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Honda Insight Validation Using PSAT

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ABSTRACT

Argonne National Laboratory (ANL), working with the Partnership for a New Generation of Vehicles (PNGV), maintains hybrid vehicle simulation software: the PNGV System Analysis Toolkit (PSAT). The importance of component models and the complexity involved in setting up optimized control strategies require validation of the models and controls developed in PSAT. Using ANL's Advanced Powertrain Test Facilities (APTF), more than 50 tests on the Honda Insight were used to validate the PSAT drivetrain configuration. Extensive instrumentation, including the half-shaft torque sensor, provides the data needed for through comparison of model results and test data. In this paper, we will first describe the process and the type of test used to validate the models. Then we will explain the tuning of the simulated vehicle control strategy, based on the analysis of the differences between test and simulation. Finally, we will demonstrate the validation of the PSAT Insight component models and control strategy using Hybrid Electrical Vehicles (HEV) test data.

INTRODUCTION

The Partnership for a New Generation of Vehicles (PNGV), a historic public/private partnership between the U.S. government and the car manufacturers, was established to develop an environmentally friendly car to triple the efficiency of today's midsize cars. In order to respond to the needs of the System Analysis Team of the PNGV and the industry, Argonne National Laboratory (ANL) maintains the PNGV System Analysis Toolkit (PSAT), a forward-looking hybrid vehicle simulation software package**.**

One of the main challenges of hybrids is to choose the configuration and the components that are best suited to achieve PNGV goals. PSAT already includes many of the possible drivetrain configurations (about 180) to help PNGV and car manufacturers make the right decisions. However, in order to verify PSAT's usefulness, the component and the drivetrain models must be validated.

Validation is a very important aspect of software development, as it provides users the degree of accuracy of the software. Modeling tools can be validated using different data sources:

- From vehicle testing
- From component testing
- From drivetrain testing

In this article, we describe the steps used to validate PSAT using Honda Insight vehicle-testing data from ANL's Advanced Powertrain Test Facilities (APTF).

PSAT INTRODUCTION

PSAT was developed for the PNGV under the direction and with the contribution of Ford, General Motors, and Daimler-Chrysler.

FORWARD-LOOKING MODEL

PSAT is a powerful modeling tool that allows users to realistically evaluate not only fuel consumption and exhaust emissions for more than 20 different standard cycles, but also vehicle performances. PSAT is a forward-looking model, meaning that the component interactions are "real world." This method is computationally more extensive than backward-looking architecture. The result is a tool that allows advanced powertrain designers to develop realistic control strategies and assess component behaviors in a system environment by using models that are closer to reality.

Looking toward the future, to be able to study transient effects and the interaction between components with accurate control commands, ANL developed a forward-looking model: PSAT.

FLEXIBILITY AND REUSABILITY

In a world of growing competitiveness, the role of simulation in vehicle development is constantly increasing. Because of the number of possible hybrid architectures, the development of this new generation of vehicles requires accurate, flexible simulation tools. Such a simulation program is necessary to quickly narrow the technology focus of the PNGV to those configurations and components that are best suited for achieving these goals. Therefore, the simulation should be flexible enough to encompass the wide variety of components and drivetrain configurations.

PSAT includes more than 180 predefined configurations, including conventional vehicles, parallel hybrids, series hybrids, fuel-cell hybrids, and power split hybrids. Users also have the capability to chose two, four, and two times two-wheel drive. Such a capability is only possible by building all these drivetrain configurations according to user inputs and component models from the libraries, thus allowing users to choose the most appropriate configuration related to their requirements.

PSAT flexibility and reusability is based upon several characteristics, as described below.

COMPONENTS MODELS

Organization Format

In order to easily exchange the models and implement new ones, a common format, based on Bond Graph, is used between the input/output of the power ports, as shown in Figure 1. The first ports are used for the information. Inputs are the components command (i.e., on/off engine, gear number, etc.). Outputs (sensors) are simulated measures (i.e., torque, rotational speed, current, voltage, etc.). The second ports carry the effort (i.e., voltage, torque), and the last ones the flow (i.e., current, speed).

Use of Library

To ensure that the models used are the last ones changed or are not modified, we decided to use a library in which all the models are saved. Libraries enable users to copy blocks into their models from external libraries and automatically update the copied blocks when the source changes.

Use of Masks

Hybrid electric drivetrain configurations can be very different from one another and also be rapidly complex. Often, one component can be used several times, such as the electric motor for the General Motors Precept or the Toyota Prius. In order to solve the problem of versioning, we decided to mask the different component models, allowing us to reuse the same model several times.

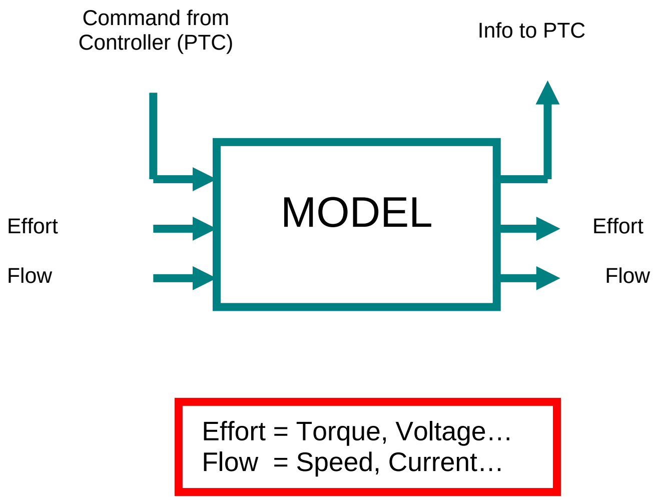


Figure 1: Global Formalism for the I/O of the Models Using Bond Graph

Use of GOTO-FROM Format

To simplify the model, we use the GOTO-FROM format. As far as the models are concerned, all the GOTO-FROM blocks are local and located at the upper level of the model (no blocks are located in the subsystems). To facilitate the work for Hardware in the Loop (Control Desk access to the parameters and variables by using the Tags), the name of the Tags are defined following strict rules.

Use of Common Nomenclature for Variable Names

PSAT names have been parameterized and follow specific rules. At the component level, all the variables and parameters also follow established rules and are named according to the component and the type of data they represent. At the software level, the names are based upon the component (e.g., mc for motor/controller). In fact:

- The component model name is defined as ‘compo’_cm (e.g., mc_cm)
- The initialization file is ‘compo’_init,
- The scaling file is ‘compo’_scale,
- The calculation file is ‘compo’_calc,
- The parameter used to choose whether we scale is gui_scale_’compo’, and
- The parameter used to scale the component is gui_’compo’.

