Report #1

Challenge X: Stock Vehicle Modeling

David E. Smith, John W. Miller
Team Leaders, The University of Tennessee

David K. Irick
Faculty Advisor, The University of Tennessee

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ABSTRACT

Modern automotive design philosophies revolve around developing an understanding of design trade-offs through mathematical modeling and simulation. In order to develop a hybrid electric vehicle powertrain that meets the design objectives of Challenge X properly, a mathematical representation of the stock conventional Chevrolet Equinox vehicle must first be established. A model has been created in the Powertrain Systems Analysis Toolkit (PSAT) environment and validated against actual vehicle test data supplied by General Motors (GM) for the purpose of establishing a simulation baseline and acclimating the team members to the PSAT modeling tool.

INTRODUCTION

The University of Tennessee Challenge X team supports and adheres to the structured design approach outlined by the GM Global Design Validation Process. The cornerstone to this approach relies on extensive mathematical modeling and parametric studies of the proposed vehicle to determine optimum powertrain configurations with respect to performance, fuel economy, and other restraints as cascaded from the Vehicle Technical Specifications (VTS) document. In a competition such as Challenge X, a vehicle level representation of the conventional vehicle must be developed and validated so that subsequent hybrid powertrain design studies can be performed and compared.

To establish a baseline vehicle level model, the conventional Chevrolet Equinox vehicle must be modeled and validated. PSAT has been designated as the development tool to accomplish this task, which utilizes the processing power of MATLAB/SIMULINK. Through the exercise of creating and validating the conventional model, a baseline for future comparison and a working knowledge of the design tool is acquired by the team.

MODEL ANALYSIS AND VALIDATION

The analysis and validation of the conventional Chevrolet Equinox model is divided into three (3) distinct regimes: 1) performance (0 to 60 MPH accelerations), 2) steady- state, and 3) fuel economy prediction over defined driving cycles.

PERFORMANCE (0 TO 60 MPH) ANALYSIS

The results of the acceleration simulation and the eight provided sets of test results are summarized in Table 1 with respect to elapsed time from initial vehicle movement (IVM) to 60mph. The simulations were performed using the vehicle model utilizing the dynamometer coefficients determined from coast-down tests performed by GM. The test data provides two vehicle speed values, one taken from the CAN bus (labeled *neo*) and one from an independent sensor (labeled *pro*), as well as a wheel speed value.

Table 1 Acceleration Results

Test ID	IVM-60mph Time (sec)
Simulation	8.9
MRG_576PER1	9.65
MRG_576PER2	9.52
MRG_576PER3	9.65
MRG_576PER4	9.42
MRG_576PER5	9.60
MRG_576PER6	9.47
MRG_576PER7	9.55
MRG_576PER8	9.50
Test Average	9.55

Figure 1 shows the initial few seconds of the simulation, and Figure 2 shows the initial few seconds of two representative tests from the GM test data. There are apparently issues with synchronizing all of the sensor signals in the test vehicle as illustrated in Figure 2. The wheel speed and *neo* vehicle speed would be expected to track each other. Based on this, it appeared to be most reasonable to use the *pro* vehicle speed values for determining the IVM-60mph times for the test data. Figure 1 also clearly shows the initial wheel spin (tire slip) in the actual tests that does not appear to be simulated in PSAT.

