gearbox with 5 gears.

2.2 Vehicle modelling

In order to optimize the fuel consumption of the bus, a dynamics model is needed. As one of the objectives of the ANGO project consists in advising the driver about his speed profile, only the longitudinal dynamics are taken into account. In that way, the bus model will be directly used by the optimizing algorithm to decrease the bus consumption on a known journey. It is also essential to simulate the HMI part of the global system before the achievement of the experimental part, then its behavior must be studied through a simulation.

Regarding the longitudinal modelling of a bus, several works were done with a turbo-diesel engine, but they are for the most not enough precise. In [1], authors proposed a simplified model of heavy vehicle (bus, truck) that uses similar data than the ones transmitted by the bus manufacturer in the ANGO project.

A model that takes into account the available numerical data of the ANGO bus is needed in order to select the longitudinal model that tallies with the reality. An adapted model is then presented in the following.

2.3 longitudinal bus modelling

x	Longitudinal displacement
v	Longitudinal speed
ω_r	Wheel speed
ω_m	Engine speed
R_g	Total gear (gearbox+differential)
R_t	Gear
R_{td}	Desired gear
T_{map}	Desired engine torque
T_m	Engine torque
T_{acc}	Auxiliairy torques (air conditioning,...)
T_f	Braking torque
C_a	Aerodynamic coefficient
C_r	Rolling resistance coefficient
m	Bus weight
g	Gravity
J_m	Engine inertia
J_r	Wheel inertia
θ	Slope (rad)
α	Throttle angle
τ_m	Time constant for engine
τ_g	Time constant for gearbox

Hypothesis In the main objective to only take into account the longitudinal mode, several hypothesis can be applied :

- The bus structure must be stiff.
- A non-slip assumption is done : $v = r\omega_r$.
- The torque converter is locked : $\omega_r = R_g\omega_m$.
- The power due to the different bus accessories (air conditioning, ...) is supposed to be constant : $T_{acc}\omega_m = P_{acc} = constant$.

State equations Using these hypothesis and the application of the Fundamental Principle of Dynamics to the contact between the pneumatics and the road, one can obtain the state equations

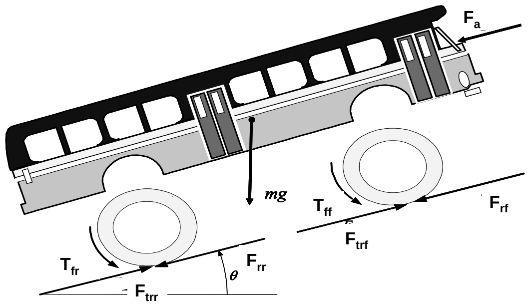

Fig. 1. Bus notations

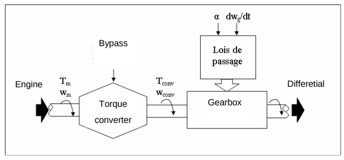

Fig. 2. Bus powertrain

$$\dot{x} = v \tag{1}$$

$$J_{eq}\dot{v} = T_m - R_g(T_f + T_{res}) - T_{acc} \tag{2}$$

$$\dot{T}_m = \frac{1}{3\tau_m}(-T_m + T_{map}(\alpha, \omega_m)) \tag{3}$$

$$\dot{R}_t = \frac{1}{3\tau_g}(-R_t + T_{td}) \tag{4}$$

$$\dot{T}_f = \frac{1}{3\tau_f}(T_{fmap}(\beta) - T_f) \tag{5}$$

where the state vector is

$$[x, v, T_m, R_t, T_f] \tag{6}$$

with the total inertia J_{eq} brought back to the engine shaft

$$J_{eq} = \frac{J_m + R_g^2(N_rJ_r = mr^2)}{R_g r} \tag{7}$$

and the strong torque T_{res}

$$T_{res} = r(F_a + F_r + mg.\sin(\theta)) \tag{8}$$

$$= r(C_a v^2 + C_r mg.\cos(\theta) + mg.\sin(\theta)) \tag{9}$$

The function $T_{fmap}(\beta)$ is the braking input function.

This dynamic model has the advantage to be easy to handle for the development of algorithms such that the fuel consumption optimization. But the torque converter is not considered and is an important element in the powertrain that must be regarded.

