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A PIECEWISE VEHICLE FUEL CONSUMPTION MODEL FOR ECO-DRIVING ASSISTANCE SYSTEM

Qi Cheng, Lydie Nouvelière and Olivier Orfila

Abstract—This paper presents a new method to model the vehicle fuel consumption in the design of an eco-driving assistance system developed by IFSTTAR within the European Commission FP7 project eco-Driver. The ambition of the driver assistance system is to combine safety requirements and fuel consumption reduction by optimizing the vehicle speed and the gear management. The exact estimation of the vehicle fuel consumption plays a key role in the driver assistance system design. This paper extends the authors' results about the vehicle fuel consumption model. The instantaneous fuel consumption rate is modelled as a piecewise polynomial of the instantaneous engine speed and the instantaneous engine torque. The real vehicle experiments show the good performances of this piecewise fuel consumption model.

I. INTRODUCTION

Reducing the vehicle fuel consumption becomes more and more important in the automobile industry. The safety and the fuel economical efficiency are the first two important issues when the customers decide to buy a new car. The automobile manufacturers have invested huge money to improve the power train efficiency. But it is a long term process. Another short term

This work is supported by the FP7 ecoDriver project Qi Cheng, and Olivier Orfila are with the Laboratoire LIVIC, IFSTTAR, 14 , route de la Minière, 78000 Versailles, France, qi.cheng@ifsttar.fr, olivier.orfila@ifsttar.fr

Lydie Nouvelière is with the Laboratoire IBISC EA 4526, CE 1455, 40 Rue du Pelvoux, 91020 Courcouronnes, France and the Laboratoire LIVIC, IFSTTAR, 14 , route de la Minière, 78000 Versailles, France, lydie.nouveliere@ibisc.univ-evry.fr

way is to change the driver's behavior which has an important influence of the vehicle fuel consumption by helping him in his driving task. The frequent accelerations and decelerations should be avoided since they cost lots of energy.

The economical-ecological way of driving (eco-driving) is a citizen driving behavior which allows to reduce the energy consumption up to 15%, limiting the GHG effect responsible for the climatic warming, and to decrease the risk of accidents (by 10 to 15%).

In the eco-driving assistance system (EDAS), an optimal profile, to be sent to the Human-machine interface module to advise the driver in real time, can be computed. This optimal profile is obtained by an optimization process on the vehicle fuel consumption. The fuel consumption model is then one of the key points in the design of the eco-driving assistance system [1] before the choice of the reference signal to be sent to the driver (speed, gear, ...).

In the current eco-driving assistance system, the vehicle fuel consumption model is described by a single equation. In this paper, a piecewise model is proposed in which the engine map could be separated into some sub-areas and in each sub-area, the fuel consumption is approximated by a single equation of a 2-order polynomial of the engine torque and engine speed. With this new modelling technique, the fuel consumption estimation precision could be greatly improved.

This paper is organized as follows. After a brief presentation of the EU ecoDriver project, a schematic diagram of the proposed eco-driving

system is given in Section 2. Then, the simple vehicle model is described in Section 3. The details of the vehicle fuel modeling technique is given in Section 4. Some experimental results are shown in Section 5. A final analysis concludes on this EDAS.

II. ECO-DRIVING ASSISTANCE SYSTEM

A. EcoDriver Project

The project ecoDriver - Supporting the driver in conserving energy and reducing emissions - an FP7 EU project - addresses the need to consider the human element when encouraging “green” driving, since driver behaviour is a critical element in energy efficiency. The focus of the project is on technology working with the driver. The project aims to deliver the most effective feedback to drivers on green driving by optimizing the driver-power train-environment feedback loop. It will carry out a substantial programme of work to investigate how best to win the support of the driver to obtain the most energy-efficient driving style for best energy use.

The project aims to examine driving not only with present and near-term power trains but also with a full range of future vehicles, including various types of hybrid and plug-in electric vehicles. A comprehensive evaluation will be carried out both in the laboratory (a variety of driving simulators) and in real world driving in both the private and fleet contexts. Scenarios will be developed to assess the implications for the future effectiveness of green driving support. The target of ecoDriver is to deliver a 20% improvement in energy efficiency by autonomous means alone, which opens up the possibility of greater than 20% savings in combination with cooperative systems.