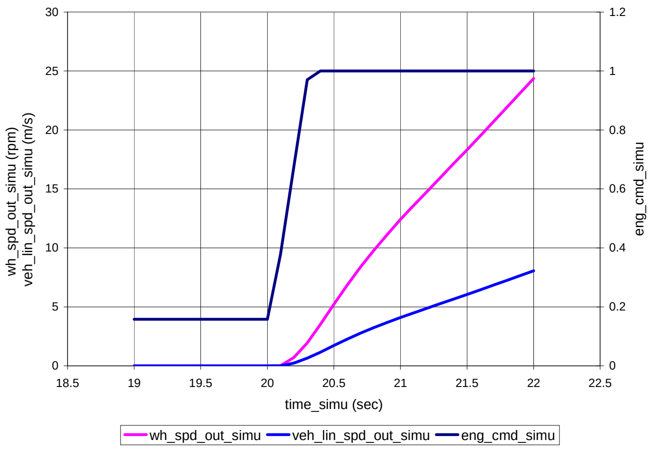

Figure 1 Start of acceleration simulation

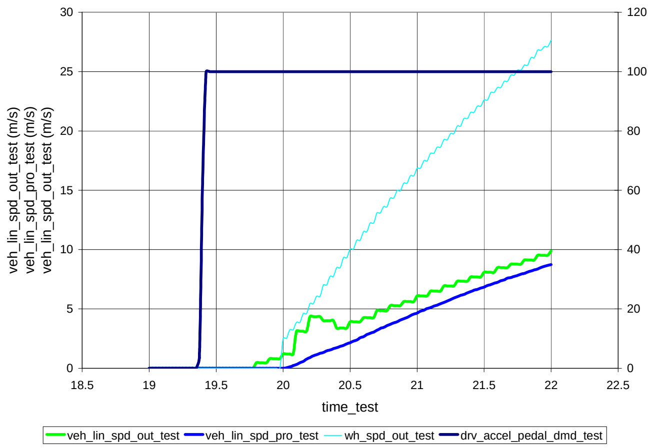

Figure 2 Start of acceleration test

Although the IVM-60mph times from the simulation are fairly close to the actual test times, the overall speed vs. time for the simulation differs greatly from the actual test results as shown in Figure 3. Understanding the source of this difference is vital to analyzing the simulation vs. test for all cases. The vehicle acceleration in the simulation is always greater than the actual test as shown by a greater slope in Figure 3; this is especially evident after the test vehicle shifts into 3rd gear. A plot of vehicle acceleration would be more appropriate, but the acceleration data for the actual tests varies widely due to being a calculated derivative of the speed data. Numerical differentiation generally results in less accurate data for the derivative than the original data [1].

Figure 3 also shows a difference in the simulation and the actual test with respect to the transmission gear shift points. The shift schedule used in the simulation is per the data supplied by GM in the Excel spreadsheet file *equinox_shift_tcc_map.xls*.

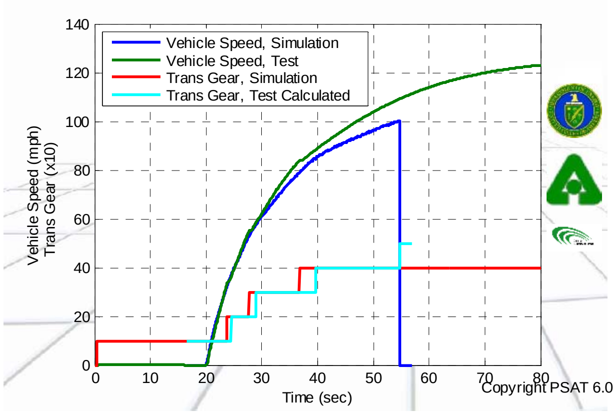

Figure 3 Acceleration results from simulation and test

The actual vehicle may utilize more than one, or perhaps an adaptive, shift schedule because it is apparent that the actual vehicle shifts at higher vehicle speeds that the simulated vehicle. It is also evident in Figure 3 that the actual vehicle does not have the momentary decrease in acceleration that the simulated vehicle exhibits. These observed differences between simulation and testing, however, would result in slower acceleration for the simulated vehicle, and the opposite result is seen. The larger acceleration values at all speeds for the simulation suggests a closer look at the engine output being used in the simulation, as well as the engine output calculated from the test data.

The engine initialization file utilized in the PSAT acceleration simulation contains the wide open throttle (WOT) torque values provided by GM as the values for the variable *eng.init.trq_max_hot_map.* The engine torque values corresponding to the WOT acceleration in the simulation are shown in Figure 4 along with the Test 1 Data, clearly showing that the WOT torque values from Test 1 are used for the simulation. Note that for certain conditions during the acceleration simulation, the engine is not providing full torque. These are associated with gear shifts and are a result of the logic in the powertrain controller, and would also affect the simulation to result in a longer IVM-60mph time.