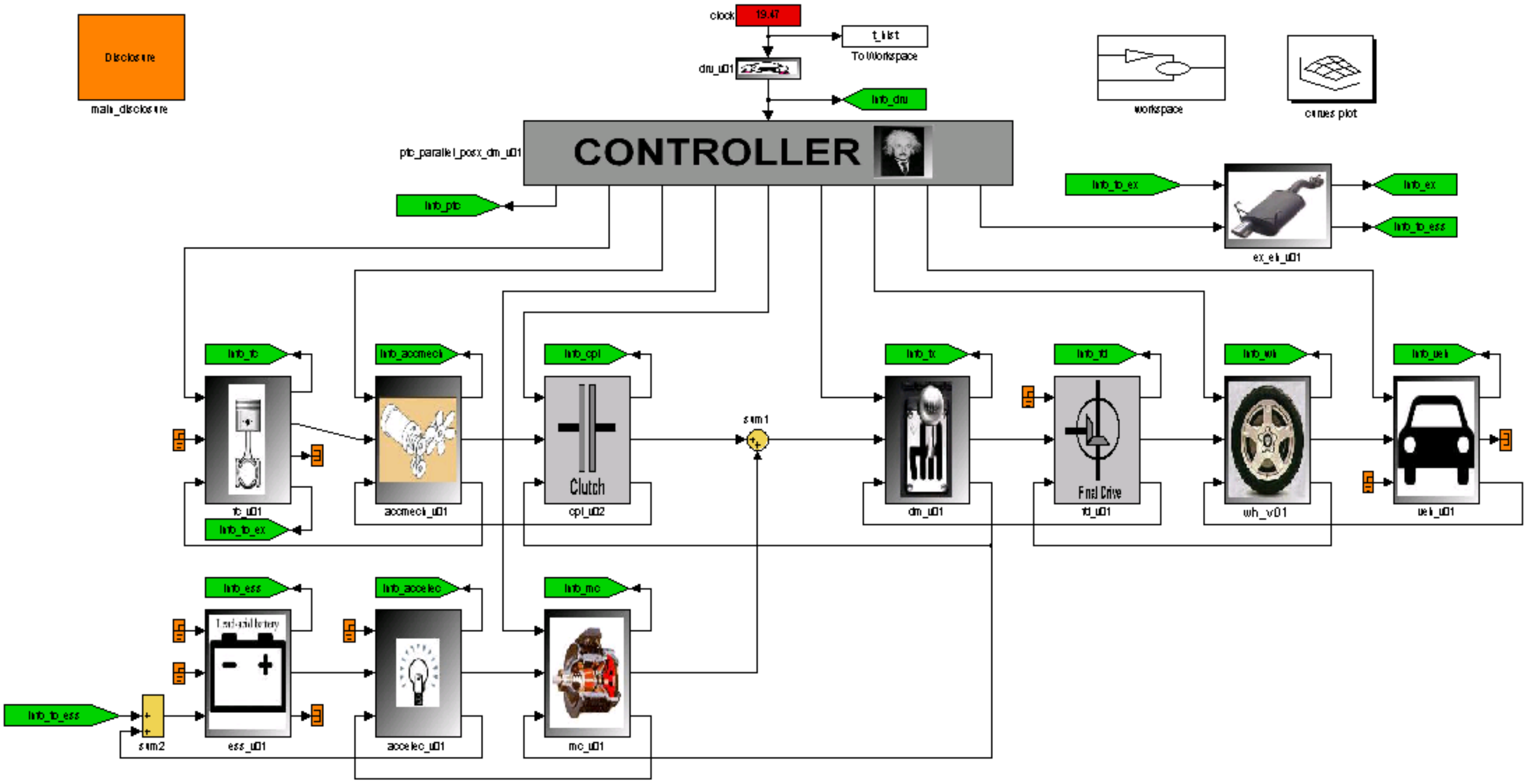


Figure 2: PSAT Single Shaft Parallel Hybrid

Powertrain Controllers

PSAT powertrain controllers, in charge of commanding the different components, have a generic structure common to all configurations. By using the accelerator pedal and the information (sensors) coming from the component models, we evaluate the constraints of the system, such as the maximum available torque of the engine. We then take these limits into account to define the optimized control strategy, which allows us to use the powertrain components to minimize fuel consumption and emissions. Finally, we take the transients into account by defining the actions necessary to satisfy the control strategy demands. For instance, if the control strategy decided to shift gears with a manual transmission, we must cut off the engine ignition, declutch, engage the neutral gear, engage the new gear, clutch, and inject once again. These steps must happen successively and lead to a modification of the demands previously sent by the control strategy.

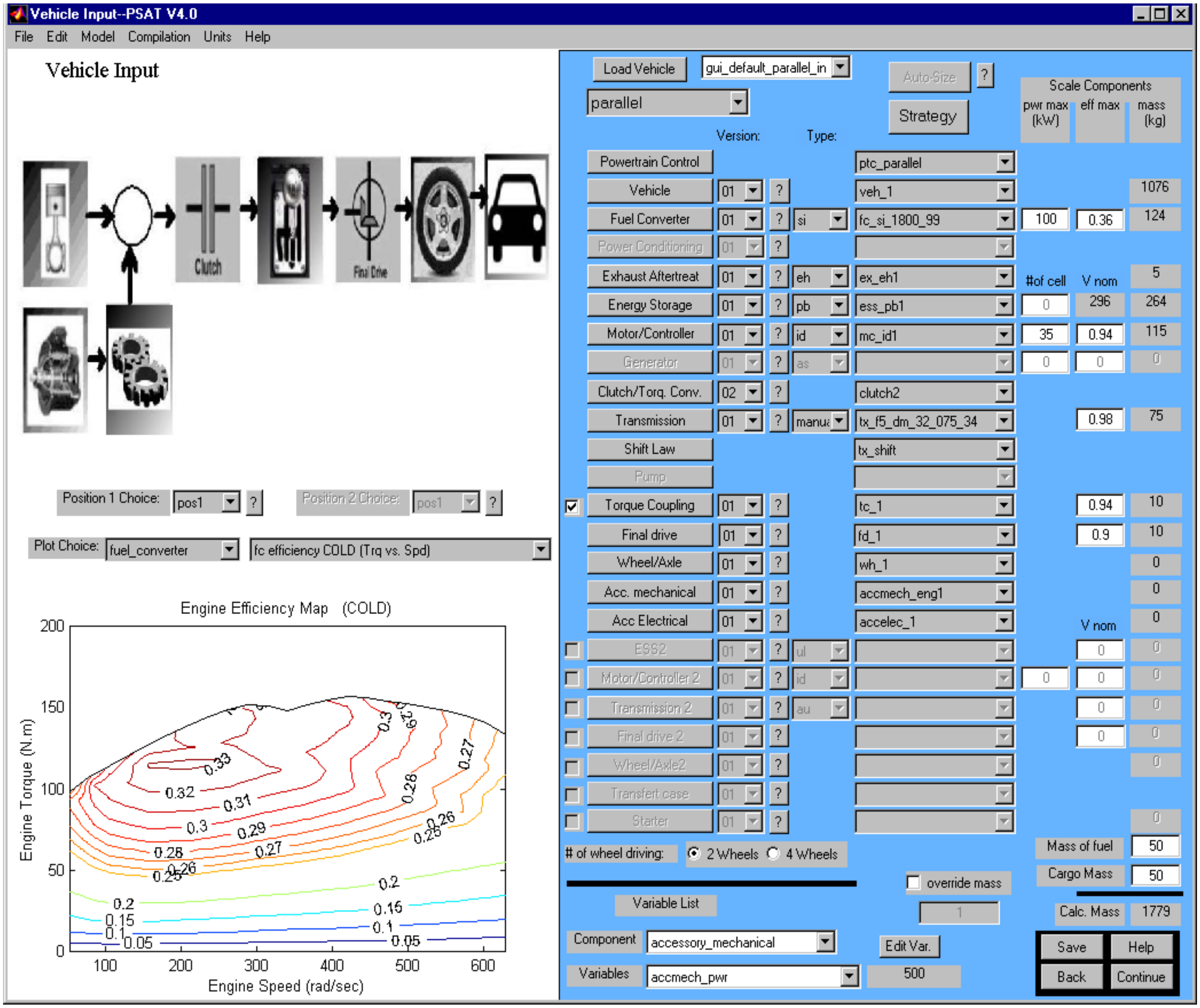
Within the PSAT powertrain controller, different strategies can be selected within a particular powertrain model. Indeed, as the strategy has an important impact on the fuel consumption, it is interesting to switch between different control strategies for comparison. In order to evaluate the impact of these different strategies, we can select and compare them using the same components models. This also allows us to easily implement new strategies.

As an example, it is interesting to look at a PSAT parallel configuration model to understand the use of a library and standard format (Figure 2).

PSAT USE

To run a simulation, a graphical user interface (GUI), as shown in Figure 3, helps users to choose the type of drivetrain and the components initialization files. Moreover, PSAT gives users the capability of creating their own components (engine, motor, battery, transmission) by scaling existing data. As PSAT is able to run both performance and consumption/emissions tests, users must determine the type of test (or series of tests) that should be done. In order to assess the influence of different parameters on consumption or drivability, a parametric study is also available. Finally, in the case of an energy consumption test for hybrid configuration, a state-of-charge (SOC) equalization algorithm is also available so that the consumption results from different configurations or strategies can be compared with the same SOC.

According to the user’s choices, the software will build the appropriate model, using components from a library. The model will then run automatically, and the results will be provided in the last window of the GUI.