B. The design of the eco-driving system

The schematic description of the model for the eco-driving system design is presented in Figure 1. The approach considers that from road and vehicle data, an optimal profile in terms of speed and gear number, is computed and sent to

the Human-machine interface module to advise the driver.

The aim of the global chain schematic diagram of the full system for eco-driving system is to combine safety requirements and fuel consumption reduction by optimizing the vehicle speed and the gear management. It requires information on various signals from the vehicle (speed, position, gear number), environment (longitudinal headway spacing), road (legal speed limitation, road geometrical attributes) to compute such an optimal profile. For that, we developed a power train model that provides the vehicle state vector and the instantaneous fuel consumption model that gives the vehicle fuel consumption information. Then, an optimization procedure is developed to suggest an optimal profile in terms of speed and gear number to the driver in order to reduce the fuel consumption considering the road data and the safety requirement.

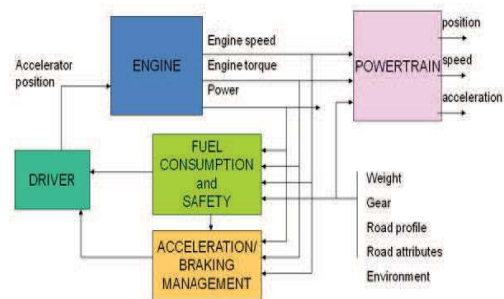


Fig. 1. Schematic diagram of the power train model in the eco-driving system.

III. VEHICLE MODEL

The main output of the vehicle model is the longitudinal dynamics vehicle state: current longitudinal position, speed, acceleration, gear number, engine speed, engine torque. An illustration of the vehicle dynamics model is given in Figure 2. A common power train model is used

Designation	Description
v_x	Vehicle longitudinal speed
r	Wheel radius
η	Total efficiency parameter of transmission
N_t	Gear ratio
N_f	Differential ratio
T_e	Engine torque at a given speed
T_b	Brake Torque
M	Total vehicle mass
g	Gravitational constant
f_R	Rolling resistance force
ρ	Air density
S	Area of vehicle front surface
C_x	Aerodynamic resistance coefficient
θ	Road grade
I_e	Engine rotational inertia
I_t	Rotational inertia of the transmission
I_d	Rotational inertia of the driveshaft
I_w	Rotational inertia of the wheels

TABLE I
NOMENCLATURE OF THE POWERTRAIN MODEL

to describe the vehicle longitudinal dynamics ([2]):

$$\dot{v}_x = \frac{r^2(Mgf_R + 0.5\rho SC_x v_x^2 + Mg \sin(\theta))}{Mr^2 + I_{et}N_f^2 N_t^2 + I_{dw}} + \frac{r(\eta N_f N_t T_e - T_b)}{Mr^2 + I_{et}N_f^2 N_t^2 + I_{dw}}, \quad (1)$$

where

$$I_{et} = I_e + I_t, \\ I_{dw} = I_d N_f^2 + I_w.$$

The designation of the variables is given in Table I. In the Model (1), the influence of the brake torque is ignored.

IV. FUEL CONSUMPTION MODELLING

A. The state-of-art of the fuel consumption model

The estimation and the prediction of the real fuel consumption play a key role in the eco-driving system. The eco-driving assistant system requires information on various signals from the

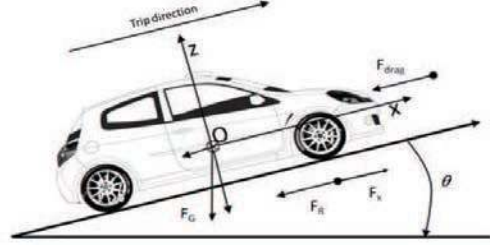


Fig. 2. The vehicle dynamics model.

vehicle (speed, position, gear number), environment (longitudinal headway spacing), road (legal speed limitation, road geometrical attributes) to compute such an optimal profile in terms of speed and gear number in order to minimise the vehicle fuel consumption. A large literature has been contributed to the modelling of the vehicle fuel consumption. Generally, there are 3 kinds of vehicle fuel consumption model:

- Instantaneous fuel consumption computes through the vehicle power, e.g. [3], [2] and [4].
- Instantaneous fuel consumption computes through vehicle speed and acceleration, e.g. [5], [6], [7].
- Instantaneous fuel consumption computes through engine speed and engine torque, [8], [9].

