Modeling of the THS-II series/parallel power train and its energy management system

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F2010-B-107

MODELING OF THE THS-II SERIES/PARALLEL POWER TRAIN AND ITS ENERGY MANAGEMENT SYSTEM

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KEYWORDS – Hybrid power train, power-split eCVT, rule-based control strategy, Toyota Hybrid System, driver's attitude, auxiliary consumption, dynamic forward-facing model.

ABSTRACT – The hybridization of the conventional thermal vehicles nowadays constitutes a paramount importance for car manufacturers, facing the challenge of minimizing the consumption of the road transport. Although hybrid power train technologies did not converge towards a single solution, series/parallel power trains with a power-split electromechanical transmission prove to be the most promising hybrid technology. In fact, these power trains show maximum power train overall efficiency and maximum fuel reduction in almost all driving conditions compared to the conventional and other hybrid power trains.

This paper addresses the model and design of one of the most effective HEV power train: case study of the 2nd generation Toyota Prius. It presents the simulation work of the overall operation of the Toyota Hybrid System (THS-II) of the Prius, and explores not only its power-split eCVT innovative transmission system, but also its overall supervision controller of the mechanical and electrical systems. The kinematic and dynamic behaviors of the THS-II power train are explained based on the power-split aspect of its transmission through a planetary gear train. Then, the possible regular driving functionalities that result from its eCVT operation and the energy flow within its power train are outlined. A feed-forward model of the studied power train is next proposed, supervised by a rule-based engineering intuition controller. The model encloses the modeling of the vehicle dynamics, the power train dynamics and its associated overall governing matrix of its series/parallel operations, the power train components and their relative ECUs, in addition to the overall vehicle ECU and the battery ECU. A PID feedback controller emulating the driver behavior is used. It generates the acceleration and braking commands in order to enable the forward-facing simulation.

The model is then calibrated and validated with road test measurements realized on a MY06 Prius in Ile-de-France, in terms of the power train performance and energy consumption, taking into consideration the effect of the auxiliary consumption and the driver's attitude.

INTRODUCTION

The Toyota Prius, with its innovative power-split power train, is the most sold hybrid electric vehicle around the world. The advantage of its power-split power train is due to the eCVT transmission system, where the additional benefit comparing to the other parallel and series hybrid power trains comes mostly from:

- the optimized control of the engine operations decoupled from the wheels speed
- the electric drive mode avoiding low efficiency engine operations at low velocity driving
- the brake energy recovery during decelerations due to high power electric generator implemented and bigger battery capacity

This paper presents a model of the 2nd generation Toyota Prius and its THS-II power-split power train. The model simulates the overall operation of the power train, and explores the overall supervision controller of its mechanical and electrical components.

The kinematics and dynamics of the power-split power train of the Prius are briefly elaborated in the first section. As a result the governing matrix of its series/parallel operation is set up. Then, the overall architecture of the THS-II power train model is outlined. In the third section, a rule-based controller of the Prius is proposed, supervising the global operation of the power train, and instantly optimizing the power-split between the engine and the battery.

Finally, the model is validated experimentally through road test measurements on a MY06 Toyota Prius. The electromechanical performance of the power train model simulation results are first evaluated on constant velocity cruising, acceleration, braking, urban, highway and roadway driving conditions, comparing to road tests. Then, the energy consumption has been evaluated according to several urban and highway road driving tests realized, and to regulatory driving cycles. In addition, the effects of the auxiliaries and the driver's attitude on the energy consumption of the power train are carried out.

KINEMATICS AND DYNAMICS OF THE PRIUS SERIES/PARALLEL POWER TRAIN

The power train of the Toyota Prius has been fully analyzed in [1]: the kinematic and the dynamic behavior of the eCVT power-split transmission, in addition to its regular driving functionalities (engine start, e-Drive, power-split, boosting, e-Braking, etc.) with a normal energy flow and an energy recirculation flow within the transmission. Full details can be consulted in [1]. For the purpose of this paper, the overall operations (series and/or parallel) of the Prius power-split transmission are given in equation 1.

Solving equation 1 allows finding the two state variables of THS: the engine speed (ω_{ICE}) and MG2 speed (ω_{MG2} proportional to the vehicle velocity), as function of the three inputs: the engine torque (C_{ICE}), and the two motors/generators torques (C_{MG1} and C_{MG2}). Note that these torque inputs are specified through a control strategy, making decisions instantly of the value of each torque, depending on the operating condition of the vehicle. This control strategy is outlined in this paper.

$$\begin{bmatrix} 1 & \frac{1-k_b}{k_b} & 0 \\ 1 & 0 & 1-k_b \end{bmatrix} \begin{bmatrix} C_{ICE} \\ C_{MG1} \\ C_{MG2} \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ \gamma & \delta \end{bmatrix} \begin{bmatrix} \dot{\omega}_{ICE} \\ \dot{\omega}_{MG2} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1-k_b}{K_D} . R_W . \left(F_{resistive} + F_{brake}\right) \end{bmatrix} \quad (1)$$

General form: A . C = B . W + D
Solution : W = inv(B).(A.C-D)

with $\alpha = \left(\frac{k_b - 1}{k_b}\right)^2 \left(J_{MG1} + J_S\right) + \left(J_{ICE} + J_{PC}\right)$ $\quad \beta = \frac{k_b - 1}{k_b^2}\left(J_{MG1} + J_S\right)$

$\gamma = J_{ICE} + J_{PC}$ $\quad \delta = \left(\frac{1-k_b}{K_D^2}\right)\left(M_{veh} R_W^2 + J_W + J_a\right) + \left(1-k_b\right)\left(J_{MG2} + J_R\right)$

J: inertia; k_b: planetary gear train basic ratio; R_w: wheel radius; PC: planet carrier gear; S: sun gear; R:ring gear; K_D: differential gear ratio; F: force; ICE: internal combustion engine; MG: electric motor/generator

A third state variable is required in order to describe the electrical path of THS: the state of charge of the battery (SOC). It is computed using equation 2, where C_{max} is the maximum capacity of the battery, C_{ini} its initial capacity at the beginning of the simulation and I the current supplied by the battery. The maximum and initial capacities are set at the beginning of the simulation; however, the current is variable, depending on the power received or supplied by the battery during the simulation.