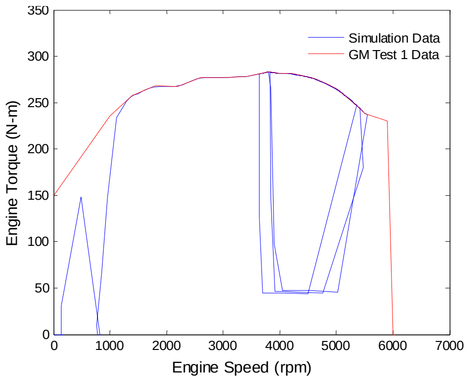

Figure 4 Engine Torque during acceleration acceleration simulation

The acceleration test data was imported into PSAT and the calculated engine torque was examined for the acceleration tests. Representative data from one of the acceleration tests is shown in Figure 5.

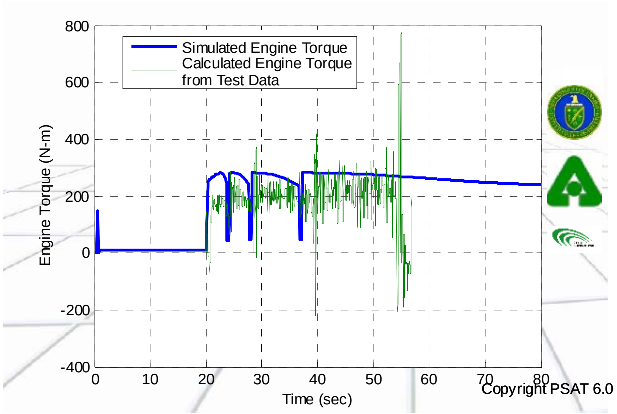

Figure 5 Simulated and calculated engine torque

This calculated data shows the expected “noise” since it is based on a vehicle acceleration that is numerically differentiated from the vehicle speed data. A rough estimate was made for a maximum torque curve vs. engine speed from these calculated torque values versus the actual engine speed recorded during the test. A simulation was then performed using this estimated maximum torque curve, and the results are shown in Figure 6. It is clear that the calculated engine torque, or at least the estimated maximum torque curve, does not result in an acceleration simulation that matches the actual test data. From this, it was concluded that the calculated engine torque values do not represent the engine torque during the actual test. It was assumed that other performance and efficiency values calculated from the test data would yield similar results, and no other parameters were examined.

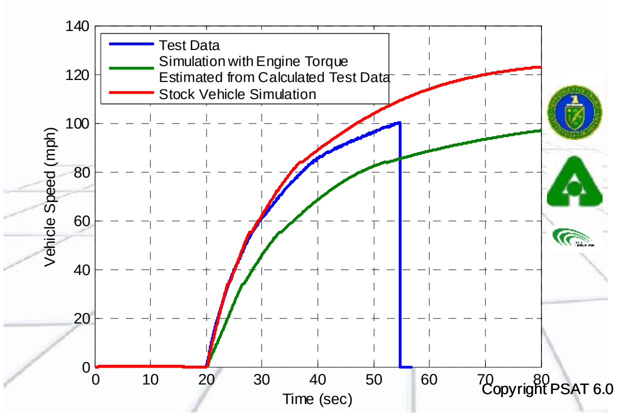

Figure 6 Simulation using estimated engine torque from test data calculation

The data that was recorded during the tests was examined to determine if the engine output was actually per the WOT torque values provided in the Test 1 data. The manifold pressure recorded during the actual acceleration test was within approximately 1% of the values in the Test 1 data. However, the spark advance data recorded during the test are significantly lower than the values from the Test 1 data as shown in Figure 7. The significance of this difference is illustrated in Figure 8. Assuming that Test 1 was performed with the spark advance set at minimum for best torque (MBT), retarding the spark as shown in Figure 4 would certainly reduce the torque produced by the engine at a given engine speed and manifold pressure. Retarding the spark is one strategy employed for traction control. As shown in Figure 2, the tires are slipping during the initial acceleration, and traction control was likely applied. This could explain the retarded spark during the initial period in 1st gear. But as the transmissions shifts into higher gears, the wheel torque is decreased, and the need for traction control is not likely. Retarding the spark is also one strategy used to prevent overheating the catalyst system. If the engine control module detects an operating condition that would result in high exhaust temperatures, certain modifications to the “normal” operating parameters, spark advance and air/fuel ratio for example, are made to prevent damage to the catalyst.

