Design Optimization of a Parallel Hybrid Electric Vehicle

Group Homework 2

Mahmoud Al-Zahrani, Andrew Carlile, Hao Chen and Nikhil Ramaswamy
# Table of Contents

1.0 **Parallel Hybrid Vehicle Optimization for Maximizing Value** .................................................. 3  
   1.1 Goals and Problem Domain ........................................................................................................ 3  

2.0 **System Simulation and Specification** ..................................................................................... 4  
   2.1 Interactions between components ............................................................................................... 4  
   2.2 Key Assumptions ......................................................................................................................... 5  

3.0 **Dymola Modeling of System** ................................................................................................. 6  
   3.1 Electric System Modeling Overview ............................................................................................ 6  
      3.1.1 *DC/DC Converter:* ........................................................................................................... 6  
   3.2 Engine and Vehicle Dynamics Simulation Overview ...................................................................... 8  
   3.3 Control System Model Overview ............................................................................................... 10  

4.0 **Verification of Models** ............................................................................................................ 13  
   4.1 Verification of Electric Drivetrain ............................................................................................... 13  
   4.2 Verification of Engine and Vehicle Dynamics ........................................................................... 18  
   4.3 Verification of Control System .................................................................................................... 21  
      4.3.1 *Input* ................................................................................................................................ 21  
      4.3.2 *Control System* ................................................................................................................ 21  

5.0 **Assembly and Verification of the Overall HEV** .................................................................... 24  
   5.1 Test 1 ....................................................................................................................................... 25  
   5.2 Test 2 ....................................................................................................................................... 27  
   5.3 Test 3 ....................................................................................................................................... 27  

6.0 **Lessons Learned** .................................................................................................................... 31
1.0 Parallel Hybrid Vehicle Optimization for Maximizing Value

1.1 Goals and Problem Domain

After reflecting on HW G1, the influence diagram was revised and updated to better reflect the way in which the parameters will affect the fundamental objective of the project. Figure 1 shows the updated influence diagram. The transmission type that will be used in the model is a CVT. The parameters that are used in the model that will be varied are the motor Power (5KW – 70KW), Battery size (1 Ah – 50 Ah), engine power (50 KW – 200 KW) and the maximum reduction ratio of the CVT drive (1 – 5). The gross weight will affect the fuel efficiency of the vehicle along with the main design parameters. The driver’s behavior will reflect how will does the driver follow the UDDS cycle which in turn will affect the fuel efficacy. The driving conditions will include the UDDS cycle and the test of the vehicle’s acceleration and maximum speed.

![Updated influence diagram](image)

The specific questions that are answered through the Dymola model are:

1- What is the fuel efficiency of the vehicle after it completes the UDDS cycle?
2- How long does it take for the Vehicle to accelerate from 0 to 60Mph?

The simulation can help in deciding the appropriate parameters of the vehicle components that should lead to increased fuel efficiency and maximum performance by seeing how these parameters affect the Vehicle performance in the UDDS cycle and how well it accelerates. Those will affect the other components in the influence diagram that will ultimately affect the fundamental objective.
2.0 System Simulation and Specification

The system can be divided into four major parts as shown in Figure 2. The red box includes the mechanical side of the system, which includes the Engine, transmission (CVT and differential), and the dynamics of the vehicle. The green box includes the control side of the Vehicle. These two boxes contain the components of the system. The blue and orange boxes contain the external influence on the system. The Black arrows indicate the power flow in the system. Blue arrows indicate how the control and feedback flows throw the system. Green arrows indicate regenerative braking path.