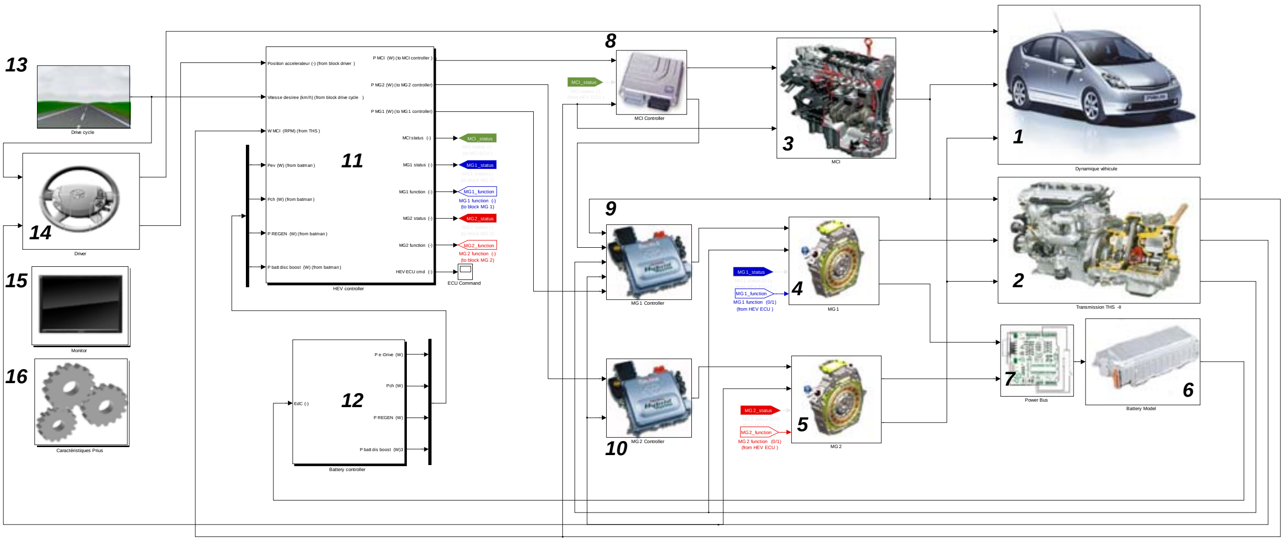
$$SOC(t) = \frac{C_{\max} - C_{consumed}(t)}{C_{\max}} = \frac{C_{\max} - \left[\int \frac{-I}{3600} dt + \left(C_{\max} - C_{ini} \right) \right]}{C_{\max}} \qquad (2)$$

OVERALL ARCHITECTURE OF THS-II POWER TRAIN MODEL

Figure 1 illustrates the THS-II power train simulation model realized in the Matlab/Simulink/ Stateflow environment. The model blocks can be identified in four main groups:

- Vehicle and power train dynamic blocks *(blocks 1 and 2)*
- Power train components: ICE, MG1, MG2, battery and power bus blocks *(blocks 3 to 7)*
- Power train ECUs: ICE, MG1 and MG2 controllers, HEV controller and battery controller *(blocks 8 to 12)*
- Driver and driving cycle blocks *(blocks 13 and 14)*

A closed-loop forward-facing approach has been used in this THS-II power train model. This approach forces the model to include a driver model that compares between the vehicle actual velocity and the reference velocity from the driving cycle block, in order to develop commands for accelerating or braking the vehicle. These commands (in addition to the SOC level of the battery) are interpreted in the HEV (and battery) ECU(s), which in turn determines the proper action of the power train and sends the power commands to the motors ECUs. Then, the power flow circulates from the THS motors and engine to the vehicle and the power train dynamic blocks, where the acceleration and the velocity of the Prius are deduced, and sent again to the driver model to be compared with the reference velocity. This process is repeated until ending the driving cycle.



1: Prius dynamics	***5: MG2***	***9: MG1 ECU***	***13: Driving cycle***
2: THS-II power train dynamics	***6: Battery***	***10: MG2 ECU***	***14: Driver***
3: ICE	***7: Power bus***	***11: HEV ECU***	***15: monitor***
4: MG1	***8: ICE ECU***	***12: Battery ECU***	***16: Prius characteristics***

Figure 1 : Overall architecture of THS-II power train model

The blocks are identified either as mechanical/electrical dynamic blocks (motor, battery, etc.), or as control blocks (motor ECU, battery ECU, etc.). For the control modules, as in the real Prius, two control levels are considered in the THS-II model [2]:

- *Components control level*, where each component is controlled by its own ECU to regulate its operation. For example, MG2 ECU monitors MG2 torque and speed, and the battery ECU monitors the SOC level of the battery.
- *Vehicle control level*, where the HEV ECU supervises the vehicle behavior by sending the proper commands to the components ECUs (required power, status (ON/OFF), function (motor/generator)), for satisfying the driver's target performance.

The mechanical/electrical blocks and their relative ECUs are not considered in this paper, and can be viewed in [1]. However, the following section concentrates on presenting the HEV ECU.

THS-II ENERGY MANAGEMENT STRATEGY

1. State Of The Art

This section describes the overall energy management of the power train in THS-II. Benefitting from two power paths: electrical (series path) and mechanical (direct parallel path), an overall vehicle supervisor is needed to decide the power splitting between the two paths, so that the vehicle is operated with the most efficient way.

Reviewing the existing literature, many different approaches are identified in energy management systems (EMS) for HEV power-split transmissions [3-9], that can be classified in terms of the cycle knowledge:

- No cycle knowledge: where HEV controllers include rules, based on engineering intuition and component efficiency maps that are intended to maximize vehicle efficiency
- Full cycle knowledge: where HEV controllers achieve maximum fuel economy over a known driving cycle, by using an overall optimization techniques such as Dynamic Programming
- Flexible forecasted knowledge about any cycle: where HEV controllers rely on route prediction from GPS and traffic information systems, to modify the control strategy

All actual commercialized HEV controllers are able to manage the vehicle in real time, and with no prior cycle knowledge. They basically fall into the rule-based category. This section explores a proposed HEV ECU of the THS-II model, relying on the rule-based engineering intuition (no cycle knowledge EMS), where a set of the THS-II power train driving functionalities are defined, and the choice of each driving functionality is decided by a set of conditions. Then, a set of rule commands is specified to each power train component to perform the driving functionality decided.

2. THS-II Control Strategy

2.1. HEV Controller

Referring to the Prius two control levels explored previously, the HEV ECU (in addition to the battery ECU) is the overall vehicle controller, which supervises the vehicle behavior by sending the proper commands to the components ECUs, for satisfying the driver's target performance. Thus, the HEV ECU receives as inputs the driver acceleration pedal request (and the battery request and thresholds from the battery ECU), and generates as outputs:

- ICE power request
- MG2 power request
- ICE, MG1 and MG2 status (ON/OFF)
- MG1 and MG2 function (motor/generator)

Figure 2 illustrates the HEV ECU block, divided into two main subsystems:

- 'Driver power demand' subsystem
- 'Power management distribution' subsystem

2.1.1. 'Driver Power Demand' Subsystem

This subsystem is in charge of translating the acceleration pedal position into a power value, requested by the driver using equation 3 and figure 3 (which represents the maximum traction force developed by the THS-II power train, as function of the Prius velocity).

