A MODEL FOR THE ENERGY MANAGEMENT IN A PARALLEL HYBRID VEHICLE

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Abstract

A model for the simulation of a parallel hybrid powertrain is proposed. The model is oriented to support the development of on-board energy flows control strategies to reduce both fuel consumption and emission levels and to improve electric driving range electric through optimal battery recharging cycles. The model has been developed in Matlab/Simulink environment with a modular structure. The adoption of a mixed modelling approach, based on different classes of models ranging from black-box Neural Network to grey-box mean-value dynamic models, allows a satisfactory accuracy with reasonable computational demand. Moreover, Fuzzy controllers have been implemented to simulate the Driver-Vehicle interaction, the torque management strategy (i.e. the splitting between electric motor and thermal engine) and the battery recharging strategy. Since the main goal of the research is the optimal management of on-board energy flows, an optimization procedure is underdevelopment to design the most suitable controllers. In this paper, a detailed description of the whole model is presented and the simulation results carried out for a real driving cycle are reported.

Introduction

In the last decade, the increasing restrictions imposed on the exhaust emissions from internal combustion engines and the traffic limitations in the urban areas have given a strong impulse toward the development of electrical propulsion systems for automotive applications. The goal of electrical and hybrid vehicles is the reduction of global emissions, which in turn leads to a decrease of fuel resources exploitation. Nevertheless, electrical vehicles seem far from being feasible in the next future because of some limitations, such as short driving distance, long recharging time and high costs. Thus, nowadays they are not considered as a realistic solution for the urban air pollution [1].

The hybrid vehicle is equipped with an electrical traction system, composed of a set of batteries and an electric motor/generator, coupled with an internal combustion engine (ICE). Depending on the energy management, two different configurations can be selected: series hybrid vehicles and parallel hybrid vehicles [1], [2], [3], [4]. In the series architecture, the ICE supplies the energy for recharging the battery and its size depends on the mean required power; therefore, the thermal engine works at constant load with reduced pollutant emissions, high reliability and long working life.

On the other hand, in the parallel architecture the two systems are mechanically connected to the transmission and can simultaneously concur to the vehicle traction. This architecture offers a major flexibility to different working conditions (i.e. mission profiles). However, both series and parallel configurations present all the advantages of the electric traction: limited pollution and acoustic impact, significant energy saving, and improved drivability.

In order to simulate the on-board energy flows (i.e. mechanical, chemical, kinetic, electrical) during arbitrary maneuvers, the proposed model accounts for the following working modes:

- Electric mode: the traction torque is provided only by the electric motor while the thermal engine is switched off. In such condition the power required to run the auxiliaries (such as air-conditioning unit, power steering etc.) is provided by a specific electric motor. This mode is suitable for urban areas due to the limited pollutant emissions from the thermal engine.
- Hybrid mode: the electric motor assists the thermal engine during the traction by providing an additional torque.
- Recharging mode: the thermal engine provides the torque for both vehicle traction and battery recharge.
- Regenerative braking: during vehicle deceleration (either braking or motored) the electric motor works as a generator for the battery recharging by converting the vehicle kinetic energy into electrical energy.

In the model, the above modes are selected as function of mission profile, urban or extra-urban route, battery state of charge (S.O.C.) and engine / motor characteristics.
The whole model has been linked to an optimization framework based on the genetic algorithm approach to design the optimal control strategies for reducing exhaust emissions and fuel consumption [5], [6], [7]; at the present this activity is in progress and in the following the model components will be described and the results of a preliminary application will be discussed.

System Configuration

In Figure 1 a sketch of the parallel hybrid vehicle is shown: the powertrain has a spark-ignition engine (4 cylinders with 16 valves and 1242 cm^3) and an electric asynchronous three-phase motor/generator (30 kW); a lead-acid battery package is considered for the electric energy storage. A cogged belt connects the thermal engine and the electric motor and an electromagnetic clutch decouples the engine from the drivetrain [6]. In order to focus the attention on the energy management and to reduce the computational effort, the driveline has been simulated as a rigid body neglecting torsional elasticity and clutch dynamics [7].

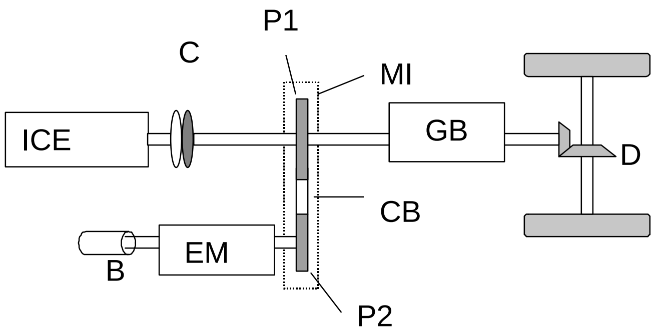

Figure 1 - Parallel hybrid vehicle powertrain - ICE=Internal Combustion Engine; C= Electromagnetic Clutch; P1, P2=Pulleys; MI=Mechanical Interface; GB= Gear Box; D= Differential Gear; CB=Cogged Belt; EM=Electric Motor; B=Battery.