Besides one can note that the T_{fmap} braking function is not known but it is not implicated in the optimizing problem because only the accelerating/decelerating phase will be taken into account. In that way, this function is chosen as a linear function.

2.4 Improvement of the bus modelling

With the intention of modifying the bus modelling (figure 2), the gearbox inertia and the effectiveness of its slowing down system are considered [4, 5, 6, 7].

ω_{conv}	Output speed of the torque converter
T_{conv}	Output torque of the torque converter
T_{diff}	Differential torque (wheel shaft)
T_{ralent}	Slowing down torque of gearbox
K_{ralent}	Slowing down coefficient
R_{diff}	Reduction ratio of the differential
J_{bv}	Gearbox inertia
$\mu()$,$\lambda()$	Intermediate functions
J_{convin}	Primary inertia of torque converter
$J_{convout}$	Secondary inertia of torque converter
ω_r	Wheel speed

The new state equations are given in the following, with a new state vector

$$X = [\, x,\ \omega_r,\ T_f,\ \omega_m,\ T_m \,]^T \tag{10}$$

$$\dot{x} = v = r\omega_r \tag{11}$$

$$J_{eq}\dot{w}_r = T_{diff} - T_{res} \tag{12}$$

$$\dot{T}_f = \frac{1}{3\tau_f}(T_{fmap}(\beta) - T_f) \tag{13}$$

$$\dot{T}_m = \frac{1}{3\tau_m}(-T_m + T_{map}(\alpha, \omega_m)) \tag{14}$$

$$\begin{cases} \omega_m = \omega_{conv}, \\ withbypass \\ \dot{\omega}_m = \dfrac{T_m - T_{acc} - \lambda(G_{conv})\omega_m^2}{J_m + J_{convIn}}, \\ withoutbypass \end{cases} \tag{15}$$

with the total inertia

$$J_{eq} = (16)$$

$$\begin{cases} \dfrac{J_{bv}R_g + J_m + J_{convIn} + J_{convOut}}{R_g^2} + mr^2 + N_r J_r \\ \quad withconverterBypass \\ \\ \dfrac{J_{bv}R_g + J_{convOut}}{R_g^2} + mr^2 + N_r J_r \\ \quad withoutconverterBypass \end{cases} \tag{17}$$

and the strong torque T_{res} and the differential torque T_{diff}

$$T_{res} = r(C_a v^2 + C_r mg.\cos(\theta) + mg.\sin(\theta)) \tag{18}$$

$$T_{diff} = \frac{T_{conv}}{R_g} + K_{ralent}\frac{T_{ralent}(\omega_m)}{R_{diff}} \tag{19}$$

with the following parameters (Speed and torque at the converter output)

$$\omega_{conv} = \frac{\omega_r}{R_g} \tag{20}$$

$$T_{conv} = \begin{cases} T_m - T_{acc}, & withbypass \\ \omega_m^2\mu(G_{conv})\lambda(G_{conv}), & withoutbypass \end{cases} \tag{21}$$

with

$$G_{conv} = \frac{\omega_{conv}}{\omega_m} \tag{22}$$

All the equations depend on the status of the torque converter (with bypass or not). One can note that the braking system and the engine are represented by a first order dynamic. The engine has time constant τ_m using an engine cartography (figure 3) linking the speed ω_m and the throttle angle α. For confidential reasons, the cartography will not be presented in this paper.