The driver power demand serves as an input parameter to the power management distribution subsystem, for determining which hybrid functionality the THS-II power train must perform. Positive values of P_d allow the HEV ECU to decide between the traction driving functionalities of THS-II (engine start, e-Drive, power-split, boosting, etc.). However, when decelerating, a negative value is attributed to P_d, so the HEV ECU switches automatically to braking driving functionalities.

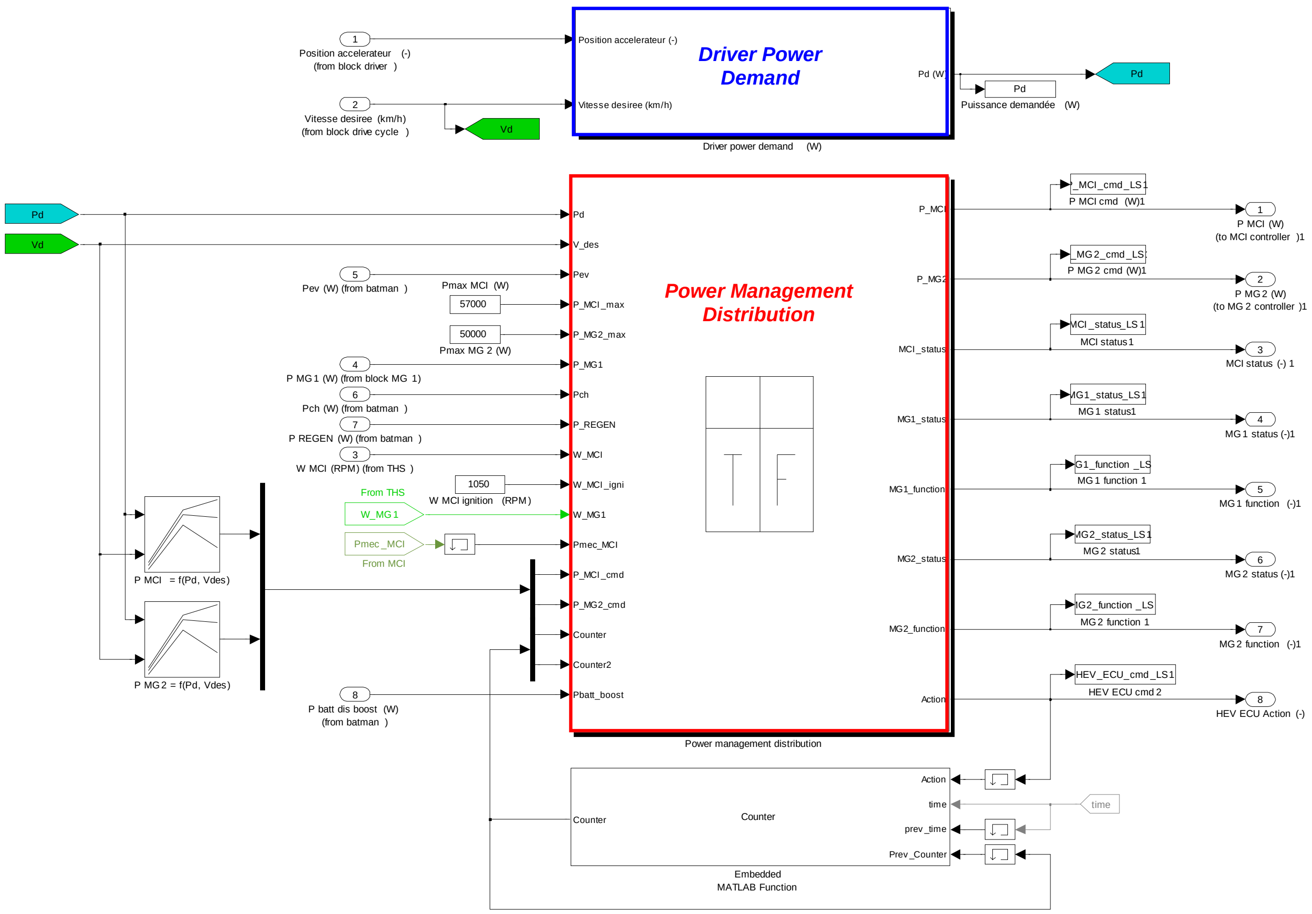


Figure 2: HEV ECU block

$$P_d = \begin{pmatrix} Driver\ pedal \\ position\ in\ \% \end{pmatrix} \cdot \frac{F_{Max\ Traction\ Force}\ V_{actual}}{100} \quad (3)$$

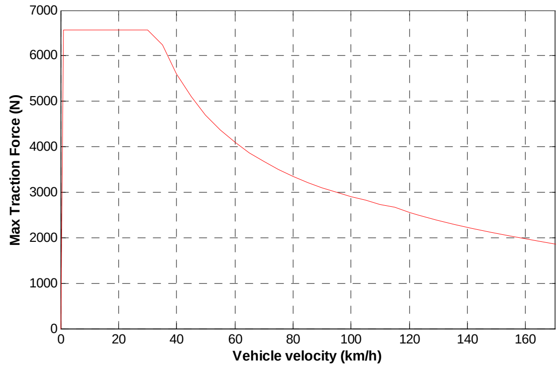


Figure 3: Max traction force of THS-II power train

2.1.2. 'Power Management Distribution' Subsystem

As mentioned above, the HEV ECU is a rule-based EMS, where no prior knowledge to any cycle is needed. The 'power management distribution' subsystem is the module where these rules are stored, and where the driver power demand (P_d) is managed and distributed between the THS-II power train components, so that the power train operates with its optimum efficiency. The rules set in this subsystem are used for identifying two tasks:

1. identifying the instantaneous THS-II most suitable driving functionality
2. generating the corresponding commands to the power train components

Table 1 summarizes this rule-based EMS, with the first task rules titled '*driving functionality conditions*', and the second task rules '*driving functionality commands*'. Note that the THS-II driving functionalities are gathered in the table as neutral, traction and braking driving functionalities. Each of them is detailed below. Full details will be presented in a future paper, dedicated for exploring in details this rule-based EMS.