Model description

In order to simulate the hybrid vehicle during a generic driving mission, the developed model describes the main powertrain components and simulates the driver behaviour in following the velocity target. A block diagram of the complete system is sketched in Figure 2 where all the main physical sub-models, the control tasks and the mechanical torque paths are shown.
The Driver Behaviour (DB) model is based on the fuzzy logic approach and provides the actual gas pedal position in following a velocity mission profile.
The pedal position and its derivative can be considered as an information on the instantaneous torque required for the traction. This latter is estimated through the Driver Interpreter block (DI) and is split into thermal and electric torque demand by means of the Torque Splitter controller (TS) whose control action depends on working modes (i.e. electric, hybrid, recharging and regenerative braking) as well as on battery state of charge, route condition (i.e. urban, extra-urban) and residual mission profile. Both the Driver Interpreter and the Torque Splitter are Fuzzy Logic controller.

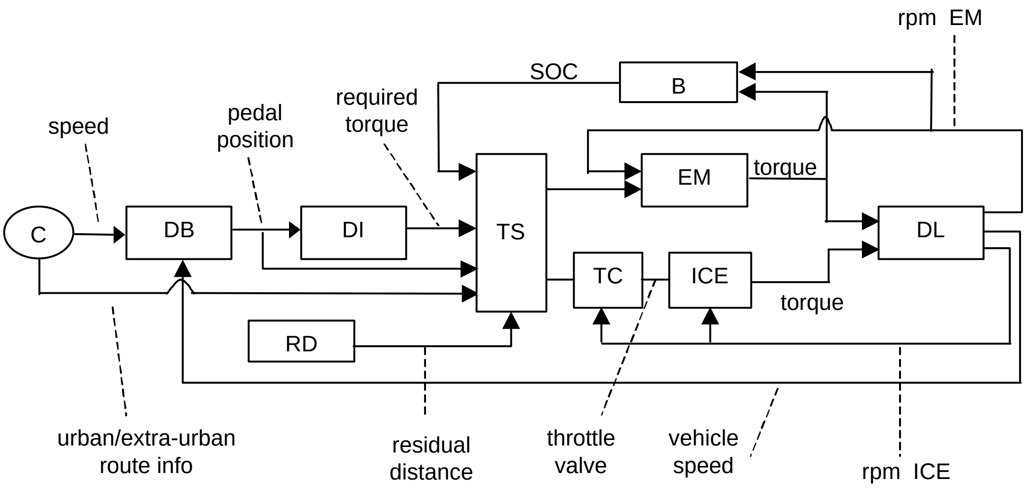

Figure 2 - Block diagram of the parallel hybrid vehicle powertrain model with the driver sub-model (DB) interface. - C = Mission Profile; RD = Residual Distance; DI = Driver Interpreter; TS = Torque Splitter; TC = Throttle Controller; ICE = Internal Combustion Engine; EM = Electric Motor; DL = Driveline; B = Battery Package.

In order to simulate the SI engine (ICE), the Throttle Controller (TC) evaluates the actual throttle opening as function of the demanded thermal torque and the engine speed. This controller is based on a two-dimensional look-up table derived from experimental data. The throttle opening is then used as input together with the engine speed for the internal combustion engine model.
The electric torque demand is computed by the Torque Splitter and the effective delivered torque is estimated accounting for the Electric Machine (EM) efficiency stored into a look-up table. The torque provided by the electric motor and the thermal engine are used as input for the driveline model (DL) to compute the actual rotational speed of EM and ICE and vehicle velocity by means of the Newton law. In the DL model, a rigid body from the crankshaft to the tires is assumed and the effects of aerodynamic losses and rolling friction are considered.
During the battery recharging the torque to the generator is supplied by the ICE (recharging mode) or by the DL (regenerative braking mode). Then the battery state of charge (SOC) and the residual distance from destination are updated. In the following sections a description of each block is provided.