Load Vehicle: gui_default_parallel_in

parallel

Position 1 Choice: pos1

Position 2 Choice: pos1

Plot Choice: fuel_converter — fc efficiency COLD (Trq vs. Spd)

	Component	Version		Type	Scale Components pwr max (kW)	 eff max	 mass (kg)
	Powertrain Control			ptc_parallel			
	Vehicle	01		veh_1			1076
	Fuel Converter	01	si	fc_si_1800_99	100	0.36	124
	Power Conditioning	01					
	Exhaust Aftertreat	01	eh	ex_eh1	#of cell	V nom	5
	Energy Storage	01	pb	ess_pb1	0	296	264
	Motor/Controller	01	id	mc_id1	35	0.94	115
	Generator	01	as		0	0	0
	Clutch/Torq. Conv.	02		clutch2			
	Transmission	01	manua	tx_f5_dm_32_075_34		0.98	75
	Shift Law			tx_shift			
	Pump						
☑	Torque Coupling	01		tc_1		0.94	10
	Final drive	01		fd_1		0.9	10
	Wheel/Axle	01		wh_1			0
	Acc. mechanical	01		accmech_eng1			0
	Acc Electrical	01		accelec_1		V nom	0
☐	ESS2	01	ul			0	0
☐	Motor/Controller 2	01	id		0	0	0
☐	Transmission 2	01	au			0	0
☐	Final drive 2	01				0	0
☐	Wheel/Axle2	01					0
☐	Transfert case	01					
☐	Starter	01					0

# of wheel driving: ● 2 Wheels ○ 4 Wheels

Mass of fuel: 50

Cargo Mass: 50

☐ override mass: 1

Calc. Mass: 1779

Component: accessory_mechanical

Variables: accmech_pwr — 500

Figure 3: PSAT GUI – Initialization Window

The results of each simulation are saved in specific folders, using four files that contain (1) initial conditions of the simulation, (2) post-processing information, (3) variables of the simulation, and (4) a file to rerun the same test.

HONDA INSIGHT PRESENTATION

To achieve the fuel economy reduction shown in Table 1, Honda integrated several advanced technologies within the system. At the center of the Insight powertrain, the Integrated Motor Assist (IMA) System combines two Honda innovations: a clean running, highly efficient, 1.0 liter, 12-valve, 3-cylinder VTEC-E engine (variable valve timing and lift electronic control) gasoline engine, which is the main power source, and a powerful, ultra-thin 10kW electric motor. The insight's IMA System uses the integrated electric motor to improve the performance by augmenting the output of the gasoline engine. Together, they produce a total of 73hp, which gives this lightweight, aerodynamic Insight the acceleration and performance of a car with a larger size.

	EPA Rated Fuel Economy (mpg)
City	61
Highway	70

Table 1: Insight EPA Fuel Economy

Lightweight, high-strength chassis construction, an aluminum-alloy front suspension, a compact torsion-beam rear suspension and an Electric Power Steering (EPS) system all contribute to the Insight's smooth ride and its responsive handling. The engine, efficient as a result of light, high-strength components and friction-reducing techniques, helps give the Insight the response and capabilities of a conventional car. Fuel economy is also increased by the VTEC-E technology and the 5-speed manual transmission.

Since one of the PNGV System Analysis goals is to benchmark HEV vehicles, as well as develop and validate the models, the choice of the Honda Insight was obvious. The main physical parameters used for the validation process are described in Appendix 1.

VEHICLE TESTING

SENSOR CHOICES

In order to validate a hybrid vehicle drivetrain model, some information is crucial and indispensable, such as current, voltage, speed, torque, and battery SOC. However, even though it is not always necessary to have all the information from one component, a minimum is necessary. As less and less information becomes directly available from the network, we usually must add new sensors. The type of sensor needed depends on the configuration to be tested. For example, in the case of the Toyota Prius, if we decided to measure the engine torque by adding a torque sensor in between the engine and the planetary set, as shown in Figure 4 [Duoba et al., 2000], such a solution is not necessary or simply not feasible for all the configurations. Because of the Insight configuration (one motor instead of two, as for the Prius), we opted for a half-shaft torque sensor located after the transmission, as shown in Figure 5.

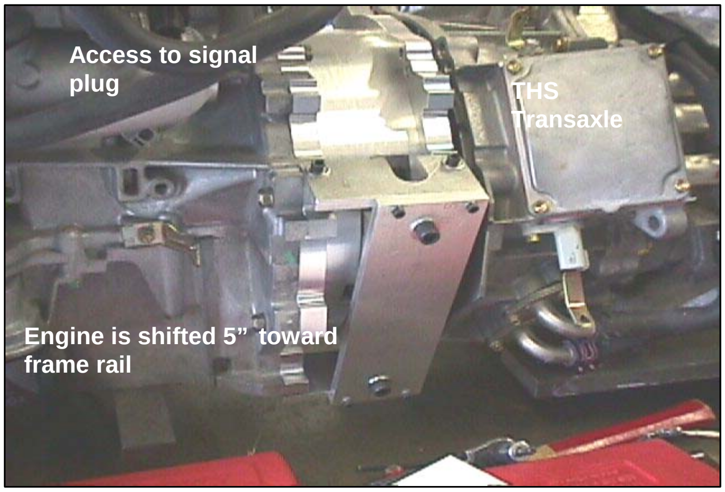


Figure 4: Location of Prius Engine Torque Sensor

Figure 5: Half-Shaft Honda Insight Torque Sensor

To summarize, the choice of sensors depends on the configuration we want to validate and the vital necessity of having access to the information, as most of the time some parameters can be calculated by using other information.

CYCLE CHOICES

The choice of cycles for the car to be tested and its order is vital in the validation process. Different cycles are indeed used different purposes:

1) Specific tests must be realized for road load match purposes.

2) When component mapping within the car is necessary, which was our case for the Honda Insight, several steady speeds using different gear numbers are used, as shown in Figure 6.

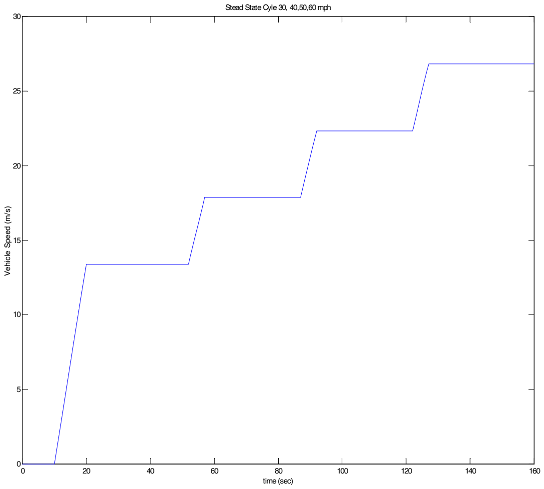


Figure 6: Steady-Speed Cycle

3) These same steady-state cycles are also used for other purposes, such as control strategy understanding. Using the constant speed operations, we were able to study the impact of the battery SOC on the control strategy. During acceleration, the battery SOC decreases and then comes back to its target value during constant speed. The engine torque and, consequently. the fuel consumption is highly dependant of the SOC.

4) Cycles with different acceleration and deceleration rates also provide an understanding of the transient behavior of the vehicle and its control strategy. For example, the Insight regenerative braking control strategy and limits have been developed according to this series of tests.

With regard to the normalized cycles, as shown in Figure 7, the European and Japanese cycles are well suited to understanding the vehicle control strategy because of their constant acceleration profiles. Once the control strategy is tuned, other tests are used to fully validate the model via the same tuning defined on previous cycles.

