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Modelling components for the fuel consumption investigation in Model In the Loop environment

Parameter tuning for an Ecological fully-Adaptive Cruise Control system

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Abstract— The research presented here is framed in the area of the design of Advanced Driving Assistance Systems (ADAS), carried out in the so-called automotive V-Cycle. In particular we concentrated our effort at the Model In the Loop (MIL) level. Indeed we developed an additional component for the fuel consumption evaluation at the MIL stage. The developed component has been based on the combination of a simplified model of the vehicle dynamics, and a fuel consumption model calibrated in previous experiments. The developed module is used for tuning the parameters of an Ecological fully Adaptive Cruise Control System.

I. INTRODUCTION

Transport systems are nowadays affected by serious negative externalities in terms of both pollutions and noises. It has been estimated that the impact of the transport sector is in the range of 20%-40% in terms of consumption of fossil fuels and emissions of greenhouse gases and particulate matter [1,2]. To limit and reduce those negative impacts, many fuel consuming and air pollution control policies have been taken in this sector, among which the promotion of sustainable transport modes [3], the improvement of the efficiency of traditional ones [4,5], or even the introduction of new mobility paradigms [6,7]. The problem can be tackled by transport engineers at different levels ranging from the setting of proper instruments for the evaluation, and implementation of strategies for the management of the mobility demand [8], to the suggestion of optimal route choice in order to limit CO_2 emission and fuel consumption for car users (eco-route; [9]), or also to the efficient operation of public transports both in ordinary [10], and in breakdown conditions [11-13]. Another relevant possibility is represented by the rise of Intelligent Transportation Systems (ITS) applications consequent to the introduction in the transportation sector of a massive quantity of Information and Communication Technologies (ICTs). Indeed ATIS - Advanced Traveller Information Systems [14,15], ATMS - Advanced Traffic Management Systems [16], and ADAS - Advanced Driving Assistance Systems [17], can be used altogether to improve the global efficiency of the transport sector.

The research presented here is framed in the area of driving behavior studies [18] for the design of Advanced Driving Assistance Systems (ADAS). ADAS are in-vehicle systems developed by using electronic control units (ECUs) and designed to supervise the safety, the comfort and/or the efficiency of the driving. Their design is carried out in the so-called automotive V-Cycle. In its basic architecture, the process is comprised of a three phases. In the Model In the Loop (MIL) the control logic characteristics and needs are conceived; in the second phase, Software In the Loop (SIL), the software needed to manage such a logic is developed; finally in the Hardware In the Loop (HIL) phase, the physical implementation of the ECU and the evaluation of its interaction with other, actually available, components of the vehicle (hardware sensors, actuators and other devices, and control units) is carried out.

An effective and promising technique to increase driving efficiency is eco-driving which is essentially based on the monitoring and control of driver behavior. It is defined as a decision-making process which influences the fuel economy and emissions intensity of a vehicle to reduce its environmental impact [19]. Eco-driving at the single vehicle/driver level can be achieved understanding what primarily affects fuel consumption, and by developing ADASs that help drivers in adopting efficient driving styles.

Generally speaking, the effects of a new ADAS logic on the fuel consumption of a single vehicle should be investigated by using a vehicle dynamics simulation software (e.g. [20]), commonly used in mechanical engineering for the testing of any vehicle component. However the execution of these kind of software is computationally demanding, and the characterization of vehicle parameters in the software is a burdensome activity too. On the other side, in the field of traffic engineering, microsimulation software are commonly used for the simulation of the interaction of vehicles in a traffic stream and the evaluation of the resulting traffic patterns. In this case microscopic fuel consumption models have been developed which have the advantage to compute fuel consumption by using kinematic quantities (and thus neglecting completely the vehicle dynamic); of course tuning opportunely parameters of these models allow to take into account different engine characteristics [21].