Internal Combustion Engine Model

The engine (the ICE block in the Figure 2) has been simulated making use of two different models, depending on the goals and the phenomena to be studied. The first model is a black box, steady state neural network which provides the engine torque as function of the throttle opening and the engine speed [7], [8]. This approach is used for the control strategy design and optimization, which requires the recursive evaluation of a cost function and can be based on either mathematical programming approach or genetic algorithms. On the other hand, the second model has been derived from the O.D.E.C.S. code, developed by the authors for the optimal design of engine control strategies for spark ignition engines [7]. This more detailed model is used when the dynamic effects of the air-fuel flow into the intake manifold have to be described especially when fast transient maneuvers are analyzed (eg. to check gear shifting, clutch maneuvers, throttle opening actuation strategies).
In the Figure 3 a block diagram of the more accurate engine dynamic model is shown. The figure exhibits the main physical sub-models corresponding to the Air-Fuel manifold dynamics, the in cylinder process and the engine control unit (ECU).
The Air-Fuel dynamics is described by means of zero dimensional filling-emptying mean value models, neglecting the unsteady fluctuations due to periodic phenomena. This approach guarantees a detailed description within the frequency spectrum of interest for control application with limited computational demand, as it has been widely shown in several application [11], [12], [13]. The intake manifold block is composed by two dynamic subsystems. The air dynamic model computes the airflow rate through the throttle body and the engine port, while the fuel dynamic model describes the effects due to the fuel wall wetting and evaporation in order to estimate the actual port air/fuel ratio which strongly influences engine torque and emissions.
Due to the need to limit the computational time with satisfactory precision, the in-cylinder processes for torque and pre-catalyst emissions estimation have been described making use of black-box neural network models, based on the synthesis of steady-state experimental data [7], [8]. The effects due to the powertrain dynamics and the engine control strategies are considered by means of the input signals (engine speed, air mass flow, AFR and spark advance) derived from intake manifold and driveline dynamic models and from the ECU module. A detailed description of the Neural Network approach is beyond the scope of the paper; for a detailed analysis of the present application, the reader is addressed to previous papers [8] and to the specific literature [9], [10].
An engine control unit module (ECU) has been developed in order to simulate the effects of different control strategies. The main objective concerns with Air-Fuel ratio control in order to guarantee optimum catalyst performance, especially in throttle transients because of the different dynamics of air and fuel flow. According to this goal the ECU module library offers a selection of several engine control strategies, which are mainly composed of a closed loop lambda control and a model based fuel film compensation [7].

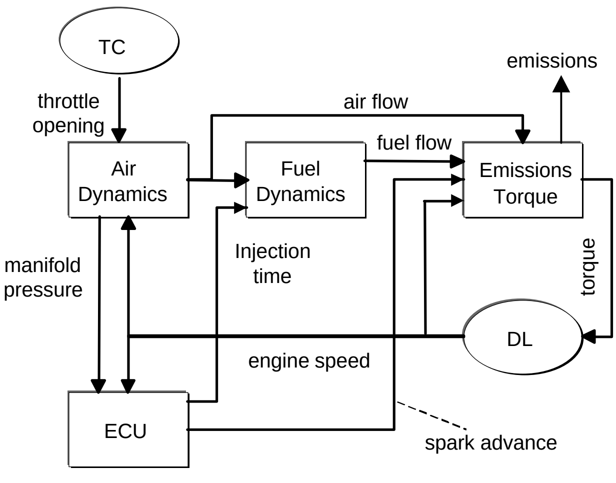

Figure 3 - Internal Combustion Engine Model (ICE); TC and DL are the blocks described in the .

Electric Machine Model

As already mentioned, in a parallel hybrid vehicle the electric machine can work as a motor or as a generator depending on the actual working mode (i.e. traction or recharging) [6], [15].
According to Guzzella and Amstutz [14], in order to reduce the computational effort, the behavior of the electric machine is modeled by means of a 2-D look-up table of the efficiency map, as function of the required torque and the motor/generator rotational speed. The efficiency map has been derived from literature data [15] and refers to an asynchronous motor with rated power of 30 [kW] at 9000 rpm, assuming the same values for both motor and generator working modes.
Depending on the electric machine working mode, the mechanical torque T_{EM} is given by the following equations [14] :

$$T_{EM} = T_{required}\ \eta(\omega, T_{required}) \tag{1}$$

$$T_{EM} = \frac{T_{required}}{\eta(\omega, T_{required})} \tag{2}$$

The former (eq. 1) holds in case of electric and hybrid working modes when T_{EM} corresponds to the traction torque (>0) supplied by the electric motor. The latter (eq. 2) holds in case of recharging mode when T_{EM} corresponds to the load torque supplied to the electric generator (<0). The $T_{required}$ is the torque demand estimated by the Torque Splitter controller.

Driveline

The driveline model describes the rotational dynamics of ICE, electric motor, transmission, final drive and wheels. It is described by a one state dynamic system, neglecting the clutch dynamics during gearshift, the torsional shaft deformation and the tire elasticity. This approach is suitable for simulating long transients where a global analysis on the dynamic behavior is required. However, a multi state dynamic model [17] has been developed for studies [6], [7] on comfort, gear shifting, vehicle – driver interface or clutch dynamics.
The driveline is modelled making use of the Newton's law, reducing all the load torque and the momentum inertia to the crankshaft; the aerodynamic losses and the tire rolling friction have been considered as resistant torque. Thus, the driveline dynamics is described by the following differential equation:

$$T_{ICE} + T_{EM} - T_{res} = Y \frac{d\omega}{dt} \tag{3}$$

where Y is the equivalent inertia of the engine-electric motor-vehicle system, T_{ICE}, T_{EM} and T_{res} are the thermal engine torque, the electric machine torque and the resistant torque respectively. In case of electric mode, the electric machine works as a motor and provides a traction torque (T_{EM} >0), while the ICE is decoupled from the main shaft and the inertia only accounts for the electric motor and the vehicle. In case of recharging mode, when the electric machine works as generator for recharging the battery, T_{EM} is considered as a load torque (T_{EM} <0).