THS-II driving functionality	Driving functionality *CONDITIONS*	Driving functionality *COMMANDS*		
Neutral driving functionalities				
		ICE	*MG1*	*MG2*
Ready ON (vehicle at rest)	*$(P_d=0)$ & $(P_{ch}<=P_{ch,\ critical})$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Engine start (vehicle at rest)	*$(P_d>0)$ & $(P_{ch}>P_{ch,\ critical})$ & $(\omega_{ICE}<\omega_{ICE,\ Idle})$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Ready ON with battery charging (vehicle at rest)	*$(P_d=0)$ & $(P_{ch}>P_{ch,\ critical})$ & $(\omega_{ICE}>=\omega_{ICE,\ Idle})$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Traction driving functionalities				
e-Drive	*$(0<P_d<P_{ev})$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Engine start with vehicle in e-Drive mode	*$(P_d>=P_{ev})$ & $(\omega_{ICE}<\omega_{ICE,\ Idle})$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Power split	***Normal energy flow:*** *$(P_{ev}<=P_d<=P_{ICE,\ Max})$ & $(\omega_{ICE}>\omega_{ICE,\ Idle})$ & $(\omega_{MG1}>=0)$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
	Energy recirculation flow: *$((P_{ev}<=P_d<=P_{ICE,\ Max})$ & $(\omega_{ICE}>\omega_{ICE,\ Idle})$ & $(\omega_{MG1}<0)$*	P_{ICE} = status =	status = function =	P_{MG2} = status = function =
Boosting	***Maximum boosting constraint respected:*** *$(P_d>P_{ICE,\ Max})$ & $((P_d-P_{ICE,\ Max})<=P_{batt\ boost\ Max})$*	P_{ICE} = status =	status = function =	P_{MG2} = $P_{batt\ boost}$ = status = function =
	Maximum boosting constraint exceeded: *$(P_d>P_{ICE,\ Max})$ & $((P_d-P_{ICE,\ Max})>P_{batt\ boost\ Max})$*	P_{ICE} = status =	status = function =	P_{MG2} = $P_{batt\ boost}$ = status = function =
Braking driving functionality				
e-Brake	*$(P_d<0)$*	P_{ICE} = status =	status = function =	P_{MG2} = Status = function =

Inputs:		P_{ICE}	*Actual engine power*	P_{ev}	*e-Drive max power threshold*
P_d	*Driver power demand*	P_{MG1}	*Actual MG1 mechanical power*	$P_{ICE,\ Max}$	*Engine max power*
P_{ch}	*Battery charging power request*	P_{Drive}	*Engine power command needed for driving the Prius*	$P_{MG2,\ Max}$	*MG2 max power*
ω_{ICE}	*Actual engine speed*			$P_{batt\ boost\ max}$	*Max allowed battery discharge power for boosting*
ω_{MG1}	*Actual MG1 speed*	**Thresholds:**		$\omega_{ICE,\ Idle}$	*Idle engine speed*
P_{REGEN}	*Braking regenerative power*	$P_{ch,\ critical}$	*Critical battery charging power request*		

Table 1: Rule-based EMS of the THS-II model - 'Power Management Distribution' subsystem

2.2. Battery Controller

The Toyota technical documentation shows in [10] that the function of the battery ECU is to monitor the conditions of the battery (SOC and temperature). In the model, the thermal behavior of the battery is not taken into consideration, thus the battery controller manages in real time the charging/discharging conditions of the battery: it monitors the actual SOC of the battery and generates the corresponding charging power request and the maximum allowed power thresholds, requested by the HEV ECU.

The battery ECU block supervises the following operating conditions:

- e-Drive power management (P_{ev}): This subsystem determines the maximum allowed power (P_{ev}) to be drawn from the battery for an e-Drive mode operation as function of the battery SOC and the vehicle speed. Thus, if the driver power demand (P_d) is lower than the resulting (P_{ev}), the HEV ECU commands the Prius to go on in electric mode; and in the opposite case, the controller switches to the power-split mode, since the battery is not able to deliver sufficient power to propel the vehicle in electric mode. This P_{ev} threshold is determined from road test measurements achieved on the Prius.
- Charging power management (P_{ch}): This subsystem determines the instantaneous P_{ch} requested for charging the battery in this model, as a function of the instantaneous SOC. So, when the HEV ECU operates in power-split mode, the corresponding P_{ch} value is added to the driving power request, for maintaining a sufficient energy level in the battery.
- Regeneration power management (P_{REGEN}): This subsystem corrects the P_{REGEN} value to be transmitted to the HEV ECU, referring to the actual battery capacity to receive braking power.
- Boosting power management ($P_{batt\ boost\ max}$): This subsystem sets the allowed battery power for boosting ($P_{batt\ boost}$) as a function of the SOC, whenever the HEV ECU switches to boosting mode. $P_{batt\ boost}$ is considered to be the product of the absolute maximum battery power discharge ($P_{batt\ boost\ max}$) set to be 25 kW, and the $P_{batt\ boost}$ correction factor, correcting this 25 kW as function of the battery SOC. This correction factor is also deduced from road test experiments achieved on the Prius.

PRIUS ROAD TESTS AND THS-II POWER TRAIN MODEL VALIDATION

In order to validate the THS-II power train model proposed in this paper, several road test measurements were realized on a Toyota Prius. The tests were organized in order to gather measurements from the Prius power train under several road driving conditions.

The gathered data are attended for validating the model on two levels:

- Validate the power train behavior and electromechanical performance (consequently, validating the driving functionalities which result from the action commands of the modeled EMS – refer to table 1)
- Validate the power train overall energy consumption: the quantity of fuel consumed as well as the amount of electrical energy consumed from or restituted to the battery

This section describes the road test methodology, the instrumentation used in measurements and the model validation process.

1. Road Tests Description

A second generation Toyota Prius, model year 2006 (MY06), was used in the road tests. This MY06 Prius is almost a brand new car, since it has been driven before starting tests for about 4500 km. The tests were realized in Paris and its suburban, between July and August 2008.

Over 134 measurement data files were recorded, covering several types of tests:

- urban driving tests in the heart of Paris, with both traffic conditions: normal and congested traffic flow
- highway driving tests in the suburban of Paris
- urban/highway driving tests through the inlets and outlets of Paris city (*Portes de Paris*)
- acceleration performance tests, recording the behavior of the Prius power train under full load acceleration from 0-100 km/h
- braking performance tests, recording the behavior of the Prius power train while braking from 60-0 km/h under several braking scenarios (hard, mild, soft braking)
- constant speed tests, recording the behavior of the power train at 40, 60 and 80 km/h
- standstill tests, recording the behavior of the power train, specifically the engine; after discharging the battery to low SOC
- electric drive mode tests, realized in urban driving conditions by forcing the power train to work in EV mode (by activating the EV mode switch in the dashboard)
- auxiliary ON tests, realized in urban driving conditions

In addition to covering different road driving conditions, each of these tests was repeated with several SOC levels of the battery. The main objective of those measurements is to cover almost all the operating range of the power train as a function of the battery energy level. Thus, these measurements have served first for validating/correcting the maps used in the model, and then validating the THS-II power train model.