![Figure 2 Major components of the system and their interaction with the environment](image)

2.1 Interactions between components

- **Input- control**: The input from the UDDS cycle influences the controller, which according to the cycle determines the torques required
- **Control – Vehicle dynamics**: The controller unit determines how much torque is required from the engine and the electric motor to ensure that the vehicle follows the UDDS cycle, monitors the state of charge of the battery and determines when the engine is needed or should be turned off and disconnected from the system.
- **Vehicle dynamics- control**: the control will monitor the velocity of the mass, ensures if it is following the UDDS cycle properly, and adjust the amount of torque and braking required by the system.
• **Environment- vehicle dynamics:** The driver’s mass and drag force from air resistance will influence the speed of the vehicle, which is monitored by the controller unit to follow the UDDS cycle.

• **Environment- input:** The Driver’s ability to follow up on the UDDS cycle will influence the amount of torque requested by the controller, which in turn will affect the other components of the system.

### 2.2 Key Assumptions

The major assumptions made in the system is that the vehicle is assumed to be running on a dry flat road, so no effects of road slope are included. The vehicle mass is assumed to be 1365 kg in this simulation. The engine is assumed to run at a constant throttle of either 0 or 0.1. The transmission of the vehicle is assumed to have no losses in power. The driver’s mass and behavior will affect the gross mass of the vehicle and how well the driver follows the UDDS cycle. In this simulation, the driver’s mass is neglected.

The battery is modeled as a constant voltage source with a series resistor, which means that the open circuit voltage is independent of the state of charge. For the real battery, the open circuit voltage drops when the SOC of battery decreases. However, this decrease is smaller and thus the assumption is valid.

For the DC/DC converter, a steady state model is created instead of building the actual DC/DC circuit, which includes the semiconductor switch and L C components. This simplified model will not be able to model the dynamic response of the converter. However, usually the transient is very fast due to the controller of the DC/DC converter. Therefore, the steady state model is enough to show the characteristic of the converter. Secondly, the efficiency of the DC/DC converter is assumed to be 100%, while in actual it is close to 98%. Finally, the rating of the DC/DC converter is not considered. The master controller of the vehicle will control the maximum power flowing through the converter.

The engine, transmission, and car dynamics are modeled using almost all ideal Dymola models and with simple rotational and/or longitudinal domains. The main assumptions are that the simple car dynamics accurately reflect a car, the inertia, and damping values are good approximations of their real world values. In addition, some changes were made to different mechanical models. The torque curve for the engine was simplified, but it still represents a plausible engine. The CVT transmission is ‘ideal’ and perfectly adjusts to the specified gear ratios. The clutch and braking models are also the simplest versions, and their normal force values are approximate. The car dynamics are loosely based on a previous homework assignment from class.

The other assumptions are with the Control System and are elucidated as follows. 1. Control System does not draw any power from the battery- it is safe to make this assumption, as the power consumed if accounted for will be negligible. 2. Control System a mathematical algorithm and not on a microcontroller- as the microcontroller is also going to be coded with the same algorithm, for simplification purposes the microcontroller and the corresponding circuitry can be neglected.3. Control System never produces stray values- since the microcontroller is not involved cases of sudden burning out of the electronics which govern the control system never arises, hence the assumption is safe.
3.0 Dymola Modeling of System

3.1 Electric System Modeling Overview

The battery is modeled as a constant voltage source with a series resistor. The voltage source has amplitude of 240V and the series resistance value is 0.05 ohms. The state of charge (SOC) of the battery is measured using coulomb counting method, where the current flowing out and into battery is measured and integrated. Figure 3 shows the battery model in Dymola.

3.1.1 DC/DC Converter:

DC/DC converter is modeled as a controllable current source connecting to the input side, and a controllable voltage source connected to the output side. The voltage source signal is determined by the duty cycle and the current signal is determined by the power delivered to the load. A buck-boost converter is modeled in this project, where the input voltage $V_{in}$ and output voltage $V_{out}$ has the following relationship

![Figure 3 Dymola model of battery](image)

$$V_{out} = \frac{D}{1-D} V_{in}$$

$D$ is the duty cycle of the converter. When the output voltage is high than the input voltage, the converter works in boost mode and $D>0.5$. When the output voltage is lower than the input voltage, the converter works in buck mode and $D<0.5$. However, it should be note that $0<D<1$. In addition, as the DC/DC converter, the input power should be almost equal to the output power without considering the loss.