Battery's Model

The Battery package (B) (see Figure 2) has been simulated using the ESS (Energy Storage System) block derived from the ADVISOR simulator [15]. This block models the battery taking into account the basic electrochemical processes including heat exchange phenomena as well. The computational block provides the battery state of charge (SOC), the actual current and other variables such as the current thermal state of the battery as function of the actual electrical power (i.e. positive or negative). The actual current is computed starting from the electrical power, making use of the Kirchhoff's voltage law [21]. For a complete description of the battery model the reader is addressed to the original work of Burch et al. [15]. For the current application the considered battery pack considered is composed by a set of 30 modules of valve-regulated lead-acid (VRLA) 12 V batteries [15].

Driver Model (DB)

In order to reproduce a vehicle mission profile, the human driving behavior has to be simulated. Actually, the powertrain model alone is not sufficient to simulate with accuracy the transient maneuver corresponding to a given speed mission profile. The actuation of throttle valve and brakes is indeed dependent upon physical and psychological factors as well as on the actual driving situation. Though the behavior of the driver is theoretically known, mathematical algorithms are not sufficiently realistic yet. Several approaches have been proposed in the literature, among others three techniques have been used addressing to classical control, fuzzy logic or a combination of them [18], [19]. The classical PID controller performs a robust tracking of a reference mission profile, but does not behave like a human driver. On the other hand driver models based on fuzzy logic theory address to human behavior but, they can only model part of the driver's cognitive process [19]. A more realistic hybrid model has been recently proposed by Kiencke et al. [18], which describes the complete cognitive process of the human operator by means of a combination of discrete event theory and classical control theory.

Table I - Rule base for Driver Model Fuzzy controller.

Acc.	A	O	ST	C	MC	MC	HC	HC
	LA	MO	O	ST	C	MC	MC	HC
	ST	HO	MO	O	ST	C	MC	HC
Dec.	LD	HO	MO	MO	O	ST	C	MC
	D	HO	HO	MO	MO	O	ST	C
		HS	MS	S	ST	F	MF	HF
		Slow				Fast		

Membership functions legend			
HS	High Slow	A	Acceleration
MS	Medium Slow	LA	Low Acc.
S	Slow	C	Close
F	Fast	HC	High Close
MF	Medium Fast	MC	Medium Close
HF	High Fast	O	Open
LD	Low Deceleration	MO	Medium Open
D	Deceleration	HO	High Open
ST	Steady		

In the proposed vehicle model, the control of the longitudinal dynamics is performed adopting a fuzzy logic controller. In order to reproduce both acceleration or deceleration transients the controller operates alternatively on the gas pedal or on the brake. The Fuzzy Logic controller has two inputs corresponding to the error between the target and the actual vehicle speed, and the actual vehicle acceleration and outputs the throttle opening or the braking intensity alternatively. The controller has been designed with seven membership functions for the first input and the output and five membership functions for the second input. The fuzzy inference process is based on the Mamdani method assuming the Fuzzy logical operator 'AND' (i.e. minimum operator). For the defuzzification the center of gravity method has been applied [20].

The rule set reported in Table I summarizes the controller output, reflecting the experience of the driver. An example of how the fuzzy controller interprets driver's behavior is the following: in case that the vehicle speed is greater than the reference speed and the vehicle is already decelerating, then an experienced driver would not brake hard but would just keep the throttle closed or eventually would brake only gently. This behavior is reflected by the rules in the lower right corner in Table I.

Driver Interpreter (DI)

The Driver Interpreter is a fuzzy logic controller which estimates the required torque to satisfy the driver intention by processing the actual pedal position and its gradient. On a spark ignition engine, this system is known as torque based control and is implemented for drive-by-wire systems in order to account for the lack of a mechanical linkage between the gas pedal and the throttle valve. In the current application the driver braking action is also taken into account. The controller outputs the current traction torque, to be generated by the whole propulsion system (i.e. electric motor and engine), or the braking torque.

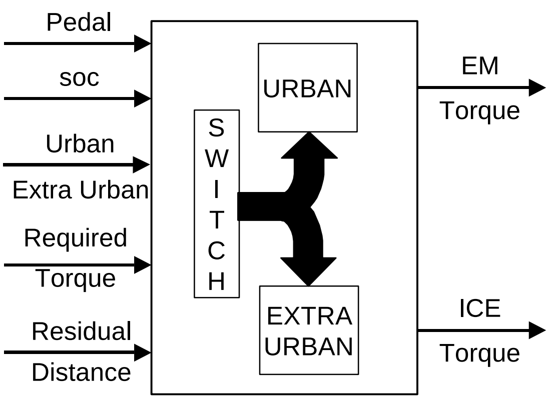

Figure 4 - Flowchart of the Torque Splitter (TS) controller.