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The research described in this paper is placed at the MIL level, and is aimed at implementing a module for the simulation of fuel consumption in a MIL testing environment; the module try to take advantage of both approaches described before. The module is based on a simple model which computes fuel consumption by using kinematic variables, but also contemplates a representation (although simplified) of the vehicle dynamics that makes reliable input quantities of the fuel consumption model. The fuel consumption model is based on previous experiments, that have been described in next sections where also an explanation of the simplified model of the vehicle has been given. Furthermore an application of this module has been reported too.

The application concerns the tuning of the parameters of an Adaptive Cruise Control (ACC) for the increase of the efficiency of the system. Among ADAS, ACC systems are actively developed and introduced into the consumer market by vehicle manufacturers since some years. They extend earlier cruise control systems (CCC – Conventional Cruise Control) to cases when driving at a fixed constant speed is not possible because of traffic conditions. The implementation of eco-driving strategies for ACC is leading to the development of so called Ecological-ACC (Eco-ACC). Earlier examples of Eco-ACC can be found in [22,23]. The analysed system has been presented in [24], and its peculiarity is the human-like characteristic. This means that the control logic is not only focused on kinematic and physical considerations aimed at ensuring safety, but it is also mimic of personal driver's behaviours. Human likeness is retained to enhance users' acceptability.

However the implementation of the system is not our concern here; it is supposed to exist, and to be effective. Our concern here is the analysis of the control logic, with particular reference to ecological aspects, that is how to use the developed module to minimize fuel consumptions maintaining the human-like characteristics.

II. Methods

A. The fuel consumption model

The computation of fuel consumption is based on experiments reported in [25]. The model has been developed for the Instrumented Vehicle owned by the University of Naples, and calculates the Fuel metering (FM_{mgi}), which represents the milligrams of fuel consumed for each injection cycle. The estimation is based on a linear model, and requires the instantaneous knowledge of the speed (v), the acceleration (a), and the throttle position (Th):

$$FM_{mgi} = 9.53 + 0.005\, v^2 + 7.30\, a + 0.222\, Th \qquad (1)$$

It is straightforward to obtain FC_{inst} [l/s] from Fuel metering [mg i] by using the following formulation:

$$FC_{inst}\ [l/s] = (4xRPMxFuel\ Metering)/(2x1000x60x825) \qquad (2)$$

Where i) 4 is the number of cylinders in the engine; ii) RPM is rated for two because we have one injection each 2 RPM; iii) 1000 is used to switch from mg to g; iv) 60 is the number of seconds in one minute; and v) 825 is the density of diesel fuel expressed g/l.

Input variables of the model can be easily read by using the On-Board Diagnostic (OBD) port of the vehicle, that was validated in experiments carried out jointly with the Istituto Motori of the National Research Council (CNR) of Italy

B. Implementation of vehicle dynamic model

In the MIL environment the tested ECU is not installed on a vehicle, and thus to obtain realistic information about the vehicle responses to the control logic, a pre-requisite is the proper implementation of a model of the vehicle. The need, in this particular case, is the estimation of the fundamental variables used for the computation of fuel consumption associated to a reference trajectory.

To achieve the goals, we obtained the longitudinal behavior through a vehicle dynamics model that involves the application of a system of ABS. Given a target acceleration, the model tracks it, and the results is an 'effective' acceleration that minimizes the error. For this purpose, the difference between the target and the actual acceleration is used to control the two subsystems responsible for the speed change: engine and braking system. In particular, it is possible to outline the model implemented by some subsystems: Control Logic (Engine and Brakes), Gearbox, Vehicle Dynamics and Tyres. The engine has been modelled through a 'look-up table' that allows to get the torque curve of the engine. It is possible to enter in this table with the RPM in order to obtain the corresponding value of torque delivered by the engine at full throttle. RPM are obtained starting from the angular speed of the driving wheels, once the gear ratios and the differential ratio are known. By means of a PI controller, the error input is used to calculate the actual throttle applied to the motor, which is saturated between the limit values [0;1]. Multiplying this value for the torque, it is possible to obtain actual driving torque to the motor shaft. It evaluates the torque acting on the drive wheels, taking account of the transmission gearbox and differential, as well as the mechanical efficiency of the transmission. To model the braking system a second PI controller has been added: the input error is used to calculate the clamping pressure of the front disc brake caliper. The braking force explicated is reached from integration of such pressure on the tablet-brake disc contact area, then the braking torque. In order to make the model more realistic, an ABS system has been implemented; it allows to detect the possible locking of the wheels during an abrupt braking and to reduce the braking pressure, in order to ensure optimal braking effect and to allow the driver to handle the vehicle. The total braking and driving torques are obtained as output of 'Control Logic' subsystem, acting on all four wheels of the vehicle. It is very relevant to properly take in account tyres' behaviour on the road [26, 27], and in our case the 'Magic formula' by Hans Pacejka [28] was implemented, which solves the dynamics of the wheels and assesses the forces actually exchanged between the tyres and the road (taking into account the available grip and the vertical load acting on all four tires). In the 'Vehicle Dynamics' subsystem the equilibrium in the longitudinal direction is considered:

$$\dot{u} = \frac{1}{m} \times (F_{x1} + F_{x2} - X_a - X_r) \qquad (3)$$

where: i) $\dot{u}$ is Actual vehicle acceleration; ii) m the Total weight of the vehicle, iii) F_{x1} and F_{x2} are Forces overall longitudinal exchanged by each axle, iv) X_a is the Drag force and v) X_r: Rolling Resistance opposite the tires.

Knowing $\dot{u}$, it is possible to allow comparison with the desired acceleration, which frees up the input error to PI. By using the integration equation it is also possible to derive the ground speed of the vehicle and the distance traveled through a further integrations.

III. Application Case Study: Parameter Tuning for an Ecological Fully Adaptive Cruise Control

A. Background

The system presented in [24], is composed by four modelling layers.

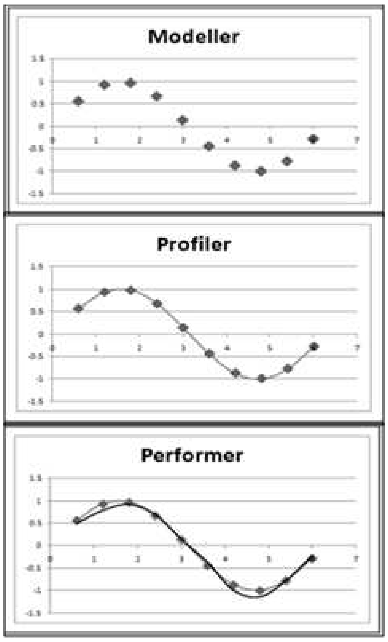

Fig. 1. The modelling layers which compose the described system

The first modelling layer (the modeller) is obtained by learning driver's preferences and is responsible for the main ACC control logic. It is aimed at suggesting a reference trajectory that the system must apply to ensure the human-like behaviour. The other modelling layers are responsible for putting into effects the reference trajectory. In particular the second (and last) modelling layer presented in [24] is the profiler. It is a crucial component to which is asked to translate the driving behaviours suggested by the modeller toward an admissible (continuous) kinematic profiles to be applied to the controlled vehicle. The third and fourth modelling layers are respectively the so called tutor and performer. The tutor ensures that the reference driving trajectory obtained by using the profiler is ultimately safe and so it can be applied by the performer. The performer is in charge of the actuation of the developed continuous (and safe) profile by controlling the vehicle actuators (e.g. the throttle, the breaks, etc.) and by interacting with the internal vehicles' dynamics and with the road. The performer assumes a relevant role in these experiments. The module introduced in the previous section is here used to implement the performer layer. Of course, once this module is used, also fuel consumptions associated to the ACC operation can be calculated.