$$P_{in} = P_{out}$$

Using above two equations, Figure 4 shows the model diagram of the DC/DC converter.
The bidirectional DC/DC converter is controlling the motor speed with a reference signal. The motor speed depends on the voltage applied to the motor armature. Moreover, the DC/DC converter should control this desired speed. Therefore, a closed loop controller is required for the converter and the motor. Figure 5 shows the controller diagram. Figure 9 shows the Dymola model of the DC/DC converter and its controller.
The DC motor model built in class was used in this project. Figure 7 shows the Dymola model of the DC motor.

![Figure 7 Dymola model of DC Motor](image)

The entire electric drive powertrain model of the hybrid electric vehicle composed of a battery, a bidirectional DC/DC converter, and a DC motor, is built in Dymola. Figure 8 shows its Dymola model.

![Figure 8 Dymola model of electric drive powertrain](image)

### 3.2 Engine and Vehicle Dynamics Simulation Overview

The engine can roughly be thought of as a model that has torque ($T_e$) and rotational speed ($\omega_e$), and mass of fuel burned ($m_{fuel}$) as an outputs. The input is a simple Boolean that toggles the needed inputs of throttle and fuel flow. The throttle will be either 0 or 0.1 (with 1 being full throttle and zero being no fuel flow) to simplify the system. This value was arrived at by being the smallest that would accurately follow the UDDS drive cycle. Most hybrid vehicles vary the throttle, but for simplification of both the control system and the physical modeling, constant throttle is used when the engine is required. For the engine $T_e$, $\omega_e$, $m_{fuel}$ will be the variables most critical for accurate simulation.
The Simple Engine model was modified in one way for simplifying the model and physics. The torque curve for the default motor was changed to reflect a simpler torque curve of an engine shown in Error! Reference source not found. with the same power output as the example (85 kW). This change was needed for two main reasons: When the default torque table was used, the torques would vary a great deal and the values would cause the control system to over compensate or undercompensate for torque required depending on the speed of the vehicle. In addition, a simple torque curve works well in conjunction with a CVT transmission because the transmission will be able to vary the gear reduction to compensate for the physical changes in the system.

The torque table still reflects the physical reality of an internal combustion running at various rotational speeds. The default fuel table (based on throttle setting) was kept for the system validation. This was done in order to narrow the scope of any problems with the engine model that is shown in Figure 10 as well as the values being used. These will be useful starting point for optimizing the engine component later. The engine model also included damping and inertia matching the “PowerSplitHybrid” example from the powertrain library in Dymola. These models represent the internal inertia and friction of the engine. Another inertial model is used in series with the CVT transmission to reflect its physical characteristics as well.
The Boolean input was used because the control system should only need to send the engine an on or off signal to optimize the fuel efficiency. The booleanToReal model receives this value and passes either a “True” for fuel flow and 0.1 for throttle or “False” for fuel and zero for throttle. The integrator simply sums all of the fuel used for calculation of total MPG later.

For the vehicle dynamics models estimated values such as vehicle mass were used, as the particulars are not important at this stage. The vehicle dynamics modeled are only for simple longitudinal factors: wind resistance, ideal rolling wheel, mass, CVT transmission inertia, and motor inertia. This useful simplification can easily be justified because these factors constitute the majority of the influential factors that determine total car behavior in the physical world.

3.3 Control System Model Overview

The drive cycle the control system drives the car on is the EPA Urban Dynamometer Driving schedule (UDDS). This model consists of a 1-D table of time versus speed. We choose this particular drive cycle as this represents city driving conditions and is used for light duty vehicle testing, which is apt for our simulation. To build this model, we first looked for its data on http://en.wikipedia.org/wiki/UDDS. We organized the data on a CSV file as Dymola can import such files directly. Figure 12 shows the CSV file of the UDDS cycle. The 1D table used in Dymola and the table matrix are shown in Figure 13 and Figure 11.