Torque Splitter (TS)

The Torque Splitter is the main component of the hybrid vehicle control system since it manages the on-board energy fluxes. It determines the most suitable working mode (i.e. traction, hybrid, recharging, regenerative braking) with respect to the actual system status which is defined as function of the pedal position, the battery state of charge, the urban/extra urban flag, the required torque and the residual distance. Two different strategies are adopted depending on urban or extra-urban drive course by means of a logical switch operated by the driver. The controller computes the torque to be delivered by the thermal engine and by the electrical machine. This latter can be positive or negative depending on whether the electric machine works as motor or generator. In Figure 4 the flowchart

of the Torque Splitter is shown.
The adopted control strategies are based on the fuzzy-logic approach and have been designed considering the following main goals: i) to limit pollution in the urban area, ii) to account for low efficiency level of thermal engine at low load, iii) to have an adequate battery state of charge. The two strategies for urban and extra-urban cycles have been designed accordingly with the following criteria and the resulting control maps are shown in Figures 5 and 6.
Urban Cycle: during urban cycle the electric traction is assumed as default with the engine switched off and the hybrid mode is activated when the vehicle speed exceeds the threshold of 30 [km/h]. In this latter condition, most of the required traction torque is supplied by the engine and the electric motor provides the residual traction torque. As the battery state of charge decreases, the amount of engine traction torque increases in order to save the residual electric energy. This control behaviour is shown in the fuzzy control map reported in Figure 5. It is worth to mention that due to the need to limit pollution, the recourse to the engine is only allowed to provide the needed traction torque, without supplying any extra-torque for recharging the battery unless the state of charge is below 0.25. In such case the recharging mode is enabled and the engine powers the electric generator until a state of charge of 0.5 is reached.

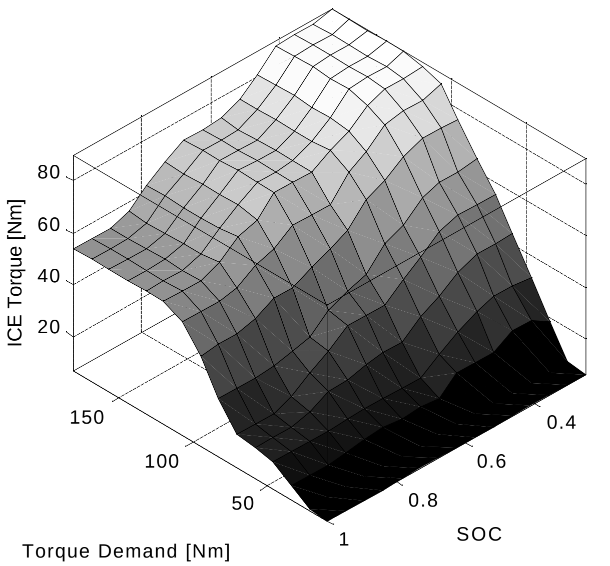

Figure 5 – Fuzzy control map for the ICE torque as function of SOC and traction torque demand for urban cycle – Hybrid mode.

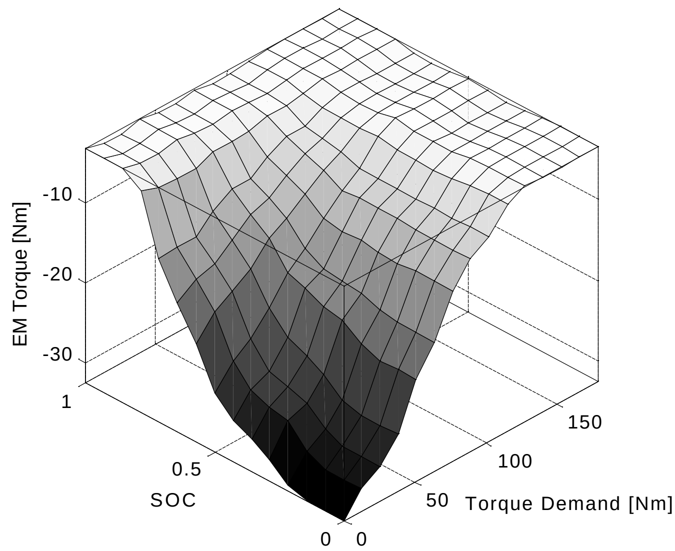

Figure 6 – Fuzzy control map for the recharging torque as function of SOC and traction torque demand for extra-urban cycle.

Extra-Urban Cycle: during the extra-urban cycle the vehicle works in recharging mode, the engine supplies the required traction torque and powers the electric generator for recharging the battery. As the required torque approaches the maximum engine torque, the power supplied to the electric machine is reduced in order to satisfy the traction torque demand. Moreover, when the torque demand exceeds the maximum engine torque, the hybrid mode is activated and the electric machine commutes from generator to motor, supplying the extra torque demand. In figure 6 the fuzzy control map of the recharging torque delivered to the electric generator as function of the battery state of charge and the traction torque demand is shown. The figure exhibits an increase of the recharging torque when the state of charge approach the minimum, unless the traction torque demand is close to the maximum engine torque. In such condition the recharging torque is strongly reduced and the hybrid working mode is eventually activated.
During both urban and extra-urban cycles, the regenerative braking mode is activated when the driver is braking, thus the vehicle kinetic energy can be converted into electrical energy for recharging the battery.