B. Focus on the profiler

The responsibility of the profiler is to produce a time-continuous trajectory consistent with the request of the modeller. This is done by representing the trajectory of the controlled vehicle (and not the controlled vehicle itself) as a linear time invariant (LTI) dynamic system evolving in a time step Δt. This evolution is controlled (forced) in order to impose the request of the modeller, expressed in terms of desired displacement of the controlled vehicle. The dynamic system has two state variables, the acceleration and the jerk of the controlled vehicle. As usual for dynamic systems, it is important that the parameters of the model ensure the stability of the system (around the fixed point). For linear systems, stability is ensured by controlling the values of eigenvalues. Eigenvalues can be also related to the so called time constants (τ_1, τ_2) which in turns can be used to compute (with excellent approximation) the so called settling time (ts_1, ts_2) of the state variables, defined as the time elapsed from the application of an instantaneous step input to the time at which the state variable has entered a $\varepsilon_{\%}$ bound around the final (fixed-point) value.

It is out of the scope of this paper repeat here mathematical assumptions on which the derivation of the sampler is based, however it was shown in [24] that both the stability of the system, and a dynamic response compatible with sampler request are ensured by very mild assumptions on two parameters, ω and ψ. They must be different ($\omega \neq \psi$), and defined in the interval $]0,1[$. The two parameters play a relevant role in vehicle dynamic, since they influence the values of jerk and acceleration the profiler impose to the vehicle.

IV. Results and Discussion

A. Experiments

The analyses presented in this section have been based on the same dataset used in [24].

TABLE I. CHARACTERISTICS OF THE DATASET USED IN THE ANALYSIS

Driving Sessions					
Number	**Length (km)**			**Average Speed (km/h)**	
	Total	**Mean**	**St. Dev**	**Mean**	**St. Dev**
8	59	7.4	2.51	63.7	7.09
5	29	5.7	1.20	47.2	2.87

Data have been collected by using the Instrumented Vehicle owned by the University of Naples during 13 driving sessions. The driving sessions were carried out on two extra-urban roads near Naples; one route had few intersections and a higher average speed, the other more flow disturbance and a lower average speed. Respectively 8 and 5 driving sessions were carried out on each of the roads. Some information concerning data collected on each site are reported in Table I.

It is worth noting that each driving session is characterized by one leader's trajectory, while the human–like ACC produces a follower's trajectory on the basis of the behavior of the human driver observed in the same driving session. Experiments carried out in [24] concerned mostly with the analysis of the performances of the modeller, and for this reason the parameters of the profiler were fixed arbitrarily, and left constant in all the simulations. Results were based on 13 follower's trajectories, one for each driving session.

The aim of the experiment presented here is the understanding of the impacts on fuel consumption and vehicle kinematic of changes in the profiler parameters. For this reason, simulations have been made by using the same 13 leader's trajectories, but carried out varying time to time the ω and ψ according to constraints given in the previous section. It is worth noting that with reference to each driving session, the value of the two parameters is varied across the simulations, but is left constant during each simulation. In particular, ω and ψ have been varied in the interval [0.1-0.94] with a step of 0.14, and consequently for each of the leader trajectory, 42 follower's trajectories have been obtained as a result of the 42 simulations. The effect of the variation of the parameters has been investigated with respect to two aspects: the kinematic behavior of the controlled vehicle, and the efficiency of the driving.

B. Impact on the vehile kinematic

The profiler is designed in such a way that sampler requests are satisfied in Δt seconds. Varying the parameters ω and ψ produces slight variations in the system responses in terms of acceleration which reflects on the behavior of the vehicle in terms of actuated speed and displacement (and consequently in terms of relative speed and spacing from the leading vehicle).