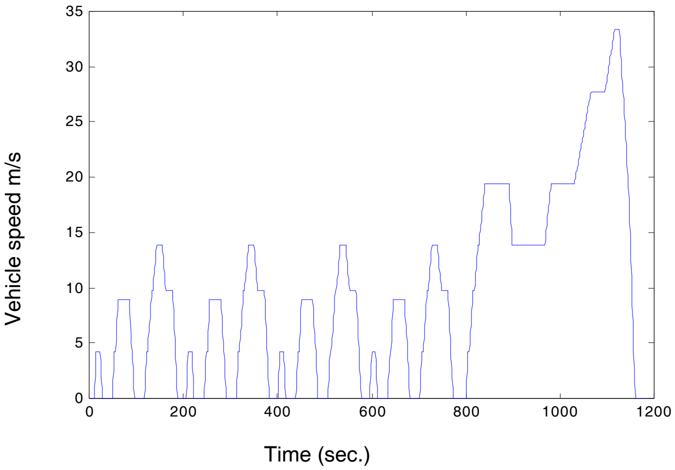


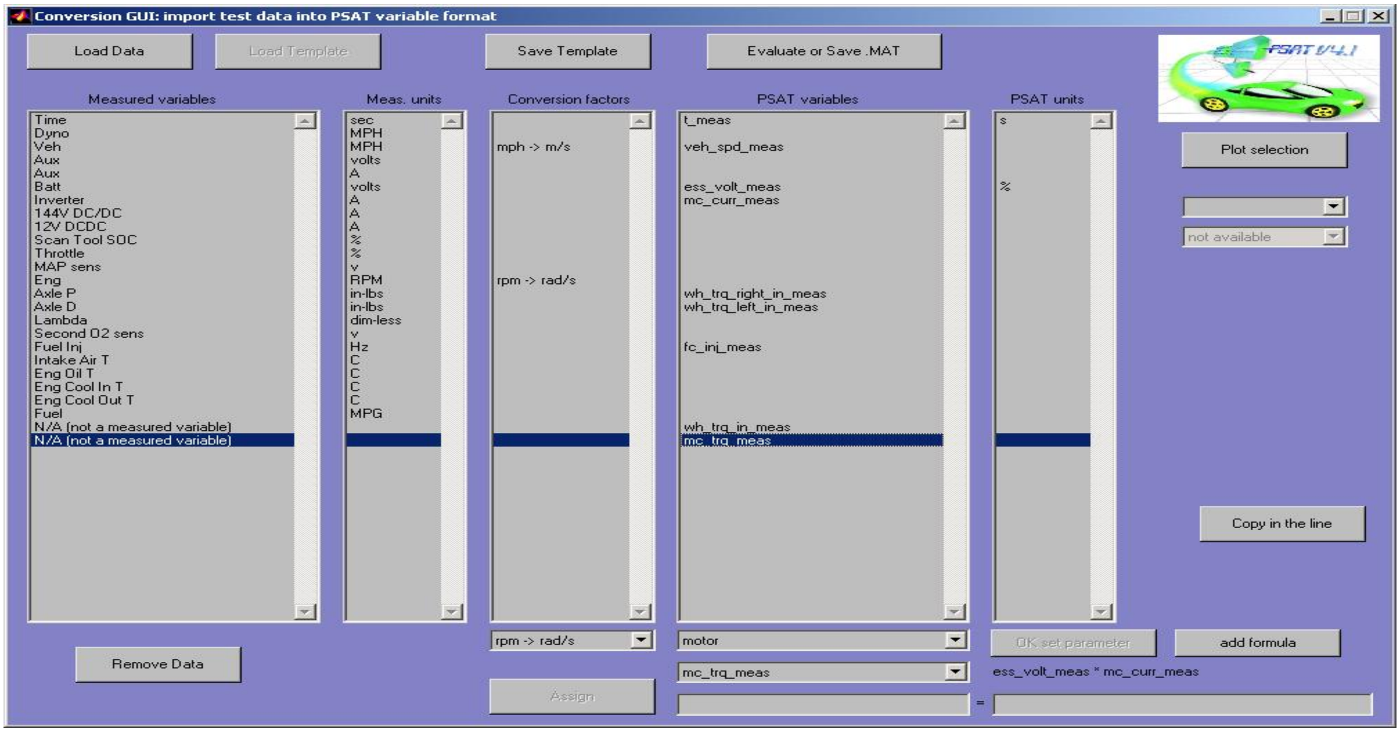
Figure 7: Normalized European Cycle

Because of the complexity of hybrid drivetrains and the vital importance of the SOC of the battery on the system, all these cycles must be realized for different SOCs.

SPECIFIC TOOLS DEVELOPMENT

IMPORT DATA FROM TESTS INTO MATLAB

In order to facilitate the importation of the data from the vehicle tests into Matlab/Simulink, a generic GUI has been developed, as shown in figure 8.



Measured variables	Meas. units	Conversion factors	PSAT variables	PSAT units
Time	sec		t_meas	s
Dyno	MPH			
Veh	MPH	mph -> m/s	veh_spd_meas	
Aux	volts			
Aux	A			
Batt	volts		ess_volt_meas	%
Inverter	A		mc_curr_meas	
144V DC/DC	A			
12V DCDC	A			
Scan Tool SOC	%			
Throttle	%			
MAP sens	v			
Eng	RPM	rpm -> rad/s		
Axle P	in-lbs		wh_trq_right_in_meas	
Axle D	in-lbs		wh_trq_left_in_meas	
Lambda	dim-less			
Second O2 sens	v			
Fuel Inj	Hz		fc_inj_meas	
Intake Air T	C			
Eng Oil T	C			
Eng Cool In T	C			
Eng Cool Out T	C			
Fuel	MPG			
N/A (not a measured variable)			wh_trq_in_meas	
N/A (not a measured variable)			mc_trq_meas	

rpm -> rad/s

motor

mc_trq_meas

ess_volt_meas * mc_curr_meas

=

Figure 8: Generic GUI to Import Data into PSAT

Using text or EXCEL files, users have the capability to:

1) Select the data of interest for the validation process and delete the ones being recorded for other purposes, such as benchmarking.

2) Rename the test data using PSAT nomenclature. As mentioned previously, each PSAT variable or parameter name follows a strict nomenclature to easily identify them. To later compare test and simulated data, similar rules have been applied as far as test data are concerned.

3) Change the units to be compatible with PSAT, which uses only SI units.

4) Save some templates. Once several choices have been made for one vehicle, the importation of new data sets is immediate.

5) Create some calculated data necessary for validation by using the measured ones (e.g., engine power using engine torque and speed).

6) Plot the main characteristics of each component (e.g. torque, speed, consumption, and injection for the engine).

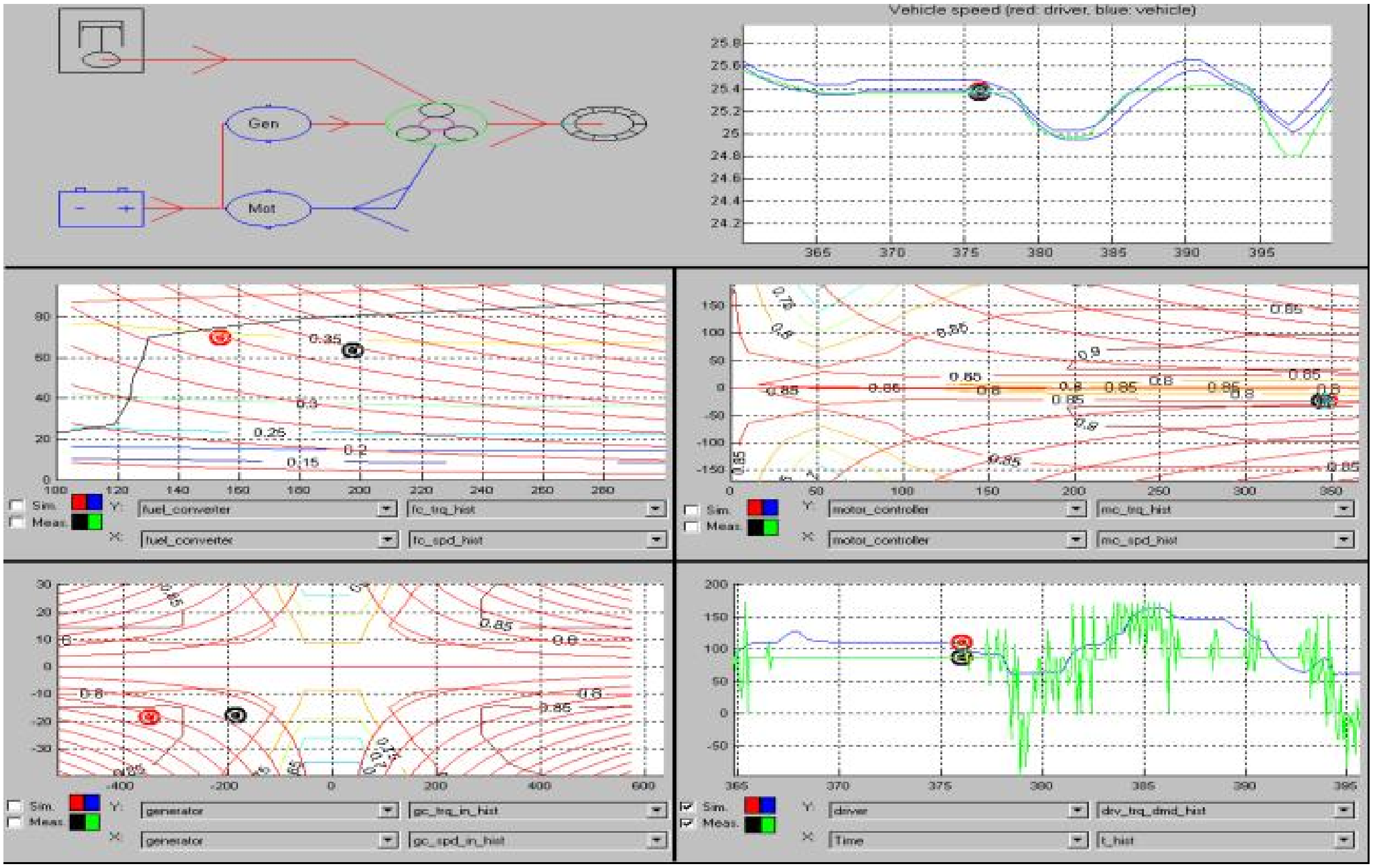
7) Study the blending between the different components by looking at the same parameter for different components (e.g., torque of the engine, motor, wheels).

