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Model-Based Design of a 2013 Chevrolet Malibu

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Abstract

Rose-Hulman Institute of Technology, located in Terre Haute, Indiana, is one of 15 North American collegiate teams selected to participate in EcoCAR2: Plugging into the Future. Headline sponsored by General Motors (GM) and the Department of Energy (DoE) and coordinated by Argonne National Labs (ANL), this three year competition challenges participating teams to hybridize the powertrain of a 2013 Chevrolet Malibu to decrease well-to-wheels petroleum consumption and emissions production while maintaining consumer acceptable levels of performance, utility, and safety. The competition is currently in the first year where the principles of Model-Based System Design (MBSD) are employed to develop Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and Hardware-in-the-Loop (HIL) approaches to investigate various architectures. The second year, the “mule” year, focuses on integrating key powertrain components into the vehicle and verifying vehicle operation. The third year, the “production” year, is one of refinement such that the vehicle looks, feels, and performs like a production model.

The first deliverable of year one was to develop a MIL of the stock vehicle and validate it with experimental data. This was to provide baseline data against which ensuing hybridized versions could be compared and to ensure that the teams were capable of successfully implementing a MIL. Utilizing tools from The MathWorks including Matlab, Simulink, SimScape, and StateFlow, mathematical models of road loads and powertrain components were created and characterized using data extracted from Autonomie initialization files. As the 2013 Malibu is a new model and still in pre-production, baseline vehicle data was not available against which to validate the model. The deliverable was changed to instead focus on a parametric study of system components and their impact on fuel consumption and acceleration. Results of the study are presented and sensitivities are discussed. Additionally, several CAD views highlighting powertrain components were added as a deliverable and included in this paper.

Keywords: education, modelling, simulation,

1 Vehicle Overview

The vehicle provided for the EcoCAR2 is Chevrolet's new 2013 Malibu. The 2013 model year begins a new phase for the Malibu, moving to the Epsilon 2 platform, and getting a full restyling to give it a more distinctive "GM look" as well as an unprecedented drag coefficient of 0.295. Beyond the body panels, the 2013 Malibu will currently be made available in two powertrain configurations. The base configuration, which was modeled for this report, uses the Hydramatic 6T40 six-speed automatic coupled to a 2.5L Ecotec 4-cylinder gas engine with an estimated 190 hp (141 kW) at 6200 rpm and 180 ft-lb (245 Nm) at 4500 rpm. The other configuration is a mild hybrid which utilizes a similar transmission but with a slightly smaller 2.4L 4-cylinder gas engine electrically hybridized with a Belt-driven Alternator-Starter (BAS) unit. The stock model with the base powertrain configuration is presented in this paper as it will be used as the benchmark through the development of the powertrain and vehicle integration.

Raw vehicle, component and performance data was unfortunately not available from General Motors for this report due to the pre-production nature of the vehicle. Data was mined from the Autonomie initialization files and we were cautioned that it should not be assumed to be accurate. However, for the educational exercise of building models and performing a parametric study accurate data was not necessary.

2 Model Structure

Rose-Hulman is an undergraduate focused Institution of Technology which has been ranked number one in undergraduate engineering the last 13 years in a row, strongly because of our rigorous academics and hands-on approach to learning. Additionally, The MathWorks, Freescale, and Mototron have sponsored a $650,000 Model-Based System Design lab which has two courses already developed to teach system modeling techniques tailored to the MIL-SIL-HIL process [1-5]. While using a packaged program such as Autonomie [6] is tempting, a tremendous amount of critical learning is achieved by having the team members develop their own models from first principles and extend them with physical data.

An extraordinarily simple Conservation of Linear Momentum model

$$m\frac{dv}{dt} = \sum F \qquad (1)$$

which completely neglected all losses and assumed complete conversion of chemical to mechanical energy was first implemented to investigate the absolute lower bounds of energy requirements to follow drive cycles while becoming familiar with the MathWorks Simulink modeling environment. With a vehicle mass of 1564 kg, the combined 4 cycle fuel economy (discussed in the Parametric Study section) is 0.937 l/100 km and represents the maximum fuel efficiency achievable for a gasoline powered vehicle of that mass.