The UDDS cycle provides the input signal i.e. is speed the vehicle should travel at each particular time instant. Thus, the UDDS cycle interacts with the control system described next.
Since the HEV’s have two degrees of freedom for energy flow controls, the performance of a HEV is strongly dependent on the control of this power split between thermal and electrical power sources. Thus, a good control algorithm is needed to optimize their fuel efficiency. Although complex control algorithms can be developed based on Optimal Control theory such as Dynamic Programming, Pontryagins Minimum Principle, etc. these are not apt for real time control. Hence, we use a Rule based control algorithm.

The Control block takes in the UDDS cycle and the SOC of battery as input and gives $T_e$, $\omega_e$, $T_m$, $T_{req}$ and gear ratio as output. The rule is elucidated as follows.

1. At a particular time step obtain the gear ratio($i_n$), by the quotient of the optimum speed of the engine and the drive cycle speed, as a CVT is being used.

2. From the vehicle dynamics and the calculated $i_n$ obtain the requested torque using

\[
\frac{[T_e(k) + T_m(k)]i_n(k)i_f\eta}{\eta_w} = \lambda M[v(k + 1) - v(k)] + c_r Mg \cos \theta_k + S c_d \rho \frac{\bar{v}^2}{2} + M g \sin \theta_k
\]

where $\bar{v}$ represents the average velocity at the $k+1$ and $k^{th}$ time steps, $\eta$ is the power transmission efficiency, $\lambda$ is the rotational inertia of the driveline, $S$ is the frontal surface area of the vehicle, $M$ is the mass of the vehicle, $c_d$ is the drag coefficient, $\theta$ is the slope of the road, $c_r$ is the rolling friction and $\rho$ is the density of the air.

3. Determine whether the engine should be On/Off by using the current and previous speed from UDDS cycle, individual cases are elucidated below
   a. if $v_k < v_{k-1}$ and $v_k \neq 0$ then torque obtained by the equation and speed is 0 hence engine OFF
   b. if $v_k$ and $v_{k-1} =0$ then engine idles
   c. all other cases engine ON

4. Determine if the motor can provide torque by ensuring SOC is > 0.3, if yes then check if $T_{req} < T_m$ then Engine OFF and $T_m = T_{req}$

5. If $T_{req} > T_m$ then Engine ON and $T_m = T_{req} - T_e$

6. If SOC< 0.3 then Engine On and $T_m = 0$

This rule-based algorithm is summarized in Figure 14.
The above-mentioned algorithm implemented in Dymola is shown in Figure 15. Figure 16 and Figure 17 show the Control System block in Dymola.

The Control System interacts with the Electric Part of the HEV i.e. the motor and the battery by providing the $T_m$ and $\omega_m$ at each time step and gets the SOC of the battery. It also interacts with the Engine by sending a signal whether it should be ON/OFF depending on the $T_{req}$. The assumptions made in this block are already elucidated in the previous section.
The key assumptions are that the Control System does not draw any power from the battery, it is a mathematical block and not a microcontroller, and that the Control System never produces stray values.

4.0 Verification of Models

4.1 Verification of Electric Drivetrain
A simple test model is built in Dymola to test the DC/DC converter. A 300V voltage source is powering a signal current source via the DC/DC converter. The reference load voltage is changing from...
200V to 400V. The converter works in buck mode at 200V and boost mode at 400V. The signal current source is changing from 50A to -50A. A positive current flow means the current source acts as a load, which means the voltage source is supplying power to the current source via the DC/DC converter. A negative current flow means that the power is flowing from the current source back to the voltage source via the DC/DC converter. Figure 9 shows the waveforms of voltage across the current source, signal current, and the current of the voltage source.

![Figure 18 Waveforms of DC/DC converter](image)

The DC motor has been tested in HW1 and the results will not be shown.