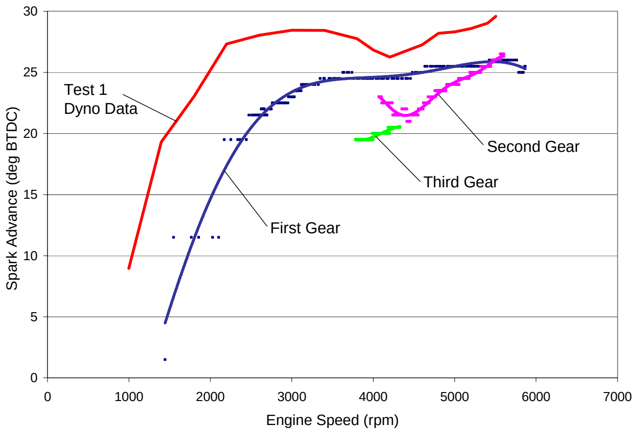

Figure 7 Spark advance for acceleration test

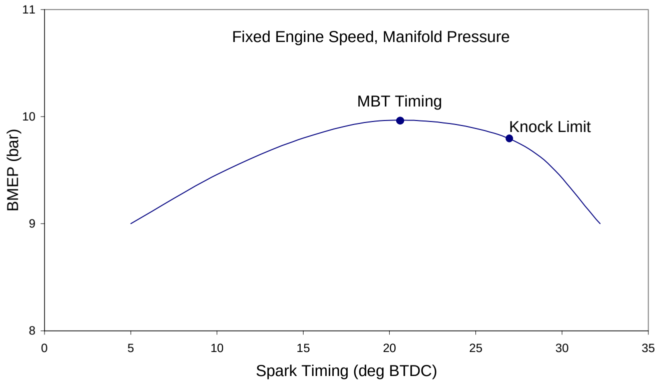

Figure 8 MBT spark timing [2]

The torque map discussed above that is used for PSAT simulations is static; it applies for all operating conditions during the simulation. Adjustment to the simulation to replicate this reduction in engine torque from retarding the spark is not practical in a map-based engine model such as that used in PSAT; the number of maps and the logic to determine which one applies would be prohibitive. To accurately simulate the actual engine operation would require a dynamic engine model, such as WAVE [3] or GT-POWER [4], and a control logic containing the spark advance strategy.

STEADY STATE ANALYSIS

PSAT simulations representing steady state operation have been performed for a host of vehicle speeds and compared against actual test data. Figure 9 depicts a summary of the fuel consumption rate results. The results from both PSAT models are compared to the test data results on a percent difference basis.