The model was then improved to include road loads, engine and transmission performance data, and weight transfer during acceleration using additional tools from The MathWorks including SimDriveline and Stateflow. Anticipating the evolution from MIL to HIL, the overall model was broken into the Vehicle Plant Model, the Vehicle Controller, and the Driver.

The Vehicle Plant consists of an engine model connected to a transmission model connected to a chassis model. A non-physical block logs data. Hotel loads are not included. The engine is two-dimensional lookup table populated with torque and fuel consumption data mined from the Autonomie initialization files. Based on the driver throttle request, the maximum torque at the current rpm is scaled from zero to one hundred percent. This torque actuates a SimDriveline driveshaft. A Stateflow state machine controls the idle logic while a series of switches "controls" the engine throttle signal to disable the throttle during gear shifts and engine overspeed conditions. The transmission includes a generic torque convertor model, also mined from the Autonomie initialization files, and idealized six speed gearbox utilizing parallel clutches from the SimDriveline toolbox. Gear efficiencies are not included. Transmission shift maps were mined from the Autonomie initialization files and implemented using two-dimensional lookup tables which are fed to a Stateflow machine to trigger clutch openings and closings. The chassis model includes the front differential ratio and tire models which allow for slip. The tractive force generated by the tire is then sent to a solver block which includes the road load, provided by General Motors, to numerically integrate the homogenous form of the two dimensional Conservation of Linear Momentum Equation to obtain path velocity taking into account weight transfer due to acceleration.

$$\frac{d\bar{v}}{dt} = \frac{1}{m}\sum \bar{F} \quad (2)$$

The Controller is currently a dummy block and has been added to reinforce that an overall system controller will need to be developed and refined for the remainder of the year. Driver requests for throttle and brake are passed through a gain of unity.

The Driver block is a feedback loop which scales the error between desired drive cycle velocity and current vehicle velocity. The loop is a simple proportional gain.

3 Parametric Study

To perform the parametric study, a nested for loop was used to vary the vehicle mass from 1514 kg to 1789 kg in increments of 25 kg. For each vehicle mass, a sweep of engine torques and fuel consumptions was performed for the stock curves ± 50% in increments of 10% by simply scaling the output from the lookup curves. The model was evaluated over four drive cycles to obtain the EcoCAR2 effective fuel economy according to

$$FE_{eff} = 0.14 * US06\ City + 0.29 * UDDS + 0.12 * HWFET + 0.45 * US06\ Highway \quad (3)$$

The sweep for estimated fuel consumption with respect to vehicle mass and engine size is shown below in Figure 1.

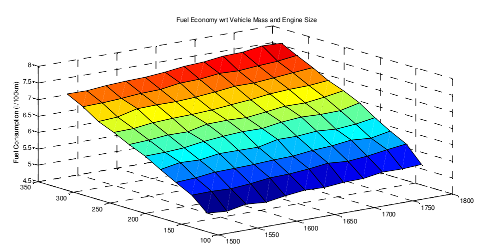

Figure 1 - Fuel Consumption wrt Vehicle Mass and Engine Size

Unsurprisingly, as vehicle mass is increased, fuel consumption increases and as engine size is decreased, fuel consumption decreases. For the standard EPS two-cycle weighting, the predicted fuel consumption for the base Malibu is 8.8 l/ 100 km. Recognizing that the EcoCAR2 four-cycle weighting will be about 25% lower, the simulated fuel consumption of 6.7 l/100 km is extremely low. Model limitations and sensitivity is discussed in the next section.

It is important to assess how well the vehicle is able to follow a drive cycle while the parameters were swept. For the gentle FU505 cycle, traces are presented below in Figure 2 and Figure 3 for the small engine/large mass vehicle (worst expected trace adherence) and the large engine/small mass vehicle (best expected trace adherence). To quantify drive cycle adherence, an RMS error measure

$$Error = \sqrt{\frac{1}{t_f}\int_0^{t_f}(v_{des} - v_{act})^2\,dt} \qquad (4)$$

in the velocity traces was weighted over all four cycles to qualify magnitude with adherence.