8) Have a first global idea of the control strategy by plotting a specific list of parameters for each item of the control strategy (e.g., when the engine will start or turn off, or the impact of SOC on the control).

COMPARE DATA FROM TESTS AND SIMULATION

Once the simulation data have been imported into Matlab/Simulink and renamed, new innovative tools have been developed to facilitate our understanding of the control strategy. Indeed, if simple tests, such as stead-state or acceleration and deceleration, allow us to understand the general ideas of the control strategy, then the final validation requires standard cycles. It then becomes more difficult to follow the step-by-step behavior of the vehicle without any appropriate tools.

Time permitting, this work consists of looking at the key parameters linked with the engine start, such as the vehicle acceleration and speed, the necessary torque at the wheel, or the battery SOC. The entire difficulty here is that more than one parameter almost always needs to be taken into account.



Y: fuel_converter fc_trq_hist
X: fuel_converter fc_spd_hist

Y: motor_controller mc_trq_hist
X: motor_controller mc_spd_hist

Y: generator gc_trq_in_hist
X: generator gc_spd_in_hist

Y: driver drv_trq_dmd_hist
X: Time t_hist

Figure 9: Interactive GUI to Understand a Control Strategy

The new generic GUI allows us to analyze, step by step, the control strategy using only test data, simulated data, or both simultaneously. An example of the tool is shown in Figure 9.

HONDA INSIGHT VALIDATION

VALIDATION PROCESS

It is necessary to first define the validation process and the limits within the model that will be validated:

- The validation must respect the test conditions: road load, shifting, electrical accessories consumption, and initial SOC must agree exactly with the tests.
- Component models must be validated independently.
- Not only should the final consumption and SOC match, but the model should also behave as in the tests: the simulated motor, engine, wheel torques, fuel rate, and SOC should track adequately the measured one.
- The final fuel economy and SOC of the model should be within 5% of difference.

The process is explained in its chronological order: data collection, component model validation, control strategy understanding, and finally cycle validation.

DATA POST_PROCESSING

In order to understand the Insight control strategy and reproduce it in PSAT, tests must be performed. The data collected at the ANL APTF during these tests will first be used to create the component initialization files. But they are also crucial to model the vehicle, being the only source of comparison for the simulation results. The main problem in collecting data for the Honda Insight concerns the fact that the engine, motor, and transmission are in one block. Consequently, it was impossible to add a torque sensor on the crankshaft, but only on the wheels axles. We then had to estimate the engine torque from the measured axle torque and the torque of the motor, which can be calculated by knowing the electrical power given to or provided by the motor.

To be consistent with the simulation, we decided to use a Simulink model to calculate the torque fed with the initialization files that will be used later in the model, as shown in Figure 10. The results given by the model are shown Figure 11.

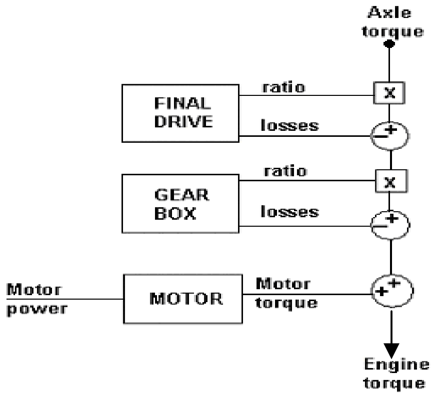


Figure 10: Engine Torque Calculation

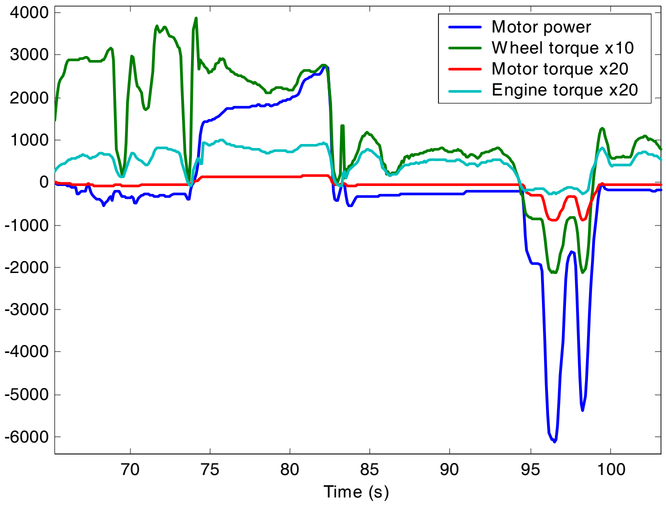


Figure 11: Engine Torque Calculation Results

COMPONENT MODEL VALIDATION

Having a vehicle model with fuel consumption results within 5% does not mean the model is validated with 5% of error, if, for instance, the engine map has more than 5% of error in the torque with the same fuel rate and at the same engine speed. To be more general, the model is as accurate as its worst component.

Methodology

To validate a component, the data measured during a drive cycle is fed directly into the component model and the simulated output is compared to the measured output, as shown in Figure 12.

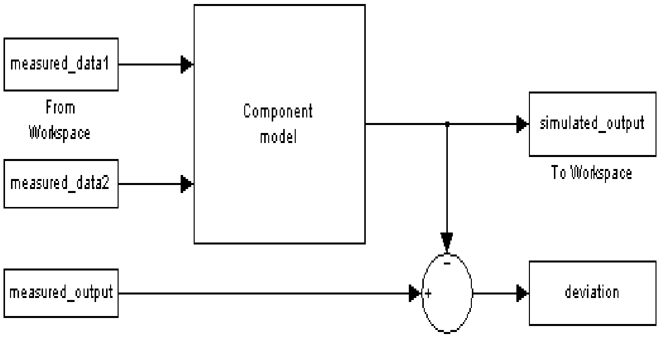


Figure 12: Generic Model Used for Component Validation

If errors occur in individual component models, this method will quickly expose them.

Example of component model validation with the engine model

For the engine validation, we compare its torque and fuel rate at the output of the model with those measured. (The engine speed is a parameter of the model to calculate the torque and, consequently, will be the same in output).