Throttle Controller (TC)

The throttle controller is located between the torque splitter and the ICE model (see Figure 2). According to the drive-by-wire system, the throttle controller provides the throttle opening as function of the engine torque demand, evaluated by the energy management system (torque splitter). Then the throttle opening is assumed as input for the IC engine model to simulate the engine behavior and to estimate the effective engine torque, the pre-catalyst emissions and the fuel consumption.

For the current application, the throttle controller is a two-dimensional look-up table, derived from engine experimental data [6], with the throttle opening estimated as function of the engine torque demand and the engine speed.

Simulation Results

In the present section the results obtained during the simulation of a real vehicle journey are discussed. The analysis is oriented to test the whole model behavior with respect to a generic driving cycle, neglecting the high frequency dynamic phenomena, such as air-fuel flow response, elastic driveline dynamics, clutch engagement and gear shifting. The considered driving mission refers to a standard traffic condition and accounts for both a 4.2 [km] (756 [s]) urban route and a 9.5 [km] (454 [s]) extra-urban route with vehicle speed ranging from 10 to 60 [km/h] and from 40 to 100 [km/h] respectively, as shown in Figure 7. A stationary speed of 7.78 [km/h] is assumed for the first 140 [s] and an initial battery state of charge of 70 % is considered.
The Figure 7 shows an excellent agreement between the target and the instantaneous vehicle speed; the two profiles are superimposed evidencing the satisfactory features of the driver behavior model. In Figure 8, the torque demand estimated by the Driver interpreter (DI) is plotted together with the electric and ICE torque, derived from the Torque Splitter (TS) depending on the actual working mode. As it emerges from the figure, the electric mode is enabled during the urban cycle up to 580 [s], when the vehicle speed is below 30 km/h. From 580 to 756 [s] the hybrid mode is activated and part of the demanded torque is supplied by the engine. During the extra-urban route, the recharging mode is activated and the ICE provides both the required traction torque and the recharging torque. It is worth to notice that when the traction torque demand approaches the maximum engine torque (in the interval 920 ÷ 960 [s]), the recharging torque is zeroed and the hybrid mode is activated, allowing the electric motor to supply the extra torque demanded for the traction.
The battery state of charge (SOC) is plotted vs. the simulation time in Figure 9. Its profile exhibits a reduction during the urban cycle up to 756 [s], when the electric and hybrid modes are enabled. A deeper gradient of SOC is detected from 520 to 670 [s], when a higher torque is supplied by the electric motor. During the extra-urban route, the SOC increases due to the recharging operation, apart from the range from 860 to 920 [s] when the electric motor supports the engine in providing a peak traction torque demand. At the end of the whole transient of 1210 [s], the final value of SOC is slightly reduced with respect to the initial one, by 7%.
In Figure 10 the tail-pipe exhaust emissions (HC, CO, NOx) are plotted versus simulation time. In the urban cycle, the emissions levels are zeroed during the electric operation up to 580 [s], while they start to increase when the hybrid mode is enabled. The higher values of exhaust emissions are reached when the engine operates at full load.
The advantages of hybrid vehicles regarding to exhaust emissions and fuel consumption (i.e. engine efficiency) have been evidenced by means of a comparison with an equivalent conventional vehicle equipped with the IC engine only and with a mass reduced by an amount of 400 kg to account for the absence of both battery pack and electric motor. The comparison has been performed vs. the vehicle mission considered herein (see Figure 7). Regarding to exhaust emissions, the results summarized in Figures 11, 12, 13, exhibit a dramatic reduction of HC, CO and NOx in the urban area, with an increase in the extra-urban area. Concerning the exhaust gas emitted along the whole transient, a slight reduction is detected for CO while HC and NOx levels are slightly higher with respect to the conventional ICE vehicle. This behavior is due to a higher engine torque supplied during the extra-urban route in order to recharge the battery. Regarding to specific fuel consumption, the hybrid vehicle exhibits an improvement along the whole cycle (from 462 to 354 [g/kWh]) and in the extra-urban area, as it emerges from Figure 14. On the other hand a slight increase of fuel consumption can be detected in the urban route, since the engine runs at very low load in order to strongly limit pollution in the city area. The proposed model allows to simulate both the decisional component and the electromechanical systems of a hybrid vehicle. The results show that it can be a useful tool for the energy control system design in order to meet the stringent pollution regulations in the city area with a significant improvement of the energy conversion efficiency. Further improvements in this direction can be obtained by means of an accurate optimization of the parameters for the fuzzy logic controllers.