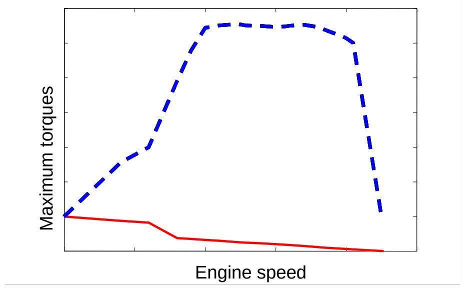

Fig. 3. Engine cartography : (-) Strong torque, -(–) Maximum torque

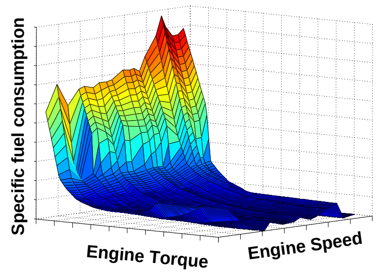

Fig. 4. Specific fuel consumption versus engine speed and torque

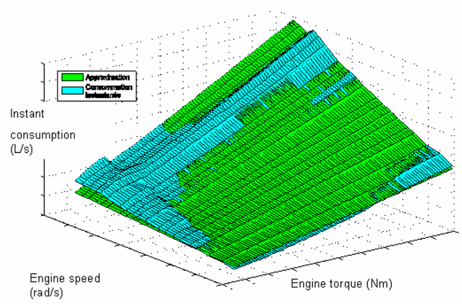

Fig. 5. Approximation of the Instant fuel consumption by a linear function of P_m

3. CONSUMPTION ASPECTS

The instant fuel consumption C_{ls} is computed from the specific consumption C_s using the following relation

$$C_{ls} = \rho_{diesel}.C_s.P_m \tag{23}$$

with C_{ls} in L/s, C_s in g/W, P_m is the engine power in W and ρ_{diesel} is the fuel density in L/g. The figure (4) shows the specific consumption versus the engine speed and torque.

The instant consumption is directly linked to the engine power and can be approximated by a linear function

$$C_{ls} = a.P_m + b \tag{24}$$

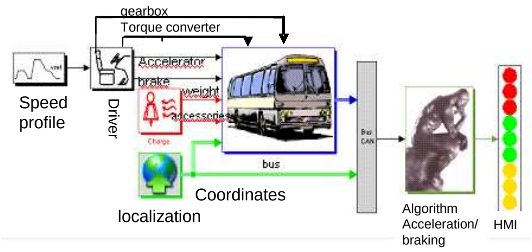

Fig. 6. Global scheme of the system of consumption optimization

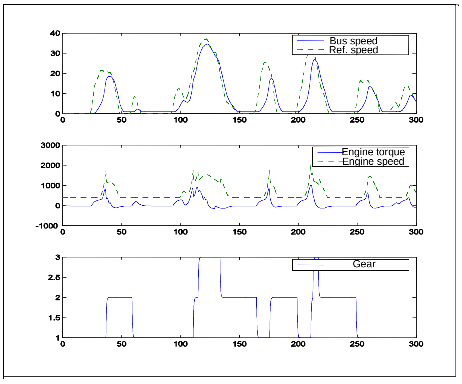

Fig. 7. Simulation of the model without torque converter versus time in (s)

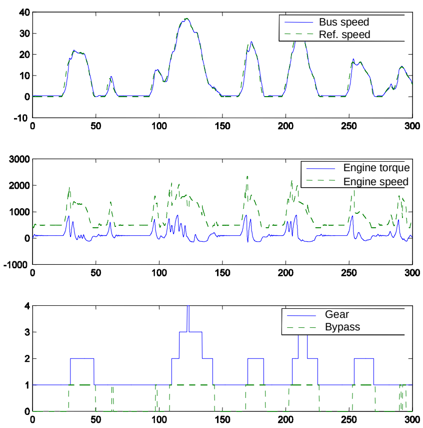

Fig. 8. Simulation of the model with torque converter versus time in (s)

where a and b are parameters function of a given vehicle. The figure (5) shows the comparison of the instant consumption with the linear case.

During a braking phase, the injectors are stopped in order to reduce the fuel consumption. Nevertheless, the engine must be kept at a minimum speed. Then a regulation loop must be considered during the computation of the consumption.

The figure (6) shows an overview of the system to be designed with its different parts. The figure (7) gives the obtained results with the model without torque converter. There is a delay and a deformation between the speed reference and the bus speed. That shows the lack of precision of the model. The figure (8) displays the comparison of the model with an integrated torque converter with the reference signal : there is quite no delay between the bus speed and the reference and one can see the bypass effect of the torque converter. The addition of the torque converter considerably improves the precision of the model. This one will be used in the following for the optimization of the bus consumption. The simulation of a journey of 1s needs 2.5ms of computation time.