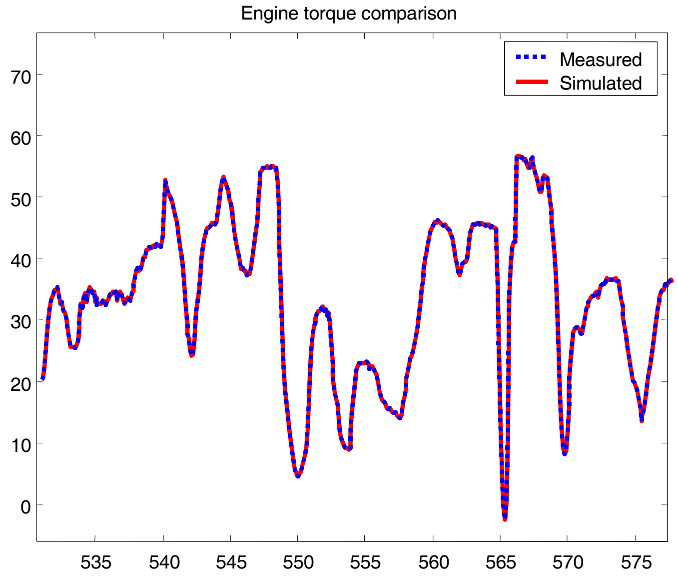


Figure 13: Simulated Torque Response to a Measured Command

Generally, the engine torque in output of the engine model exactly follows the command, as shown in Figure 13. It would seem probable for a model to give the same answer as its input. However, the engine model is commanded with a [0,1] command and uses a closed throttle torque curve (minimum torque curve) and a wide opened throttle torque curve (maximum torque curve). Having the same engine torque in response leads us to conclude that the maximum and minimum torque curves are correct and the PSAT model performs correctly.

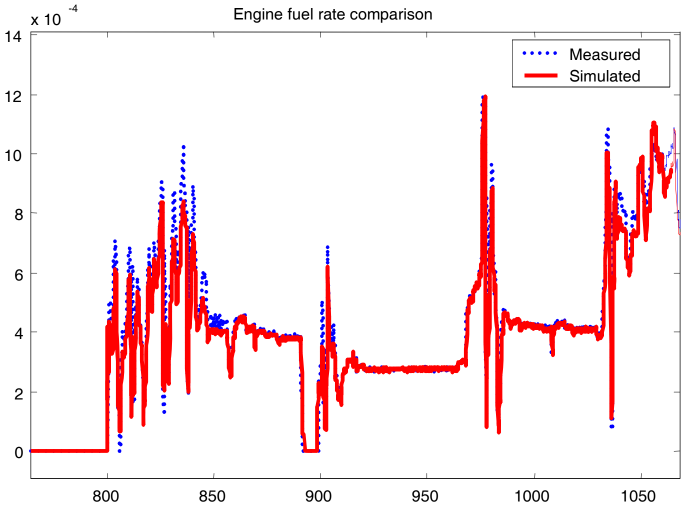


Figure 14: Simulated Fuel Rate to a Measured Command

The engine model is producing very satisfactory results for the fuel rate. Figure 14 shows that the fuel rate curve predicted by the model tracks the measured one very closely on steady states and does not diverge much on transients either.

The same process was achieved on the battery PSAT model with satisfactory results.

INSIGHT CONTROL STRATEGY

From ANL test data, we identified the vehicle control strategy:

- When and how the motor provides some assist.
- When the engine is turned ON or OFF.
- When and how the motor is used to charge the battery.
- The amount of regenerative braking compared to friction braking.

Five modes or operations are then dissociated to analyze the Insight strategy:

1. Engine starting: must not be confused with the action of turning on the key.
2. Acceleration.
3. Cruising: in our case this notion will be extended from the steady states to the small accelerations and decelerations, which do not necessity motor assist.
4. Deceleration: concerns either cases where the driver will brake or only back up the acceleration pedal.
5. Stationery mode: when the vehicle comes to a stop.

1. Engine starting

On a conventional vehicle, the driver must turn the key to the start position to start the engine. On the Insight, this is not the only condition that will result in an engine starting. There are two other types after an engine Auto-Stop (see Stationery mode):

- Shift a gear (it must be precise; the Auto-stop will only occur in neutral).
- Accelerate in neutral.

If the main battery pack SOC allows the start (superior to a certain limit), the IMA will be used to start the engine, which allows it to be spanned to a higher speed before starting the injection where the compression is more stable.

2. Acceleration mode

The Insight is a mild hybrid: the power of the motor is only 17% of the total power available in the power train. Furthermore, the accelerator pedal has been directly connected to the throttle, which means the control strategy does not share a torque demand between the two sources of power, but the motor is an “extra-boost,” an assist that will help during the transients in acceleration. The other consequence is that the torque demand at the wheel will be, at the same time, an engine torque demand. The added torque given by the motor must be managed by the driver by backing off the accelerator pedal: the driver is the controller. This finally implies that the motor cannot run by itself: the engine will always be running in propelling mode. In order to analyze the behavior of this assist, it is necessary to separate three cases: high SOC, low SOC, and very low SOC.

a) High SOC

Logically, it is when the SOC is over a certain limit that the most assist will be given (. an example of motor assist is shown in Figure15). However, SOC is not the only condition that determines whether assist should be given and the amount of assist to give. The condition to start or end the assist will be on the engine torque demand and the derivative of the engine torque demand. But the amount of assist will depend only on the value of the engine torque, as shown in Figure 16.

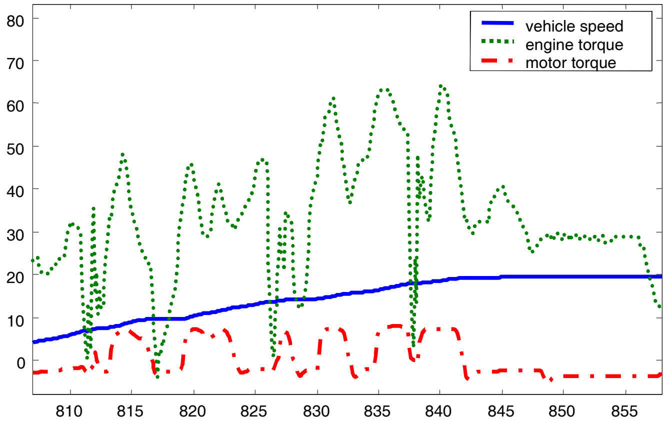


Figure 15: Motor Assist at High SOC

The assist, depending on engine torque demand, is a slow rate. It is possible to have much more assist by totally pressing the accelerator pedal when the engine torque is initially low. The controller will record a demand, which is exceedingly higher than what the engine is able to provide, and we will notice values of motor torque going up to 50 N.m.

In fact, being in the high SOC mode for assist depends on SOC limit, but the amount of assist will not be SOC dependant.

b) Low SOC

If the SOC is low, the assist only happens when the torque demand is really high. It would correspond to the case of a full acceleration with a wide opened throttle. But the amount of assist is still the same function of the torque demand.

c) Very low SOC

If the SOC gets too low, then it will just turn off any assist and wait until it comes back to an acceptable level.

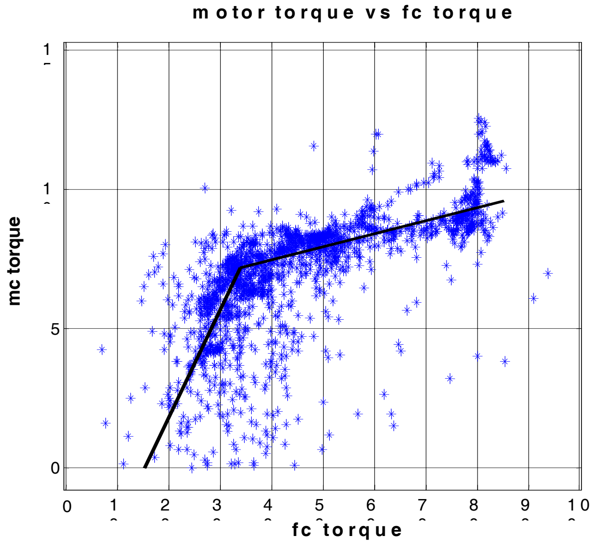


Figure 16: Motor Assist Torque vs. Engine Torque

3. Cruising mode

When the vehicle has reached a steady state and will only have small and low variation in its speed, we are in cruising mode. At the end of the acceleration, the torque demand will drop because the vehicle no longer needs to counter its inertia, but only road losses. The IMA will work as a generator, but the amount of charging will be different in the three cases of SOC (high, low, and very low).

a) High SOC

The SOC being high enough, it is unnecessary to charge the main battery pack. The charge will then correspond only to the 12V-battery load (see Figure 17). But if the SOC of the main battery pack is too high, it will even cut the charging done by the motor for the 12V-battery and will use the main battery pack in order to always be able to use the regenerative braking.