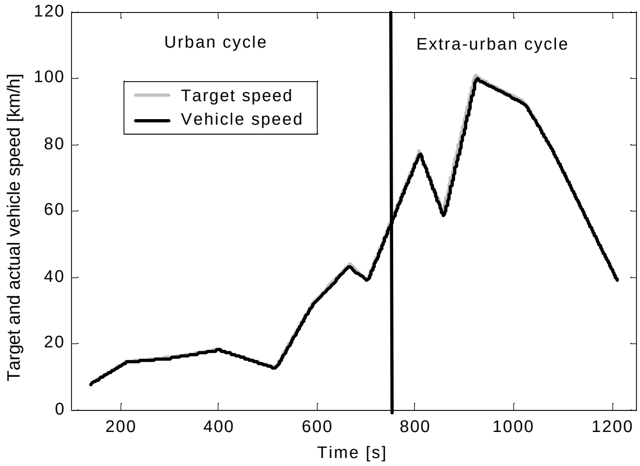

Figure 7 - Target and actual vehicle speed for the simulated transient.

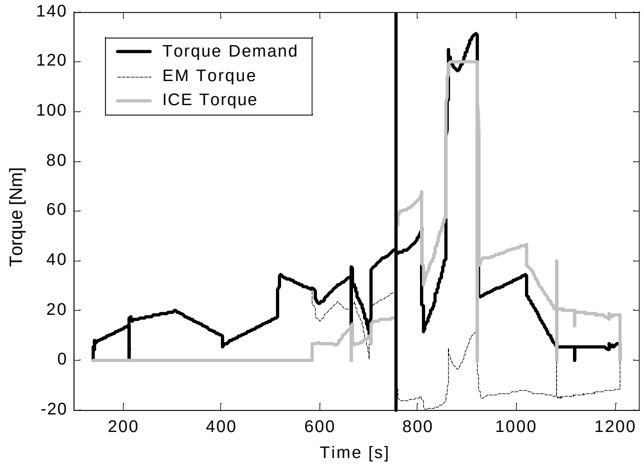

Figure 8 – Torque demand, engine torque and electric torque vs. simulation time .

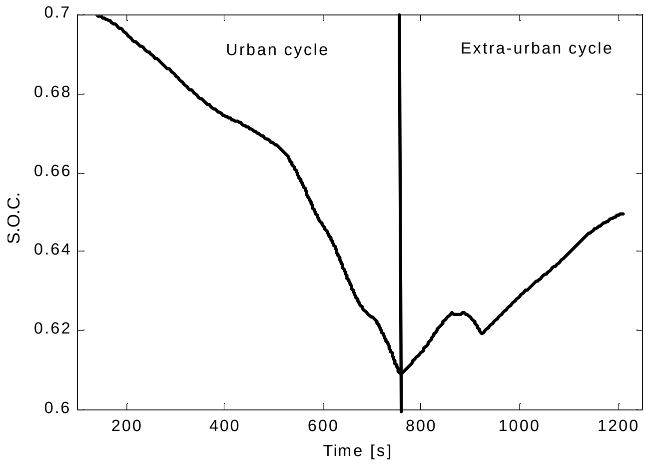

Figure 9 – Battery state of charge (S.O.C.) vs. simulation time.

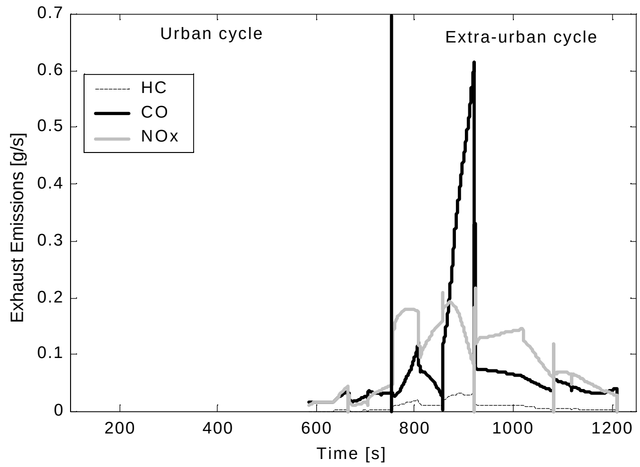

Figure 10 – Tail-pipe HC, CO, NO exhaust emissions vs. simulation time.

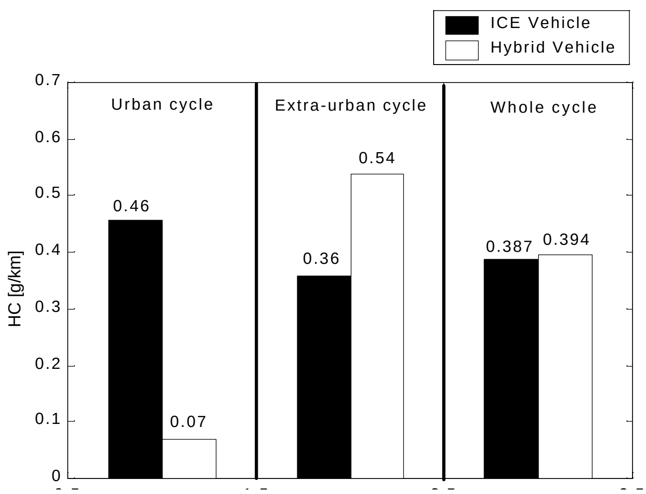

Figure 11 – Comparison of HC emissions for ICE and hybrid vehicles.