2. Road Tests Instrumentations

Several instrumentation tools are used in taking on-road measurements. Figure 4 shows the used tools. The main measurement tool used is the Toyota Intelligent Tester II (IT-II). IT-II is a multifunction device, basically used by Toyota/Lexus repair technicians as Diagnostic Trouble Codes (DTC) detector. In our missions, the IT-II has served as a data logger, visualizing and recording all the ECUs data, summarized in table 2. Therefore, this device replaces almost all the sensors needed on a test bench, since it allows analyzing the ECUs data of the Prius from road tests.

Hybrid Control	Engine and ECT	HV Battery
Vehicle speed	Vehicle speed	Vehicle speed
Battery SOC	Engine torque	Battery pack current
Engine request power	Engine speed	Battery pack voltage
Battery current	Air/Fuel ratio	Battery pack internal resistance
Battery voltage	Mass air flow	Battery SOC
Regenerative brake torque	Ambient temperature	Battery temperature
MG2 speed	Coolant temperature	
MG2 torque	Throttle position	
MG1 speed		
MG1 torque		
Engine speed		

Table 2: Displayed parameters of measurement groups of the IT-II

1: Intelligent Tester II (IT-II)
2: RoyalTek GPS
3: Garmin GPS
4: 12 V DC connector for Garmin GPS
5: Data Link Connector (DLC) for IT-II
6: PC/Intelligent Viewer
7: Multi display LCD screen /Information display

Figure 4: Instrumentation tools

3. Validation and Updating of the e-Line Curve and the Engine Performance Map

Before validating the electromechanical performance and the energy consumption of the THS-II power train model, a characterization work is needed for validating the maps and graphs used in the model. Different maps are defined, specifically in the battery controller, where the maximum e-Drive power (P_{ev}), the charging power request (P_{ch}) and the allowed boosting power ($P_{batt\ boost}$) are determined from road test measurements as function the battery SOC.

In addition to the battery controller maps, the engine performance map and the economic line (e-line) curve are strategic maps to be validated from test measurements, since they affect both: the power train performance and the vehicle energy consumption of the model. These two maps are presented in this section, figures 5 and 6. The other maps can be viewed in [1].

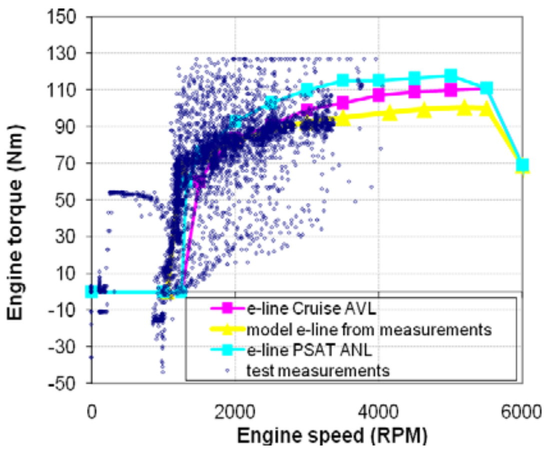


Figure 5: The model e-line deduced from road test measurements, compared to PSAT ANL and Cruise AVL e-lines

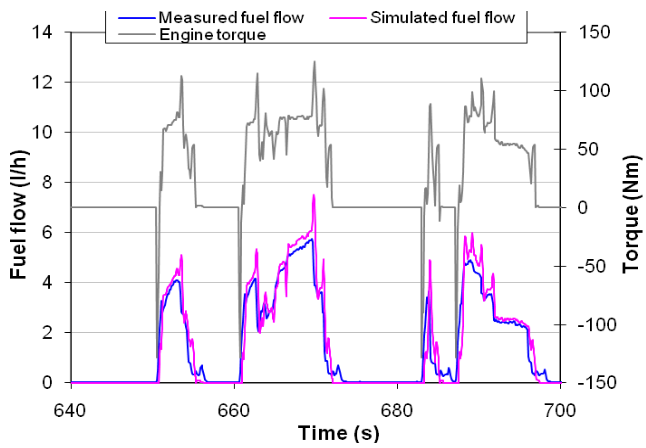


Figure 6: Comparison between the measured and the simulated fuel flow consumed

Figure 5 compares the e-lines available in PSAT (by ANL), Cruise (by AVL) and the e-line used in the model deduced from the road test measurements. Note that the model e-line is extended manually for engine speeds above 3500 RPM. This extension needs to be validated with more tests.

Figure 6 illustrates the flow of fuel consumed by the Prius during a specific road test and the flow consumed simulated by the model on the same specific test. The objective of this comparison is to validate the engine performance map provided by AVL Cruise which is used in the model. The graph shows that the consumed fuel flow almost fit together (slightly higher in simulation than the effective fuel flow measured, particularly for high engine torque values). Thus, the AVL engine performance map is validated.

4. Model Validation during Constant Velocity Cruising, accelerating and braking phases

Before proceeding in validating the power train model fuel consumption by comparing to road test consumptions measured in urban and highway driving conditions, the model was first validated with respect to the power train behavior in the basic driving phases of any vehicle: constant velocity cruising phase, accelerating phase and braking phase.

The model is run first on the constant velocity profiles measured during the cruising road tests (40, 60 and 80 km/h), and the simulation results of all components are compared to the recorded measurements of the power train during these tests. Similar procedure is followed for the acceleration performance tests (0-100 km/h) and braking performance tests (60-0 km/h).

Simulation results of all the power train components have shown the same behavior as the road test measurements. These results can be consulted in [1], and won't be presented in this paper due to the large number of graphs and the restricted number of pages of this article.

5. Urban Driving Model Validation

Several urban driving tests are realized in Paris, covering the normal and congested traffic flow. This section presents one of the urban tests achieved between *Place de la Concorde* and *Avenue des Champs Elysées*. The measured parameters of the power train during the test are compared to the model simulation results, as the model is run on the same velocity and slope profiles measured. Note that the road test measurements are realized with a warm engine.

5.1. Validation of the Power Train Model Electromechanical Performance

Figure 7 illustrates the electromechanical performance measured of the power train components and compares it to the model simulation results. It validates the power train model behavior in urban driving conditions, as the compared curves almost fit together. Note the different driving functionalities observed on the graphs, summarized in table 3.