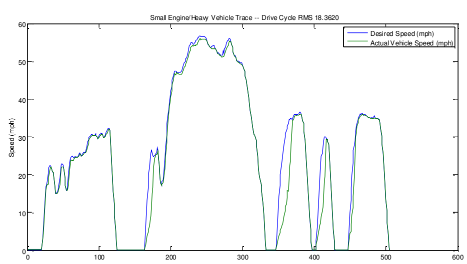

Figure 2: Drive Cycle RMS error for Small Engine/Large Mass

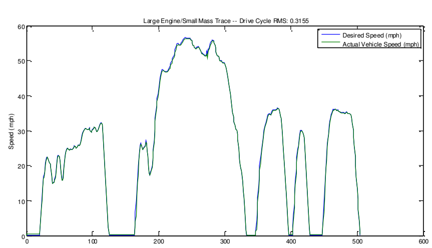

Figure 3: Drive Cycle RMS error for Large Engine/Small Mass

While the small engine/large mass combination demonstrated excellent four-cycle fuel economy of 5.1 l/100 km, the rms error of 18.4 is completely unacceptable with velocity differences between actual and cycle exceeding 30 mph under acceleration. At the near opposite end of the spectrum, the large engine/small mass vehicle demonstrated excellent cycle adherence with an RMS error of 0.3 and a maximum trace error of 0.4 mph at the cost of a higher-than-stock fuel consumption of 7.1 l/100 km. The RMS error for the entire sweep is shown below in Figure 4. This will be a powerful tool helping screen candidate architectures and size components for future work as the best fuel consumption combinations exhibited the worst drive cycle adherence (please note the reversed xy axes to more clearly show the trend). The important takeaway is that a great way to improve fuel economy is to not follow the drive cycle.

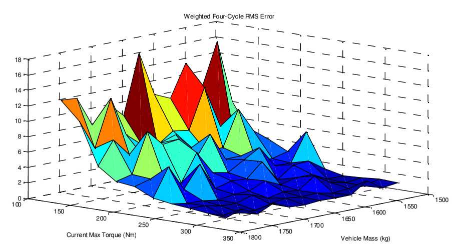

Figure 4: Weighted Four-Cycle RMS Error

Along with fuel economy, acceleration is an important metric. Time required to accelerate from 0 to 60 mph was collected across the same mass and engine sweep space as the fuel consumption. Results for the engine sweep with constant mass are shown in Figure 5, the mass sweep for constant engine in Figure 6, and the overall sweep in Figure 7