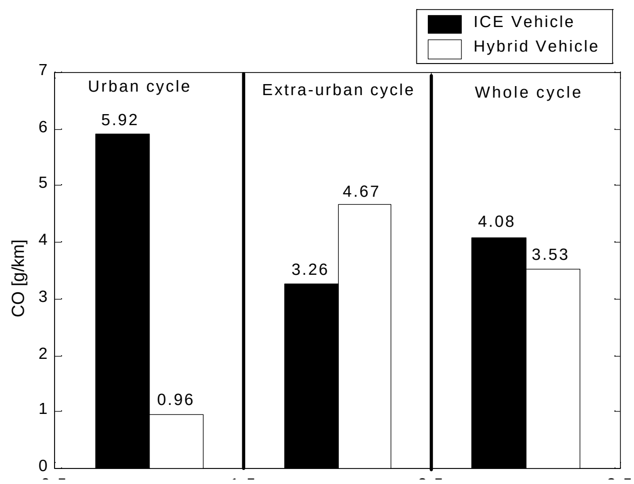

Figure 12 – Comparison of CO emissions for ICE and hybrid vehicles.

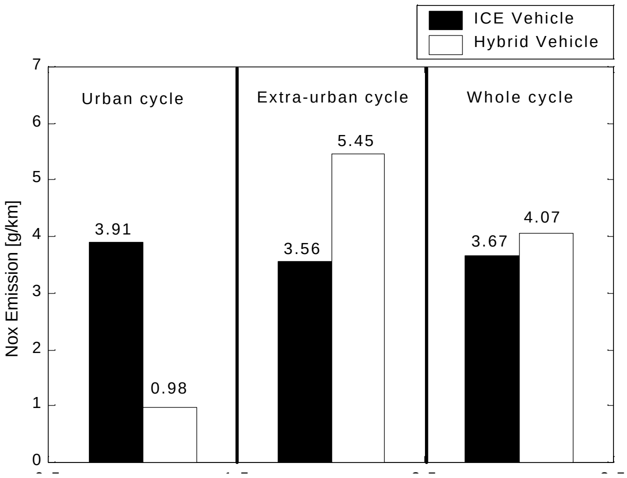

Figure 13 – Comparison of NOx emissions for ICE and hybrid vehicles.

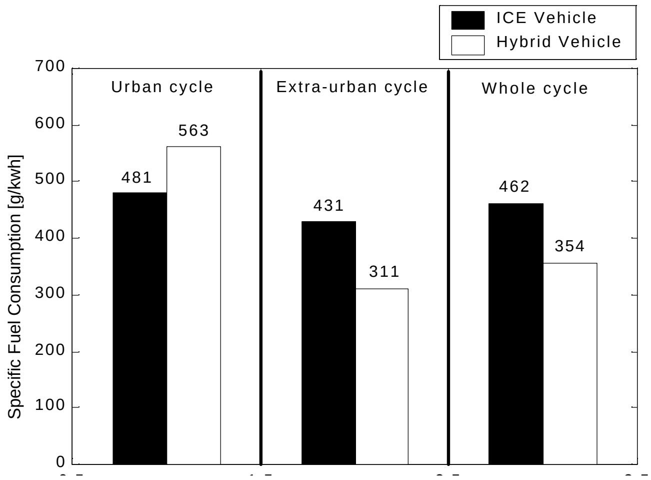

Figure 14 – Comparison of specific fuel consumption for ICE and hybrid vehicles.

Conclusions

A simulation model of a parallel hybrid powertrain for the design and the optimization of on-board energy management has been presented. The model estimates both engine and vehicle dynamic states and control parameters (speed, battery state of charge and required torque) and also accounts for the mission profile. Each physical subsystem has been modelled by either an independent block or a library of sub-blocks, in Matlab/Simulink environment. The main system controller manages the torque partition between the thermal engine and the electric machine and is based on a fuzzy-logic approach. It has been designed to limit both the fuel consumption and the exhaust emissions during urban driving cycles.
The model has been tested on a real driving cycle, with an excellent accuracy in following the target speed. Moreover, the adopted energy management strategy has shown the expected improvement of the whole energy conversion efficiency with respect to a standard vehicle equipped with a ICE together with a strong reduction of the emission levels during urban operation.
Further work is underdevelopment to embed the developed model into an optimization framework for the optimal design of control strategies to further improve the energy efficiency and reduce emission levels during urban and extra-urban driving cycles.

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