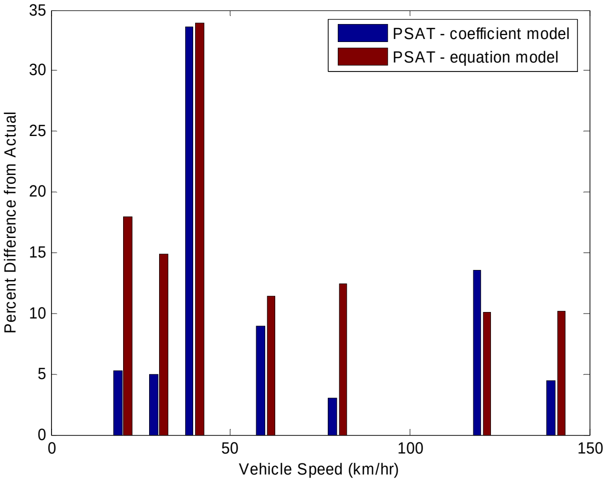

Figure 9 Steady state fuel consumption rate comparison to actual GM test data

The results representing the test data are calculated by taking an average of engine speed and manifold pressure at points where the test data most closely represents the prescribed constant speeds. Fuel rate data from Test 18 is used to determine the fuel rate for the engine conditions recorded in the steady-state test data. The data suggests that the PSAT model based on coefficients derived from coast-down testing provides a more accurate representation of the vehicle when predicting fuel consumption rate than does the vehicle model utilizing the frontal area and coefficient of drag. Differences between the simulation data and the test data can also be contributed to the inability of the test driver to follow a constant speed trace, whereas the simulation follows the speed trace exactly. The simulations using the dynamometer coefficients represent the data more accurately than does the equation model.

The simulation results for a steady state speed of 40 kph display large deviations from the actual test data. It can be observed that the simulated vehicle at this test condition is in third gear, while the actual test vehicle is operating in fourth gear. The transmission shift map provided by GM shows the transmission is commanded to shift from third to fourth gear at a value just below 40 kph, 39.98 kph, at low throttle positions such as steady driving at 40 kph. Figure 10 shows the simulation shift schedule and the calculated shift schedule for the test data for 40 kph. The actual vehicle is not shifting as evidenced by a nearly constant engine speed during the time when the calculation shows the up-and-down shifting.

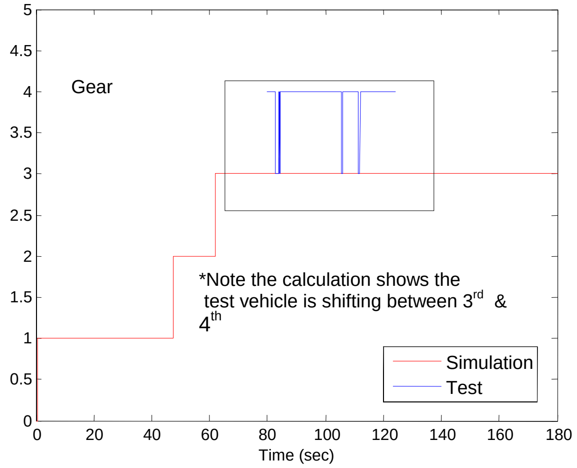

Figure 10 Comparison of simulated and calculated shifting

FUEL ECONOMY ANALYSIS

An initial indicator of the predictive ability of the model was determined by running three (3) common driving cycle simulations. These are summarized in Table 2. The PSAT equation based model again predicts the actual fuel economy in all cycles more accurately than the coefficient based model.

Table 2 Fuel Economy Comparison for Selected Drive Cycles

	Fuel Economy (MPG) (% diff from actual)		
Source	**UDDS**	**Hot 505**	**HWFET**
GM Actual Data	**20.5**	**22.5**	**29.9**
PSAT – coefficient	**21.2** **(+3.2%)**	**22.9** **(+2.0%)**	**30.0** **(+0.5%)**
PSAT - equation	**21.4** **(+4.1%)**	**23.4** **(+3.9%)**	**31.8** **(6.4%)**

Note that for the cold UDDS, there is no cold engine fuel consumption data, and PSAT used the hot data for the simulation, and it also used a coolant temperature of 90°C for the entire cycle. The test data shows that the cycle was not actually begun with a cold start; the coolant temperature was approximately 50°C at the start of the cycle. An actual cold start would exhibit greater fuel consumption due to the cold start fuel enrichment, and a greater difference between simulation and test would be observed.

Figure 11 represents an excerpt of the HWFET cycle. The encircled area marked “A” represents an anomaly in the actual vs. simulated transmission operation. This is due to a difference in the shift logic between the actual test vehicle and the model. This is confirmed by the transmission gear plot directly above the marked region. This phenomenon was shown earlier in the performance data analysis. It is highly probable that the actual test vehicle utilizes an adaptive shift strategy and/or multiple shift maps in the actual transmission control module whereas the simulation uses only one map for all operating conditions.