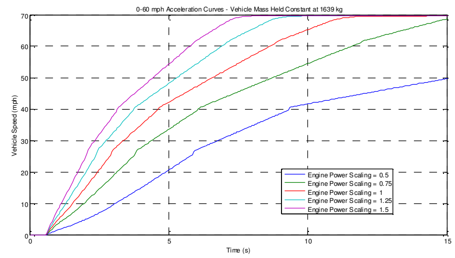

Figure 5: Acceleration Times for Engine Sweep

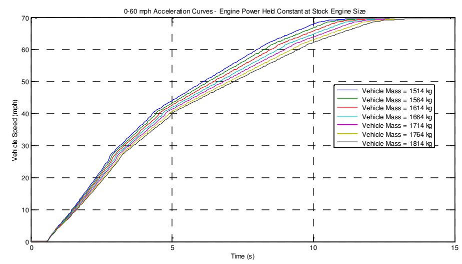

Figure 6: Acceleration Times for Mass Sweep

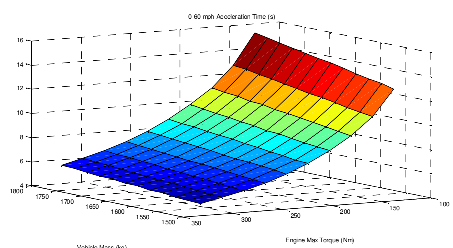

Figure 7: Acceleration Times for Mass/Engine Sweep

Unsurprisingly, as mass increases the acceleration time increases and as the engine power decreases the acceleration time increases. Importantly, for a 50% reduction in engine size, the vehicle is unable to meet the metric – a key danger for vehicles operating in charge sustaining mode with a downsized engine. The model predicts the stock vehicle to accelerate from zero to sixty mph in 7.6 seconds, 0.6 seconds faster the provided stock Malibu metric. This is a plausible number considering the data and will be used in the future to verify and validate the components and model. Input sensitivity is discussed in the next section.

4 Model Limits and Sensitivities

During the course of the parameter sweeping a number of model limitations were discovered. The model was built using readily available component blocks from within SimDriveline with a focus on understanding the model. The tire blocks allowed friction but required small time steps when the model approached a slip condition. Similarly, the use of clutches to select gears was elementary but the slip condition while the clutch was brought up to speed also resulted in small time steps. Simulation time to complete the UDDS drive cycle was almost four minutes. For future work, these components will be replaced with no-slip tires and a variable gear block from SimDriveline.

Additional limitations arose from the absence of vehicle data and performance results. All vehicle data was mined from Autonomie initialization files with the team being cautioned that the mined data was not truly General Motors Data. As an example, the Autonomie engine torque curve exhibited several discontinuities and was smoothed to prevent simulation torque spikes. Also, the capacity factors and velocity ratios for the torque converter were generic and did not represent the stock six speed automatic. Further limitations arose from the model itself. As stated earlier, geartain losses were neglected and the engine model was, by design, a steady state model incapable of reflecting transients. While the model ran and produced results, with no vehicle performance or even external simulation data for comparison, it was challenging to determine if the vehicle model was performing correctly.

System sensitivity can, however, be investigated as an educational exercise for future work and an opportunity to observe general trends.

Acceleration and fuel consumption sensitivity to mass and engine size is presented below for the stock mass with respect to a set increase in engine size and stock engine with respect to a set increase in mass.

Table 1: Acceleration Times for Mass/Engine Sweep

Metric	Fixed Parameter	Varied Input	Input Change	Output Change
Acceleration Time (s)	Mass	Engine Size	+10%	-5%
	Engine Size	Mass	+10%	+10%
Fuel Consumption (l/100 km)	Mass	Engine Size	+10%	+2.4%
	Engine Size	Mass	+10%	+4.5%

For acceleration, the model was more sensitive to mass than engine size. Increasing the mass by 10% increased the acceleration time by 10% while increasing the engine size decreased the acceleration time by 5%. For fuel consumption, the model was more sensitive to mass than engine size. Increasing the mass by 10% increased the fuel consumption by 4.5% while increasing the engine size by 10% increased the fuel consumption by 2.4%. A good rough lesson is that mass is twice as important as power for vehicle performance.

5 CAD Modeling

The following images below are the required CAD Modeling views of the unmodified vehicle. Figure 8 is a front view of the vehicle with the hood open and the bumper removed showing the engine, engine cooling system, invertor, transmission, and air induction. Figure 9 is the bottom view of the vehicle showing the exhaust system and fuel system. Figure 10 is an isometric view of the floor pan. Figure 11 is a side view with the rear bumper removed showing the rear crush zone.

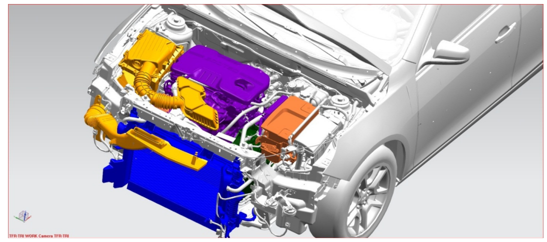

Figure 8 - Powertrain (Blue: Engine Cooling, Green: Transmission, Orange: Inverter, Purple: Engine, Yellow: Air Induction)