[5] gives a simple equation to calculate the instantaneous fuel consumption based on the vehicle speed and acceleration. Then, a complicated model based a 3-order polynomial of the vehicle speed and acceleration is proposed by [6]. Along the same direction, [7] uses only part of terms in [6] to calculate the vehicle fuel consumption.

Another way to model the vehicle fuel consumption is to use the vehicle power directly. [3] proposes a linear relationship of the vehicle power to calculate the instantaneous fuel consumption rate. An modified fuel consumption model using the vehicle power and the engine instantaneous speed is proposed in [2]. Recently,

the idea of using a 2-order polynomial of the vehicle power to compute the fuel consumption rate is developed in [4].

A new method to model the vehicle fuel consumption using the engine torque and engine speed is proposed in [8],[1] and [10]. The instantaneous fuel consumption is calculated by a linear combination of the engine torque and engine speed. Differently, a 2-order polynomial of the engine torque and engine speed to compute the vehicle instantaneous fuel consumption is proposed in [9].

It is difficult to say which kind of model is better than the others, since one kind of these models can be converted into the others kind of fuel consumption models. A comparison of these models are given in [11].

B. A new piecewise fuel consumption model

To extend our previous results ([11],[8], [1], [10]), A new vehicle instantaneous fuel consumption is proposed in this paper. The innovation of our new model is that a piecewise model is used to describe the non linear relationship among the instantaneous fuel consumption and the engine speed ω_e and engine torque T_e . According to the real fuel consumption data, we find that it is difficult to calculate the fuel consumption rate by a single equation. However, the engine map could be separated into some sub-areas which can be approximated by a single equation.

In our new fuel consumption model, the instantaneous fuel consumption rate FC is cut into several pieces according to the values of the engine speed ω_e and engine torque T_e , see Figure 3. First, we separate the entire engine map into some sub-areas in which the fuel consumption can be expressed by a single equation; Second, we estimate the parameters of the fuel consumption model in each sub-area. In each sub-area, the vehicle instantaneous fuel consumption rate is expressed by

$$FC = \sum_{i=0}^2 \sum_{j=0}^2 L_{i,j} \omega_e^i T_e^j. \quad (2)$$

The key problem of this modeling technique is to set the number of the sub-area and find the brake point of each sub-area. Generally speaking, the more the number of sub-area is, the more precise the model is. The brake point of each sub-area is detected by the least squares method. The shape of some sub-areas are regular, while the one of the others are not (e.g. $FC10$ in Figure 3).

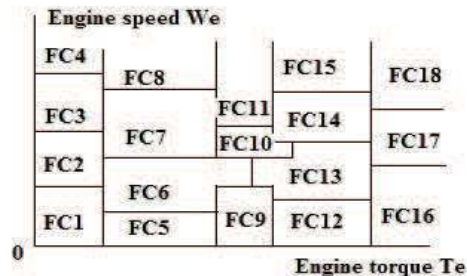


Fig. 3. Sub-area division of the engine map.

V. EXPERIMENTAL RESULTS

A. Test vehicle

A middle class manual transmission car, the RENAULT Clio 3 Eco 2 equipped with CAN fuel consumption measurements see Figure 4, is chosen in our experiments for its popularity in France. All the parameters of the powertrain model and the fuel consumption model are estimated from the real experimental data of the RENAULT Clio 3 Eco 2.

B. Test scenarios

Several basic scenarios are required for the validation of the powertrain model and the fuel consumption model to verify its coherence:

- SC1: Constant speed scenario - The driver will drive at a given steady speed v_c taken on the interval 10 to 130 km/h, with a different gear ratio N .
- SC2: Reaching a desired speed v_d from 30 to 130 km/h with change of every 10 km/h



Fig. 4. The test vehicle: RENAULT Clio 3 Eco 2.

- Starting at a null velocity, the driver has to accelerate to reach v_d then decelerates until stopping.
- SC3: Realistic scenario - On open road, the driver will travel 5 km at urban roads, interurban roads and highway.

C. Experimental validation of the model

To achieve the vehicle dynamics state, some sensors were installed in the test vehicle: Vehicle speed and acceleration sensors, engine speed sensor, acceleration pedal sensor and fuel flow meter. The speed is recorded using the vehicle own odometer. The fuel consumption is acquired from the CAN Bus channel. Its resolution of measurements is $80mm^3$. A RTMAPS (INTEMPORA, France) platform is used to guarantee the real-time data logging phase and registration. The experimental plan consisted in travelling on a dedicated route constituted of different road profiles.