The second area, marked “B,” represents a departure of the simulated data from the actual data. From the transmission gear plot, this is *not* due to shift logic. The engine speed increases for the actual test vehicle data during a moderate acceleration portion of the drive trace that immediately follows a steep deceleration. This does not happen for the simulated vehicle. It is evident that the torque converter is unlocked during these moderate accelerations and has a greater speed ratio than the simulation. This can be attributed to the difference in test driver aggressiveness in following the prescribed vehicle speed schedule and/or the possibility of multiple torque converter lock-up maps in the actual test vehicle control strategy.

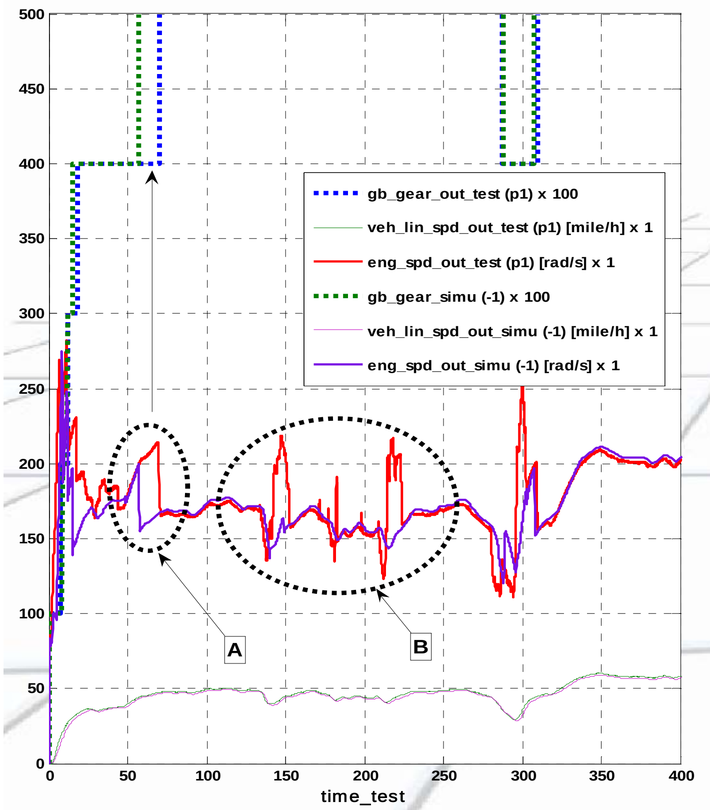

Figure 11 HWFET comparison of actual vs. simulated engine and transmission operation

CONCLUSION

The accuracy of the acceleration simulation is limited by the structure of the PSAT modeling tool. The map-based engine model can only use a static WOT torque map and cannot be adapted to different torque maps as determined by the engine controller. However, for the purpose for which it is intended, the tool is sufficient to make the objective comparison of different powertrain options. Such engine control strategies as discussed here are likely to be similar for most engines and engine controllers, and therefore a comparison study would yield usable results even though the simulation may not match test data exactly.

As seen during the steady state simulation at 40 kph, the shift schedule of the transmission can cause the simulation results to deviate from actual vehicle test by running the simulated vehicle in a gear different that the test vehicle. This occurs at points in which shift command is very close to the prescribed constant speed. The driver’s inability to follow a constant speed condition causes the vehicle’s speed to vary around the test condition, and when the vehicle reaches the scheduled speed for up-shifting, the transmission will shift to the next gear. As the driver reduces his demand to attempt to maintain the prescribed vehicle speed, the down-shift point may not be reached, and the transmission remains in the higher gear. The PSAT driver model maintains the prescribed speed exactly, and therefore, the simulation does not replicate the vehicle speed variation response to the real driver that results in the described shifting.

Simplification of the shift logic strategy in the PSAT vehicle model plays a significant role in accounting for the differences of the predicted fuel economy to the actual fuel economy. However, this simplification is adequate to provide reasonable results for directional development of a prospective powertrain. In addition, the structure of PSAT is such that the shifting model could be enhanced to include more representative control algorithms should a more accurate model be needed. This feature will be particularly useful during hybrid control strategy development.

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