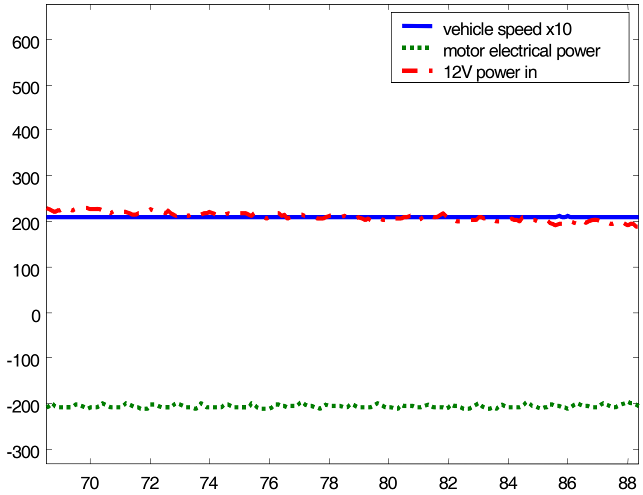


Figure 17: Motor Used for 12-V Battery Load

b) Low SOC

At low SOC, during cruising mode, the IMA will be used to charge the main battery pack as well as the 12V-battery (see Figure 18). The charging mode will stop only when the SOC is equal to 70%.

Although the principal condition for charging the main battery pack is a low SOC, it is not the only one. In a case where the SOC drops too fast, without being low, the charging will start as well. The assist will also be given with the conditions of low SOC (only for full acceleration).

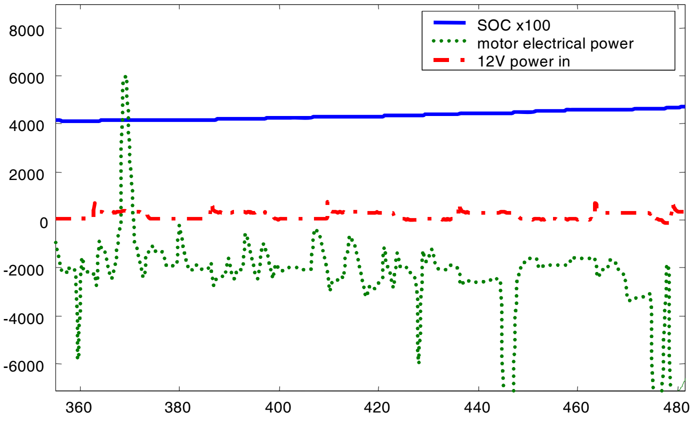


Figure 18: Battery Charging at Low SOC

c) Very low SOC

The general behavior will be the same as at low SOC; the difference concerns only the assist.

4. Deceleration mode

When the driver brakes or just backs off the accelerator pedal to its initial position, the engine will be shut down (injection and ignition stopped) and the motor will be used as a brake and will use the current created to charge the main battery pack. The amount of braking given by the motor is only limited by the value of current allowed by the battery. The engine friction and the mechanical brake will provide the rest of the braking. But as for the acceleration mode, the driver is yet the controller: if no regenerative brake can be given (e.g., if the clutch is unlocked), he will have to press the pedal harder to compensate.

Except when the SOC is really too high (in that case the regenerative brake simply will be cut), the amount of braking will always be the same and depend only on driver brake torque demand.

5. Stationery mode and engine Auto-Stop.

We have just mentioned that the engine was off during the deceleration. In the case where the driver shifts back in neutral before the engine has downed under idle speed, the motor will be used to actively stop the rotation of the engine (by maintaining a negative command on the motor). If the vehicle stops, the engine will remain off (if the driver shifts back to neutral with the engine still on and the vehicle stopped, the engine will stop as well). It will only start again when the driver shifts back to first gear or accelerates (see Engine Starting, above).

STANDARD CYCLE VALIDATION

The validation was performed on four standard cycles: Japan 10-15, NEDC, FHDS, and FUDS.

Once the components have been validated and the road load match achieved, the consumption and SOC will be influenced only by the control strategy. Indeed, the charge of the battery, the assist, the regenerative braking will be the parameters determining the final fuel consumption and SOC.

Because the speed trace of the Japan 10-15 was made of a succession of simple trapezoids, it was easier for validation to preliminary tune the model on it. That cycle will be used to explain the process for proving the validity of the PSAT model.

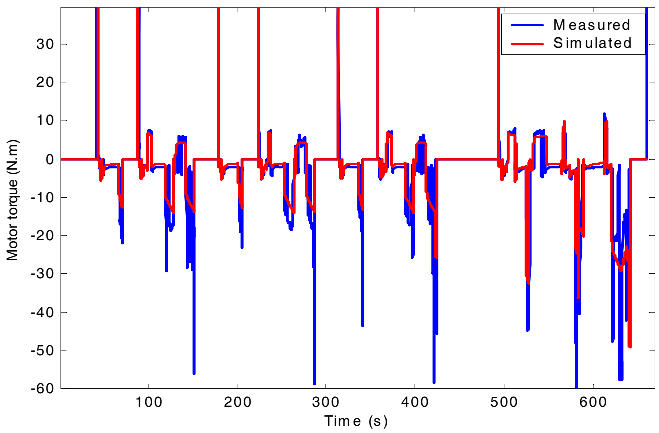


Figure 19: Simulated vs. Measured Motor Torque

Figure 19 shows that the assist, charging, and regenerative braking occur at the right moment and apparently with the right amount. Nevertheless, a closer view is necessary to assess whether the strategy is effectively right in the PSAT model.

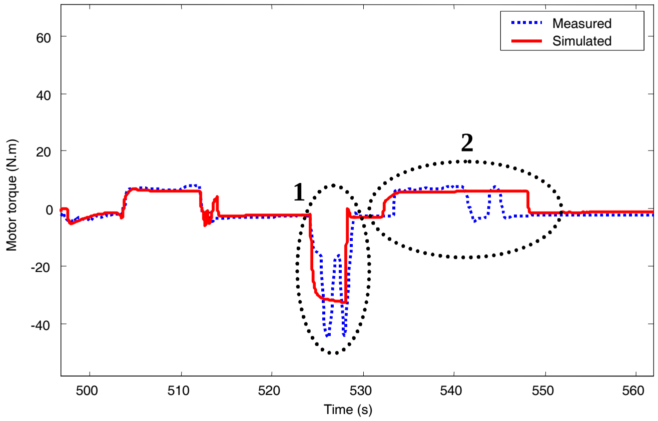


Figure 20: Zoom on Figure 19

As shown Figure 20, the simulated motor torque tracks the measured one, except for slight differences shown in zones 1 and 2. These have explanations:

- Zone 1: The driver is braking on this phase of the cycle, and the motor is used both to brake and to charge the main battery pack. In this case, the test driver braked harder than he should have, then released the pedal and finally braked again. Unlike the real driver, the driver model will calculate the exact amount of braking torque he needs to decelerate and follow the trace, which will result in a smoother command. But the average braking torque is the same, as well as the average regenerative braking torque. Consequently, the SOC will still match well during those decelerations.
- Zone 2: The driver is accelerating on this phase, and the motor is providing some assist to the engine. The reason for the difference is the test driver, who is not as smooth as the model. But the average amount of assist given is approximately the same and will therefore affect the fuel consumption and the SOC in the same way.

Moreover, as shown on Figure 21, the simulated SOC is following the measured on every satisfactorily.