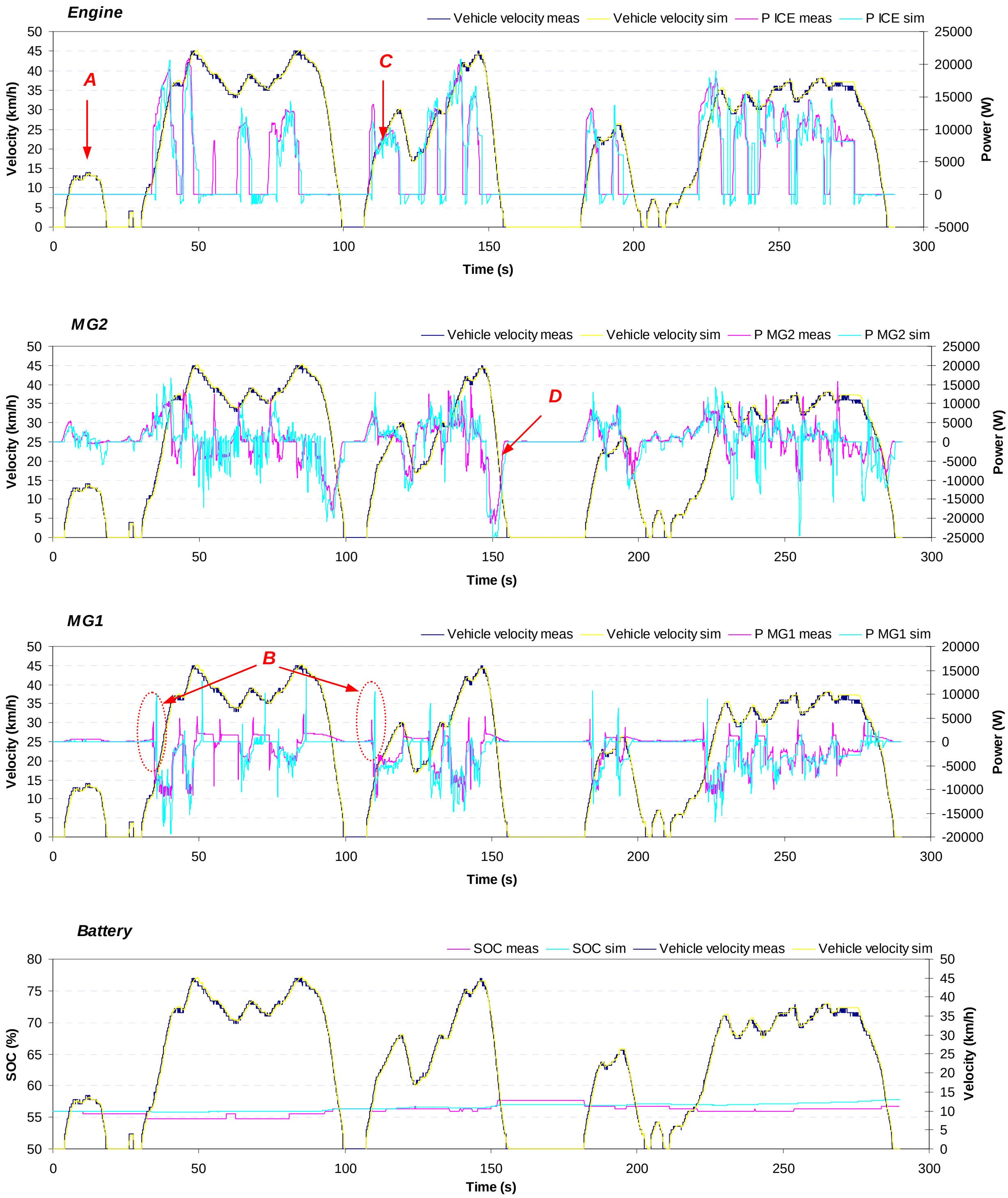


Figure 7: Comparison between measured and model simulation power of the power train components

Point	Driving functionality	Description		
		ICE	*MG1*	*MG2*
A	Driving at low speed (e-Drive)	OFF	OFF	Operating as motor for driving the car
B	Engine start	cranking	Operating as motor to start the ICE	Operating as motor for driving the car
C	Normal driving conditions (power-split)	ON	Operating as generator for power-split	Operating as motor for driving the car
D	Deceleration (braking energy recovery)	OFF	OFF	Operating as generator for recuperating breaking energy

Table 3: Power train driving functionalities observed during urban driving conditions

5.2. Validation of the Power Train Model Energy Consumption

In terms of validation of the consumed energy, the comparison is performed on both Prius energy sources: the fuel consumed by the engine and the electrical energy exchanged with the battery. Table 4 summarizes and compares the measured fuel consumption/battery SOC during road tests and the model simulation results. The results show a small relative difference between simulation and measurement results.

	Road test measurements	Simulation results
FC (l/100 km)	5,8	6,0
$SOC_{initial/final}$ (%)	56/56,8	56/57,8

Table 4: Fuel consumption and battery SOC comparison in urban driving conditions

Similar validation is realized in highway and roadway driving conditions. Additional comparison is done with the published results of energy consumption on regulatory driving cycles. Results can be viewed in [1].

6. Effects of Auxiliaries on Energy Consumption of THS-II Power Train

This section uses the validated model in order to study the effect of the auxiliaries on the energy consumption of the THS-II power train.

6.1. Scenario Overview

The power train model is run on NEDC, UDC and EUDC cycles, with three auxiliary consumption cases:

- Basic auxiliary consumption of 300 W
- Basic consumption + A/C ON (300 W +1300 W)
- Basic consumption + A/C ON + remaining electric equipments ON (300 W +1300 W + 900 W)

Then the NEDC results are compared to the UTAC chassis dynamometer results, realized by G. El-KHOURY for the first two scenarios [11].

6.2. Results Interpretation

Table 5 outlines the fuel consumption in l/100 km resulting from the three cases adopted on NEDC, UDC and EUDC. The first column compares between the fuel consumption measured on the chassis dyno and the fuel consumption resulting from simulation. The last two columns display the additional fuel consumed from cases 2 and 3, relative to the basic network supply of case 1.

On EUDC, the additional fuel consumption is less sensitive to the increase of the power of auxiliaries than on UDC. This is due to the fact that the engine is always turned ON on highways and supplies the required power for the auxiliaries (through MG1), which is not the case in urban driving, where MG1 is deactivated and the power of the auxiliaries ($P_{auxiliary}$) (in addition to the power of MG2 to drive the vehicle, P_{MG2}) are totally drawn from the batteries. Thus, when the engine turns ON, it must provide additional power to recharge the battery (P_{ch}). Consequently additional fuel will be consumed to readjust the SOC of the battery to its initial value.