4. FORMULATION OF THE OPTIMIZING PROBLEM

The model used for the optimization of the fuel consumption is

$$\frac{x_{k+1} - x_k}{T_e} = v_k \tag{25}$$

$$\frac{v_{k+1} - v_k}{T_e} = \frac{1}{M}(F_k - (a_{slope} + bv_k^2)) \tag{26}$$

4.1 Criterium definition

The criterium of optimization for a given journey is J_N

$$\begin{aligned} Criterium: \quad & min(J_N) \\ J_N \quad = \quad & \sum_{k=0}^{N}(\max(0, F_k).v_k) \end{aligned} \tag{27}$$

under the constraints

$$Constraints: \quad \begin{cases} 0 t t_f \\ 0 x_k x_f \\ 0 v_k V_{\max}(x_f) \\ a_{\min} a_k a_{\max} \\ F_{\min} F_k F_{\max} \end{cases}$$

The chosen parameter for the consumption optimization coincides with the product between the effort F_k and the linear speed v_k, that is to say the bus power. The criterium J_N is then defined as the minimum of the cumulation of the positive powers. Minimizing the consumption consists in minimizing the energy needed to the bus displacement. This optimization is thus independent from the powertrain. The advantage is the decrease of the number of variables to be considered in the optimizing problem under constraints and of the processing time.

The fixed constraints are :

- the journey duration issued from a schedule database
- the distance x_f to be covered coming from a cartography
- the maximum speeds $v_{\max}(x_f)$ from the cartography
- the maximum acceleration $a_{\max}$ due to comfort aspects
- the maximum effort $F_{\max}$

The optimization problem must be achieved off line. As the journey to be carried out and the model to be used are known and the criterium being additive, one of the only methods of optimization that can be formulated is the "dynamic programming" [2].

Then the criterium can be written :

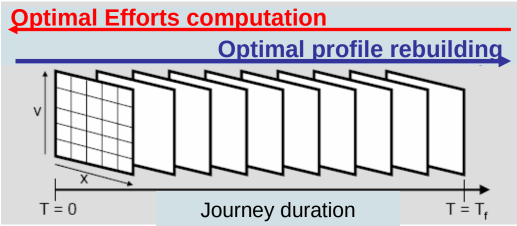

Fig. 9. Dynamic programming method

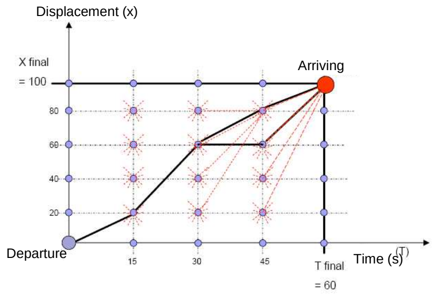

Fig. 10. Dynamic programming method (2)

$$\min_{F_{1,N}}(J_N) = \min_{F_N}(C_N) + \min_{F_{1,N-1}}(J_{N-1}) \tag{28}$$

$$C_N = \max(0, F_N).v_N \tag{29}$$

4.2 Dynamic programming method

This method permits to build a 3D abacus (Time, Distance, Speed) in which the whole of the optimal speed profile will be put down. Then, whatever the initial position, speed and time of the bus on its journey, this abacus gives the optimal speed profile to be followed to get to the final position by minimizing the fuel consumption under the constraints.

The focusing of this abacus is done by a recursive computation from the final position (figure (9)), setting step by step some slices of abacus for each sampling time. The method analyses the cost of each segment that permits to go from one initial point to the next one by minimizing the energy of the bus (the shortest path). Then the addition of all these segments or costs will constitute the minimum energy to be spent by the bus to go from its initial position to the final position of its planned journey (figure (10)). This recursive building process is repeated for each sampling time from T_{max} to 0. The main interest of this method is to have at disposal a family of optimal profiles and not only one. It is thus not needed to recompute a speed profile at each drift of the current speed, because all the needed information used to determine a new profile are in the abacus.

4.3 Applied method in ANGO project

Referring to the figure (11), the method used in the ANGO project consists in minimizing the bus energy to optimize the fuel consumption with the dynamic programming. The result can be viewed by adding all the instants where the bus is accelerating. In that way, we can know when the bus is spending some energy. Thus if the accelerating period is less important than the decelerating one, one can be able to conclude to a consumption decrease.