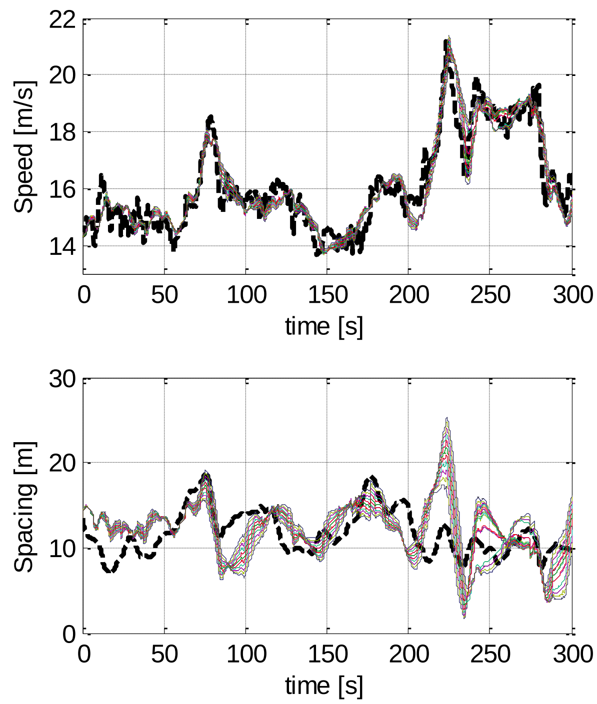

Fig. 2. The speed and spacing applied by the observed driver in the IV (bold line), and the ones reproduced by the ACC varying ψ and ω

In practice, given a leader's trajectory, one trajectory of the following vehicle can be determined from each simulation, and thus an envelope of the follower's trajectories is obtained once all 42 simulations concerning one driving session are carried out. The sensitivity of the vehicle kinematics with respect to the variation of the two parameters can be qualitatively deduced considering the width of the envelope, and its relative position with respect to the observed behavior. An example for one of the trajectories has been depicted in Figure 2.

The effects of these variations could be evaluated qualitatively by using the Percentage Error. The Percentage Error has been computed both with respect to speed and spacing, considering the absolute value of the difference between the speed (spacing) reproduced by the system and the one observed by using the IV; this quantity is rated to the observed speed (spacing). The cumulative frequencies of the Percentage Error for the trajectories of Figure 2 have been plot in next Figure 3 with reference to both speed and spacing.

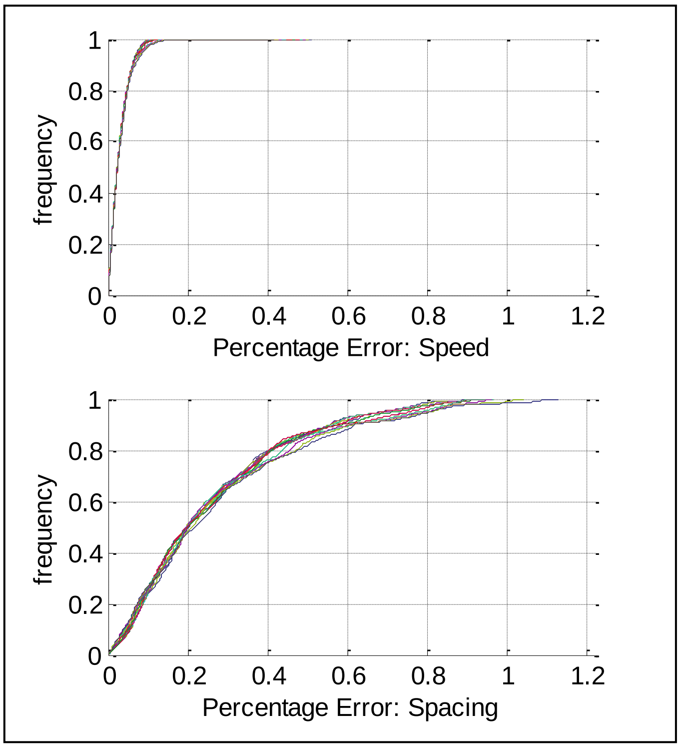

Fig. 3. Cumulative frequency of the Percentage Error computed for the trajectories depicted in Figure 2 with reference to both speed and spacing

Figure 3 confirms results of [24], where it was shown that the system reproduces observed behaviours in terms of speed very accurately; also the performance of the system in terms of spacing is quite satisfying, given that (for the case presented in Figure 3) the Percentage Error is lower than 20% in 50% of the cases, and lower than 60% in about 90% of the cases. Interestingly variations of the Percentage Error associated to the variations of the parameters ω and ψ are very negligible.

Considering all the simulations (all the cases for all the trajectories) the Percentage Error in 50% of the cases range in the interval [2% - 5%] and in the interval [17% - 45%] respectively in terms of follower's speed and spacing from the leading vehicle. This result are fully comparable with those reported in [24], thus it can be concluded that modifications in the two parameters do not affect significantly the macroscopic behavior of the system.