	Basic onboard network supply	Basic supply + A/C ON (1)	Basic supply + A/C ON + all remaining electric equipments ON (1)
	300 W	300 + 1300 W	300 + 1300 + 900 W
		NEDC	
Power train model (sim. results)	4,29	+1,58 *(+36,83%)*	+3,44 *(+80,19%)*
UTAC chassis dynamometer tests	**3,7** (2)	+1,4 *(+37,83%)*	-
		UDC	
Power train model (sim. results)	5,05	+4,68 *(+92,67%)*	+7,62 *(+150,89%)*
UTAC chassis dynamometer tests	**2,7** (2)	+2,6 (+96,3%)	-
		EUDC	
Power train model (sim. results)	4,01	+0,44 *(+10,97%)*	+0,98 *(+24,43%)*
UTAC chassis dynamometer tests	-	+0,6	-

(1) *additional fuel consumption relative to basic supply*

(2) *2wd chassis dyno: all break energy is recovered by MG2, no energy dissipation in hydraulic brakes (which leads to an overestimated fuel consumption)*

Table 5: Fuel consumption (l/100 km) relative to each of the three auxiliary consumption cases

Note that the UTAC chassis dyno tests has shown a lower fuel consumption then the simulation results, on UDC and NEDC for the basic network supply. The explanation comes from the nature of the tests achieved: the UTAC has two wheels chassis dyno, so all the braking energy is recovered by MG2, and there is no energy dissipation within the rear brake. Thus, the consumption on UTAC chassis dyno is overestimated compared to road test consumption. For that reason, the relative additional fuel consumption has been calculated when studying the effect of auxiliaries in cases 2 and 3 on the power train fuel consumption, and compared with the fuel consumed in case 1.

7. Effects of Driver's Attitude on Energy Consumption of THS-II Power Train

In order to study the effect of the driver's attitude on the energy consumed by the Prius, three driver's attitude are simulated (Figure 8):

- Normal driving attitude
- Aggressive driving attitude
- Extremely aggressive driving attitude

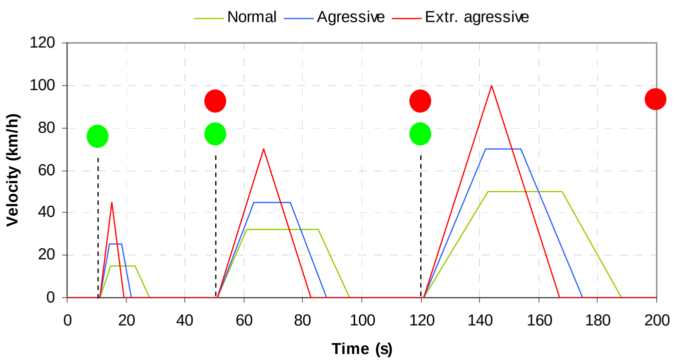
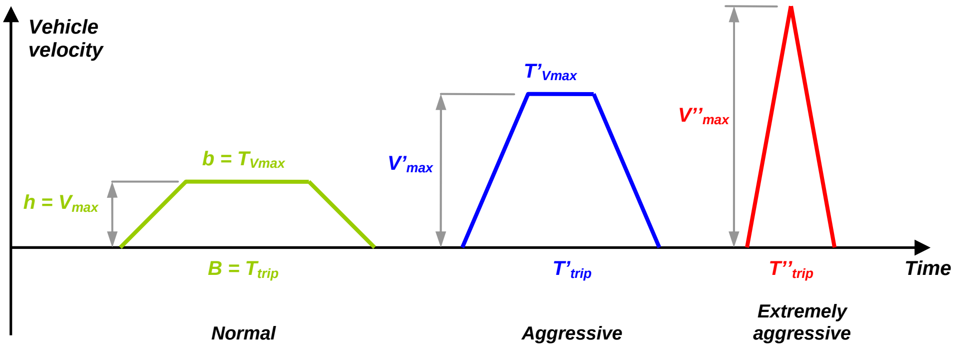


Figure 8: Velocity profiles simulating three driver's attitude: normal, aggressive and extremely aggressive

7.1. Scenario Overview

Each driver must drive his Prius for the same distance "d", on an urban circuit divided into three segments. The segments are separated by red light stop signals. The driver must absolutely stops on the red light, waiting for the green light to restart the Prius. The light turns to green when the three drivers are present.

The three velocity profiles of figure 8 are determined in order that the three drivers travel the same distance "d" at the end of the test. Figure 9 summarizes the mathematical approach used in determining these profiles (equations 4 and 5).



$$d = \int_0^T V(t).dt = \frac{(B+b)h}{2} \qquad (4)$$

$$d = \frac{(T_{trip} + T_{V\max})V_{\max}}{2} = \frac{(T'_{trip} + T'_{V\max})V'_{\max}}{2} = \frac{T''_{trip}.V''_{\max}}{2} \qquad (5)$$

Figure 9: Mathematical approach for specifying the three attitude profiles

For making the scenario simple, the velocity profile simulating the normal attitude is inspired from UDC. This profile is considered the basic profile. The profiles of the two aggressive attitudes are derived from the basic profile by using the mathematical approach of figure 9, in order to have the same distance "d" after the 200 seconds test.

To summarize the test scenario overview, the three drivers with different attitudes:

- must travel the same distance "d" with different velocity profiles
- must stop on the same red light and wait for each other
- must reaccelerate at the same time on the green light

7.2. Results Interpretation

Figure 10 summarizes the simulation results of the three attitudes. The model is run with several initial SOC. The ΔSOC in % and the fuel consumption in l/100 km are calculated. Comparing between driver's attitudes for the same initial SOC, the fuel consumption increases with aggressiveness. Note that these values of fuel consumption are not corrected for ΔSOC=0, so the gain and loss of electric energy from the battery is not taken into consideration in the displayed value of fuel consumed. Thus, the fuel consumption results must be corrected on ΔSOC=0 basis in order to compare between the results.

Consider the case of initial SOC = 50% (yellow bar):

- In case of normal driving attitude, the vehicle consumes 6,9 l/100 km of gasoline, and 14,36 Wh of electric power from the battery since ΔSOC is negative (-1,09%)
- In case of aggressive driving attitude, the vehicle consumes additional +0,35 l/100 km of gasoline than the normal attitude, however, the battery gains 2,88 Wh (ΔSOC=+0,22%)
- In case of extremely aggressive attitude, although the vehicle consumes +2,4 l/100 km of gasoline that the normal attitude, the battery is recharged with more electric power 36,9 Wh for ΔSOC=2,82%.

Thus, after making the corrections on ΔSOC=0 basis (with the linear regression method), it is observed that the fuel consumption decrease with aggressiveness (Figure 10).