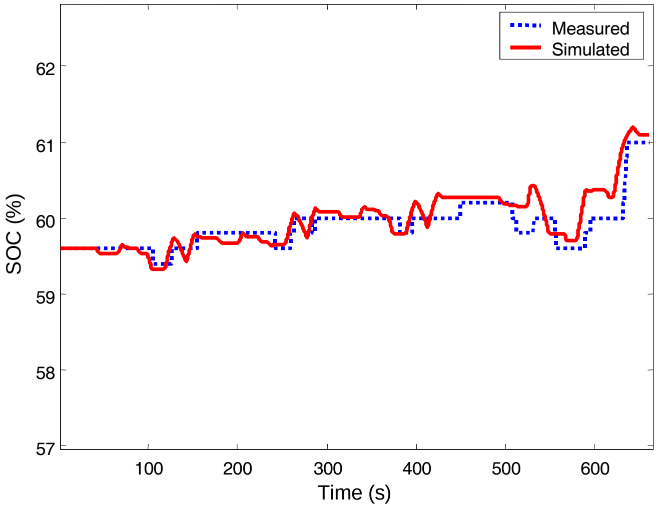


Figure 21: Simulated vs. Measured SOC

Even if the control strategy is not defining the amount of engine torque given and the engine model has been yet validated independently, it is still interesting to compare the engine torque to see whether the model commands and gives the right engine torque for any torque demand. In our case, Figure 22 shows that the simulated torque follows the tests one, proving the PSAT model validity.

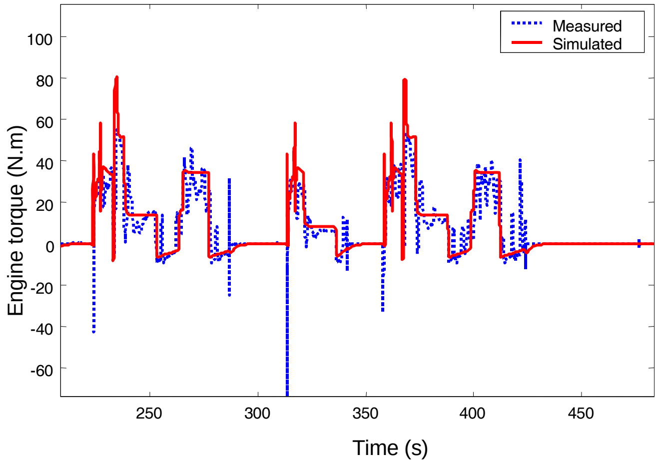


Figure 22: Simulated vs. Measured Engine Torque

In order to check whether the ABC model used to simulate the road losses is effectively giving fine results, it is essential to compare the torque at the wheels axle of the model to the measured one. Figure 23 shows that the torque on the wheel axle is really close, either when it is positive or negative. That lead us to affirm that the road load is effectively right in the model, as well as the part of braking provided by the motor and the engine friction.

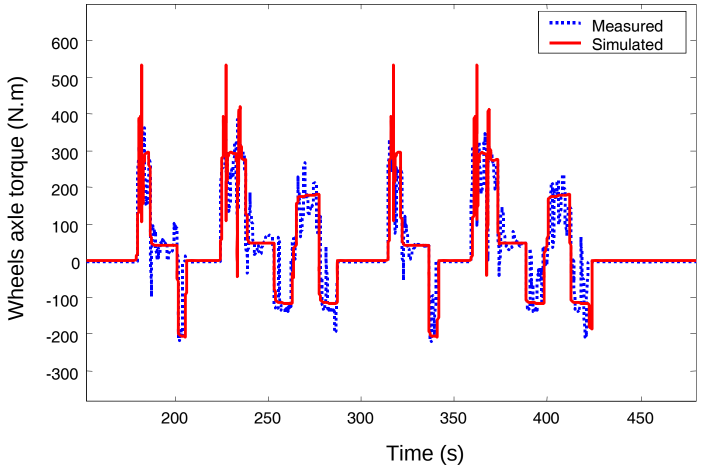


Figure 23: Simulated vs. Measured Wheels AxleTorque

We stated previously that one goal of the validation was to reach a final consumption within 5%. Nevertheless, we may be lucky and, as for the SOC, it is essential to determine whether the fuel rate of the model follows the test one on the cycle. Figure 24 shows that the fuel rate is tracking the measured one very well.

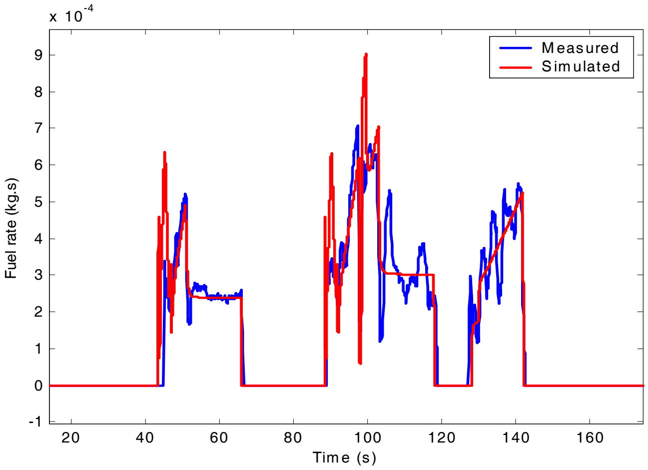


Figure 24: Simulated vs. Measured Fuel Rate

To conclude, on the Japan 10-15, the results given by the model are very close to the tests: the strategy controls the motor very satisfactorily, either in assist, in charging, or during regenerative braking. Moreover, the road load is also well estimated. The validity of the process used to estimate the engine torque has been established, showing it actually gives very consistent results with the tests and the right global efficiency for the drivetrain. The final consumption and SOC are correct (see Table 2), and both the fuel rate and SOC follow the test trace all along the cycle.

The same analysis was achieved on the other three cycles and also gave very satisfactory results.

Table 2 gives the final consumption and SOC for the tests and the simulation with the percentage difference on the four cycles.

Table 2: Final Results

Drive Cycle	Measured Fuel Economy (mpg)	Simulated Fuel Economy (mpg)	% Difference	Initial SOC	Measured Final SOC	Simulated Final SOC	% Difference	ANL Test
Japan 10-15	57.95	58.8	1.5%	59.6	61	61.1	0.16%	0#12 04-12-01 1015 JAA 1165805.txt
NEDC	60.65	60.25	0.66%	60	60.2	58.3	3.26%	0#5 04-12-01 ECE JAA 1165580.txt
FHDS (U.S. Highway)	74.25	75.3	1.4%	59	58.8	58.9	0.17%	0#9 04-12-01 HWY JAA 1165750.txt
FUDS (U.S. City)	58.3	57.85	0.8%	72.8	70.6	72	2%	0#2 04-11-01 UDDS JAA 1164340.txt

CONCLUSION

Validation appears to be a crucial process for a modeling tool. Moreover, the complexity of this process is proportional to the complexity and the diversity of hybrid electric vehicles. In this paper, a generic methodology has been used not only to validate a model, but also to understand the vehicle behavior and control strategy. The validation of the PSAT drivetrain model of the Honda Insight has also been demonstrated. A common understanding of what validation means is necessary to be able to compare and improve the different models.

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APPENDIX 1: Honda Insight Main Parameters

Parameters	Published values	Units
Vehicle		
Mass	855.9	Kg
Wheel base	2.4	M
Frontal area	1.905	M^2
Coeff. drag	0.25	
Tires	165/65R14	
Engine – 1.0L VTEC-E gasoline		
Cylinder	3	
Displacement	1000	cc
Air-fuel ratio	23-24:1	
Power	50 kW @ 596 rad/s Net 54.4 kW @ 596 rad/s with IMA	
Torque	89.2 Nm @ 502 rad/s Net 123 Nm @ 209.4 rad/s with IMA	
Transmission – 5-speed manual		
Ratio	Gear 1: 3.46 Gear 2: 1.75 Gear 3: 1.10 Gear 4: 0.86 Gear 5: 0.71	
Final drive	3.21	
Electric Motor – PM DC Brushless		
Power	10 kW @ 300 rad/s	
Torque	126 Nm @ 209 rad/s	
Battery – NiMH Panasonic		
Rated capacity	6.5	Ah
Pack voltage	144	V
Number of modules	20	
Cells per module	6	
Cell voltage	1.2	V