C. Effects on the fuel consumption

Once evidenced that the kinematic behavior of the system is not significantly affected by the variation of the parameters, the most interesting analyses can be carried out with reference to the fuel consumption. Indeed varying the parameters ω and ψ influences the values of jerk and acceleration the profiler impose to the vehicle. The consequence is that the instantaneous power, RPM, etc. requested to the vehicle can vary significantly within each simulation, and fuel consumptions alike.

This impact has been measured in terms of total fuel consumed in the driving session, obtained by integrating the FC_{inst} over the total duration of the driving session itself.

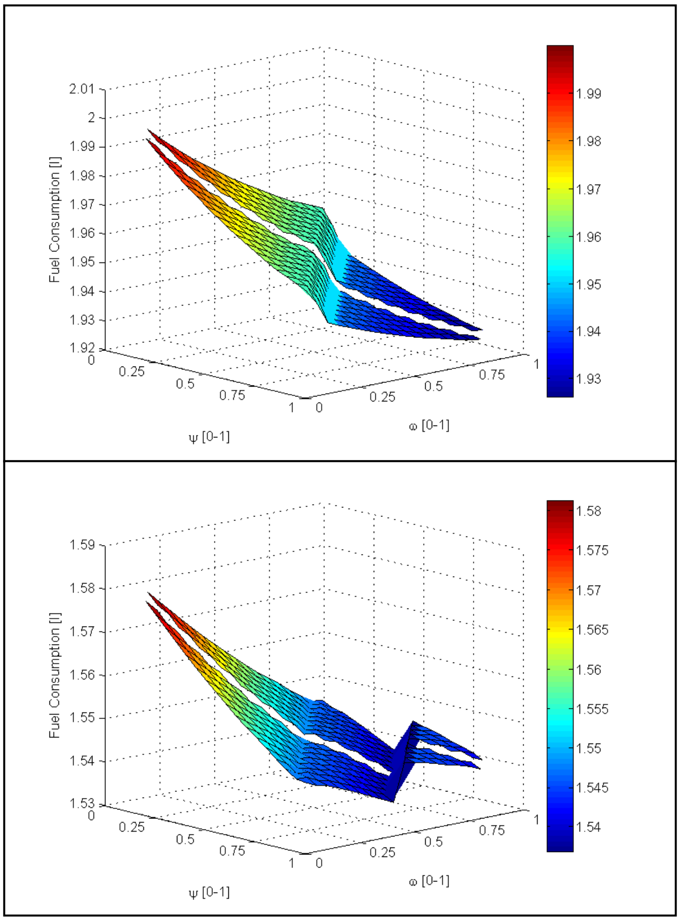

Fig. 4. The parameters tuning effect on the total fuel consumed showed for the 42 simulations concerning two different driving sessions

Two examples concerning the effects of the variation of the parameters have been reported in Figure 4. In the Figure the total fuel consumed for each of the 42 follower's trajectories corresponding to two different driving sessions have been reported. The colormaps show that the values of the parameters affect fuel consumptions with differences in the total fuel consumed of about 3% in both the cases.

Interestingly, in contrast with the first example, the second colormap shows that not necessarily the minimum total fuel consumed is attained when the values of the two parameters are the highest possible.

In any case, considering all trajectories similar results are found in terms of impact of the parameter tuning on the fuel consumptions, with differences on the total fuel consumed up to 4% between the best and the worst cases.

V. CONCLUSION

We showed that a simplified vehicle dynamic model coupled with a simple model for the estimation of the fuel consumption can be used effectively in the MIL environment for the optimization of the efficiency of the implemented control logics.

We also showed an application of this framework to the tuning of the parameters of an Human-like Adaptive Cruise Control. The system described is originally designed in order to reproduce the behavior of a real driver (once ensured that it is safe) and increase driver's acceptability; however we showed that the same goal can be achieved also optimizing the efficiency of the reproduced driving behaviour.

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