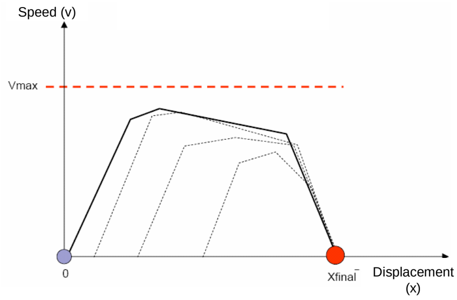

Fig. 11. method adopted in the ANGO project

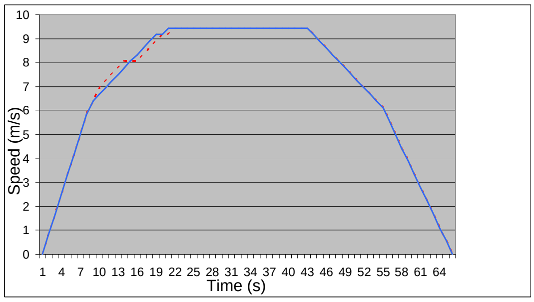

Fig. 12. Simulation result with $A = 0.5$ - (-) optimal profile, (- -) Speed profile

5. SIMULATION RESULTS

After some tests of the algorithm of optimization, a phenomenon of oscillation can sometimes appear. This is caused by the form of the criterium that authorizes some fast changing phase of the effort and does not penalize the strong deceleration. Thus the braking phase is lengthened to the detriment of the acceleration phase where the the amplitude of the efforts is higher to catch the delay.

To solve this problem, a new criterium is chosen :

$$J_N = \sum_{k=0}^{N} \max(0, F_k).v_k \tag{30}$$

(31)

$$J_N = \sum_{k=0}^{N} (1 - A)(\max(0, F_k).v_k)^2 \tag{32}$$

$$+A(\min(0, F_k).v_k)^2 \tag{33}$$

with a constant A that balances the braking phase. The final simulation result shown on figure (12) offers some good performances and the acceleration phase is shorter than the deceleration one.

6. EXPERIMENTAL WORKS

6.1 HMI architecture

The accelerating/braking algorithm is divided into two parts : the first one computes the optimal speed profile that is an input of the second one that gives the information levels to be transmitted to the HMI.

The HMI permits to translate the information levels in lighted signals destinated to the driver on his board (figure

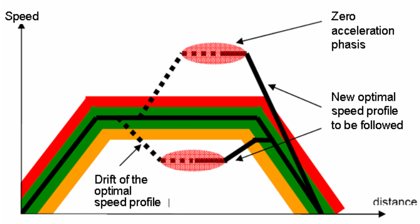

Fig. 13. Global system strategy

(13)). Each level corresponds either to a red light for a bad driver in a consumption point of view, or a green level for a good driver or an orange light for a driver at the limit.

6.2 embedded system

The advisor system is coupled to an embedded computer (is not focussed in this paper). The first results show that the embedded computation time is 27s for a 60s journey, which is an important time to obtain the different abacus. Then the real time at each bus stopping is not conceivable. The solution then consists in creating off line a database containing this abacus presenting the speed profiles versus the distance and the journey time. It will be more precise with a small sampling time. Besides, it will be needed to create N abacus for N sampling times of the carried load.

Finally, for a given journey, one can obtain an optimal speed profile around which several envelopes will be defined to determine the thresholds of control of the HMI display (colored lights). If the driver's speed profile is out of the optimal speed profile then a new optimal speed profile will be computed (chosen in the loaded abacus) (see figure (13)). This can be done only during a zero acceleration in order to avoid an oscillation between several profiles.

7. CONCLUSION

An advisory system is presented in this paper to set an optimal speed profile to be followed by a bus driver to decrease his fuel consumption. A precise model is studied taking into account the torque converter and the gearbox. An optimizing problem is formulated and uses the dynamic programming. This algorithm computes an optimal speed profile off line and it is sent to an HMI by display to the driver. The auxiliairies like the air conditioning are not considered in the algorithm but it will be possible in the future to tune it with the reference input in relation to the followed optimal profile.

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