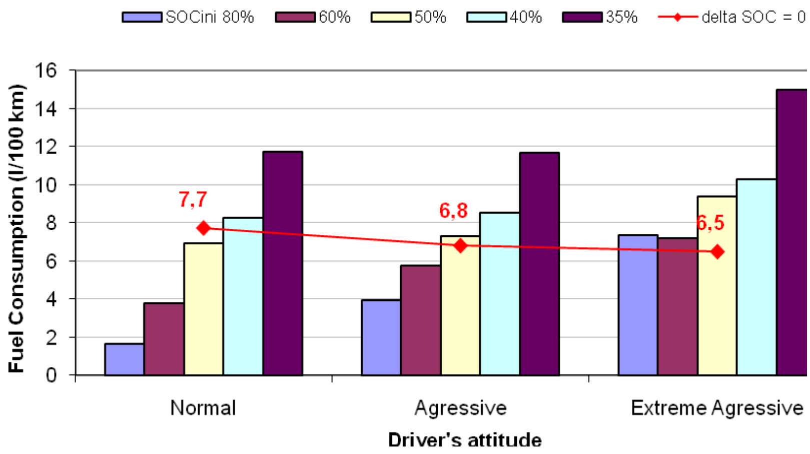


Figure 10: Fuel consumed with different initial SOCs (bar chart)
Fuel consumed on nil ΔSOC basis (red line)

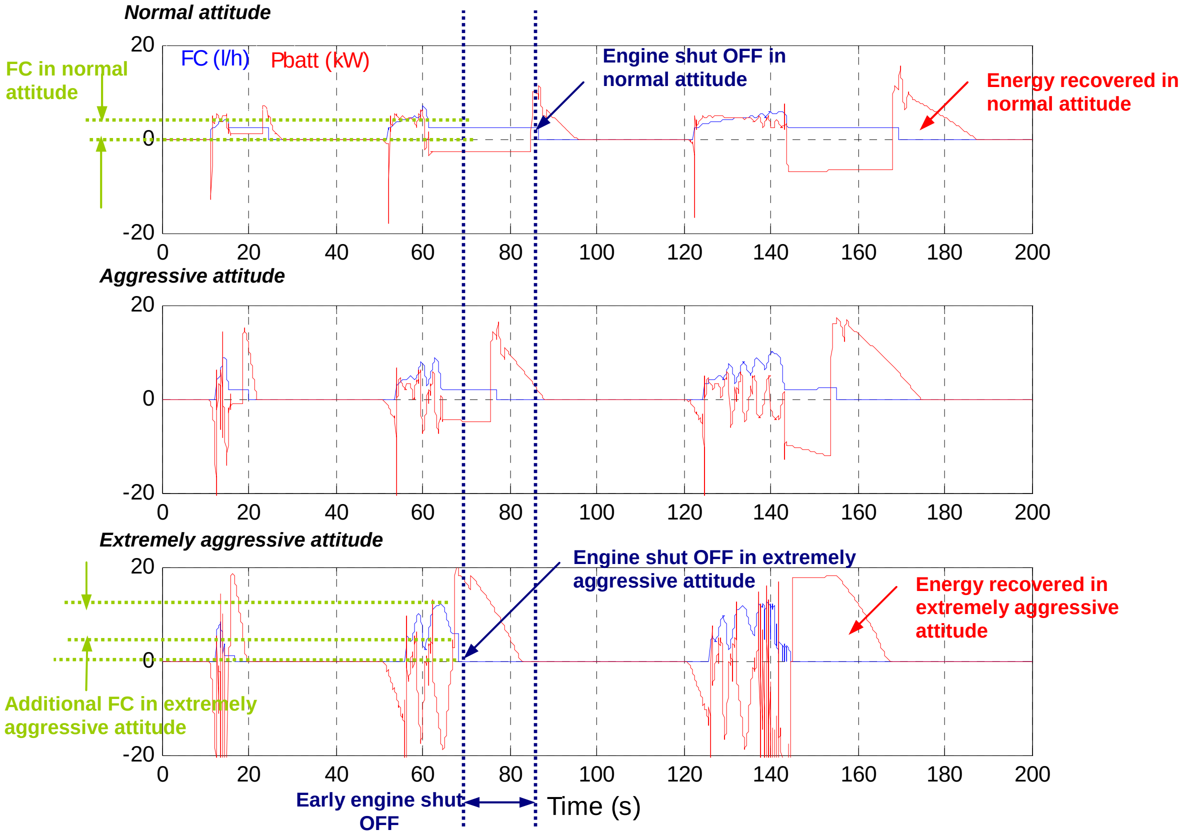


Figure 11: Engine and battery consumptions during the test for normal, aggressive and extremely aggressive attitudes

This surprising observable occurrence is explained by the fact that the engine is switched ON for less time as aggressiveness increase and that the braking scenario is long enough to recover larger amount of electricity with increasing aggressiveness (which does not simulate the reality of aggressive drivers style, they rather retard their braking to the maximum, consequently loose an important part of the brake energy in the hydraulic brakes and recover a small part of the kinetic energy because of the limitation of the electric braking torque of MG2 – limited to 200 Nm).

Figure 11 highlights the early shut off of the engine as the aggressive driver arrives first to the red light, and the extra fuel consumed due to his aggressive attitude. In addition, the figure shows also the additional energy recovered during braking with the aggressive driver (which does not simulate reality as mentioned above).

So, comparing the aggressive attitude to the normal attitude of the proposed scenario in this section, the early shut off of the engine with the aggressive attitudes in addition to the high energy recovery during braking compensates the extra fuel consumed. However, it should be mentioned that without the high recovered energy during braking, the aggressive driving attitude would consume more total energy (fuel+electric) than the normal driving attitude, and the advantages of hybridization of the power train will be lost in terms of fuel consumption.

CONCLUSIONS

A model of the Toyota Prius and its THS-II power-split power train has been elaborated.
The series/parallel developed power train has brought the following new elements, comparing to the models proposed in the literature:

- A feed-forward detailed model of the THS-II power train; simulating the kinematic and dynamic behavior of its power-split power train, and the behavior of its several components.
- The kinematic constraints of the power train have been investigated and included in the model.
- The two power flows within the power train have been modeled: the normal energy flow and the energy recirculation flow. The energy recirculation flow is only mentioned in the literature but neither modeled nor explained.
- Two control levels are elaborated in the model: the overall supervisor controller of the vehicle, and the components local controller, which represent the real Prius power train.
- The model is validated experimentally through road test measurement realized on a Prius in realistic operating conditions
- The validation includes the comparison between the model results and the measurements, in terms of:
  - The power train overall behavior (THS-II driving functionalities)
  - The power train components behavior
  - The vehicle fuel and battery electric energy consumption
  - The vehicle acceleration performances and constant cruising performances
  - The brake energy recovery of the power train
  - The auxiliary consumptions
- The components characteristic maps have been updated from the road test measurements. Furthermore, the control parameters of the control strategy have been calibrated from the measurements too.
- The feed-forward type of the model has allowed studying the attitude of the driver on a series/parallel hybrid power train, not presented in the literature to our knowledge.
- The auxiliary consumptions have been considered in the model, which allowed simulating several scenarios of auxiliaries consumptions, also not reviewed in the literature to our knowledge.
- The developed model serves as a reference THS power train model, where the first Prius generation or the new third Prius generation, and even the plug-in hybrid Prius can be easily modeled by modifying the components characteristics (and some rules of the control strategy for the plug-in).

ACKNOWLEDGMENT

The authors would like to thank Toyota France for their sympathy and assistance to test the Toyota PRIUS.

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