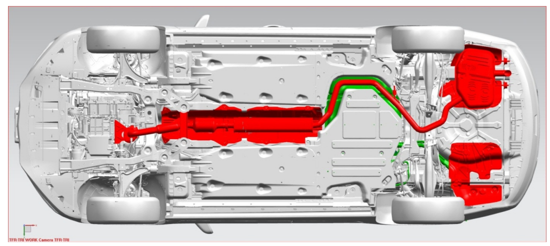

Figure 9 - Underbody (Green: Fuel System and Tank, Red: Exhaust System (Including Heat Shielding))

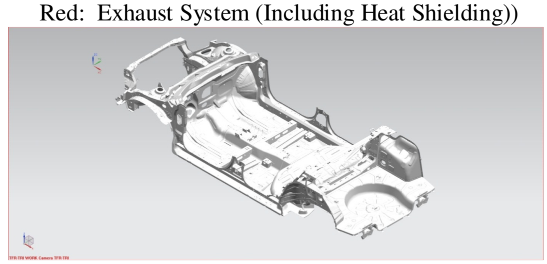

Figure 10 - Floor Pan

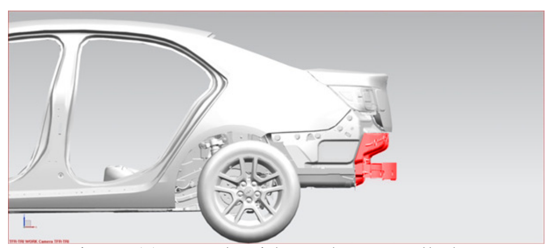

Figure 11 - Trunk with crush zone called out

6 Conclusion

The Rose-Hulman EcoCAR2 team successfully created a stock vehicle model using tools from The MathWorks including Simulink, SimDriveline, SimScape, and Stateflow. Parameter sweeps on vehicle mass and engine size were performed to estimate impact on the EcoCAR2 four-cycle fuel consumption and zero to sixty acceleration time.

The stock vehicle fuel consumption was lower than expected at 6.7 l/100 km. Fuel consumption was found to increase as both mass and engine size increased with the magnitude being twice as sensitive to mass increase as to engine increase. An RMS error plot for the drive cycle and actual vehicle speed clearly demonstrated that the low fuel consumption combinations were not able to acceptably follow the traces. Acceleration times also trended with mass and engine; increasing mass increased acceleration time while increasing engine size decreased acceleration time. The acceleration time was twice as sensitive to changes in mass as it was to changes in engine size. Requisite CAD models were prepared and presented.

7 Future Work

When this paper was originally proposed, the Rose-Hulman EcoCAR2 team was under the assumption that component and vehicle performance data would be available to validate the model. Unfortunately, the vehicle remains in preproduction at this time and validation data remains unavailable except for estimates of acceleration and fuel economy. When the team receives its vehicle in the spring of 2012 one of the first orders of business will be to collect data to validate the model. This validation will be presented in a following paper.

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Advisors

Zac Chambers has his BS and MS in Mechanical Engineering from Rose-Hulman Institute of Technology and his PhD in Engineering Science and Mechanics from the University of Tennessee, Knoxville. He has been on the ME faculty for Rose-Hulman since 2000 and has worked with Marc Herniter as Mechanical Advisor for ChallengeX, EcoCAR, and now EcoCAR2 racking up 7 years of experience in hybrid vehicle powertrain design and execution. He additionally serves as the Program Director for the Advanced Transportation System Program at Rose-Hulman.

Marc Herniter is a Professor at Rose-Hulman Institute of Technology (Ph.D., Electrical Engineering, University of Michigan, Ann Arbor, 1989); Dr. Herniter's primary research interests are in the fields of modeling of complex systems, power electronics, hybrid vehicles, and alternative energy systems. He has worked on power electronic systems that range in power levels from 1500 W to 200 KW. He is the author of several text books on simulation software including PSpice, Multisim, and Matlab. He is currently the co-advisor for the Rose-Hulman EcoCAR Hybrid-Electric vehicle team and the faculty supervisor of Rose-Hulman's Model-Based-Systems Design laboratory.