The results of one real test are shown in the Figure 5, 5, 6, 7, 8, 9 and 10. The vehicle speed v is shown in Figure 5, the unit is km/h . The road slope and the gear number are shown in Figure 5. The corresponding engine torque and engine speed are shown in Figure 7 and Figure 8, respectively.

The instantaneous fuel consumption rate FC (mL/s) calculated from Model 2 are shown in Figure 9 in blue line, while the instantaneous fuel consumption rate read from the CAN bus is plotted in green line. It is clear that the estimated instantaneous fuel consumption rate

(blue line) could track its real value (green line) as a whole. The error occurs when this is a strong brake. This is because the influence of the brake torque is ignored in the Model (1).

The cumulated fuel consumption is shown in Figure 10, the blue line indicates the results estimated from the Model 2 and the green line indicates the results from the CAN bus. In Figure 10, we can see that the cumulated error of the fuel consumption calculated from our model is not big and the performance of our new piecewise model is confirmed.

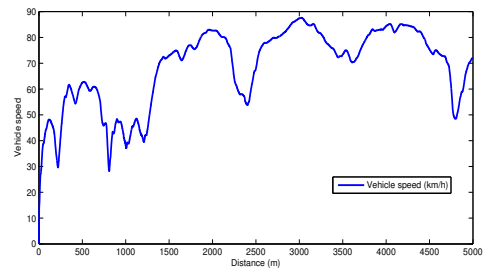


Fig. 5. Vehicle speed.

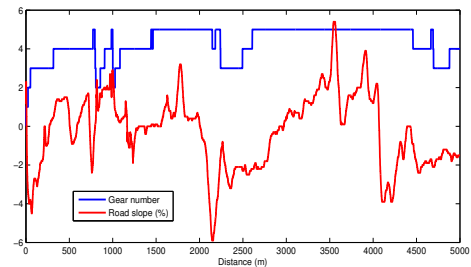


Fig. 6. The road slope and gear number

VI. CONCLUSIONS

An innovative fuel consumption modelling technique is proposed in this paper in order to develop an eco-driving assistance system. The vehicle fuel consumption is estimated by a piecewise polynomial of the instantaneous engine speed and the instantaneous engine torque.

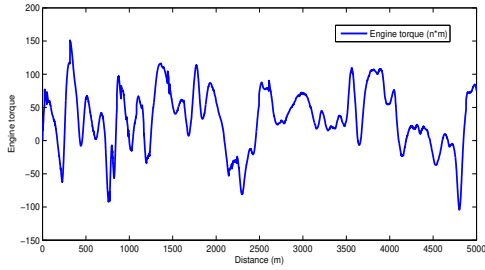


Fig. 7. Engine torque.

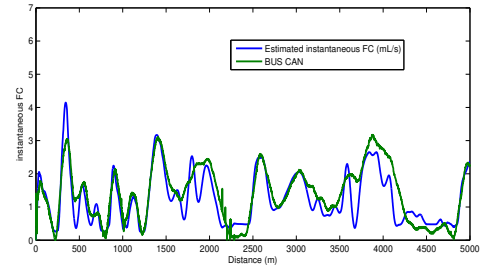


Fig. 9. Instantaneous fuel consumption rate FC .

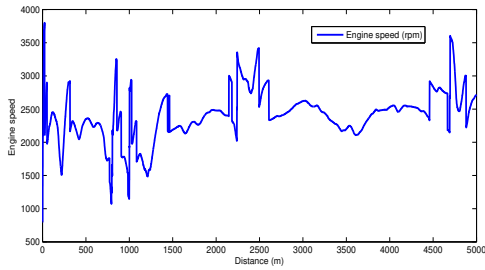


Fig. 8. Engine speed.

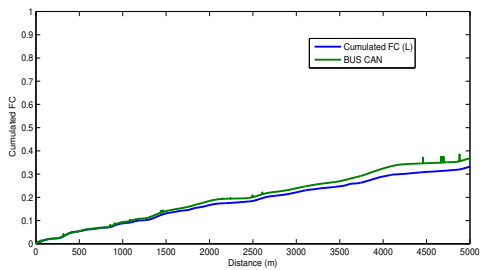


Fig. 10. Cumulated fuel consumption.

The accuracy of the model is improved through piecewise modelling technique. The key issues of this new fuel consumption model is to find the brake points of each sub-model.

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