The electric drive system model is tested in Dymola. Battery is powering the DC motor via the DC/DC converter. The DC motor is driving a load, whose torque is changing from -300N.m to +300N.m (positive number means the motor acts as a generator). The speed command is changing from 500rad/s to 200rad/s. Figure 19 shows the test model and Figure 20 - Figure 22 show the waveform of motor torque, speed, battery current and the battery state of charge (SOC).

![Figure 19 Electric drive test model](image)
Figure 20 Motor torque and speed

Figure 21 Battery Current

Figure 22 Battery state of charge (SOC)
The master controller of the HEV controls the electric drive. The controller provides the required torque and speed command for the motor and the DC/DC converter control the motor operation based on those commands. Figure 23 shows the test model of Dymola.

![Dymola model of electric drive with controller](image)

**Figure 23** Dymola model of electric drive with controller

The car is running with the UDDS cycle. Figure 24-28 show the motor torque, motor speed, battery current, battery voltage, and battery SOC.

![Motor Torque](image)

**Figure 24** Motor Torque
Figure 25 Motor Speed

Figure 26 Battery Current

Figure 27 Battery Voltage
4.2 Verification of Engine and Vehicle Dynamics

For our project, only longitudinal vehicle dynamics will be considered. The modeling in Dymola is based on examples from class or from tutorial files in Dymola. An example “PowerSplitHybrid” system from the Powertrain library in Dymola was referenced a great deal. The “SimpleMotor” and damping coefficients from this example were used or slightly modified. Figure 29 shows an example of electric drive train coupled to vehicle dynamics.

Figure 28 Battery SOC

Figure 29 Example of electric drivetrain coupled to vehicle dynamics
Figure 30 is the entire tester for the engine, CVT transmission, and vehicle dynamics. To verify that it is an accurate representation of the physical system, the simulation was run with throttle of 0.1, mass 1500 kg, ideal CVT with gear reduction of 5, and matched damping from previous examples or the PowerSplitHybrid example. Validation of the Engine Test model begins by checking for ‘squareness’ of the model. Figure 31 shows the compiler message from Dymola. Once this is complete, the model is at a minimum square and should compile. Once this check has been performed, the model can then be simulated. The Engine Test compiled, and the simulation was run for 60 seconds. The car should behave in a manner similar to a normal car overall with a few exceptions. First, the throttle and gear ratio are set variables, so the acceleration should start fast, and slower taper down as the car encounters more wind resistance. The motor rotational speed should reflect that physical trend by having a small initial value, increase to a realistic value and then level off when the speed levels off due to wind resistance. For the expected fuel flow, the engine should be using fuel at every stage, and the total used should increase. If these general trends hold with reasonable values for an average medium sized car than an assumption that the Engine Test models are all valid is made.

All of the variables examined behaved as expected, and are logical values for the system in the physical world. This system verifies that the models used for the engine, CVT transmission, and vehicle dynamics are valid. This is shown in Figure 32 -36.
4.3 Verification of Control System

4.3.1 Input

EPA Urban Dynamometer Driving Schedule (UDDS)

The input is stored in a 1D table and in particular, it cannot be tested except that by plotting the values one can verify if it is storing all values in order correctly. Figure 37 shows the plot of the UDDS drive cycle.

![Plot of UDDS drive cycle in Dymola](image)

**Figure 37** Plot of UDDS drive cycle in Dymola

4.3.2 Control System

To verify the correct working of the Control System we design two test cases 1. When the SOC < 0.3 2. When the SOC ≥0.3. Since the input cycle is the same for both these cases, these tests will capture all of the conditions encountered when all the subsystems are integrated. The reason is elucidated below.

During the actual working of the HEV the initial SOC will be maximum (0.8 in our case) at this point the Control system can command a value from the motor and hence the engine may be Off at these points thus minimizing fuel efficiency. However as the cycle progresses, the SOC will gradually decrease and be less than 0.3 (minimum value for our case). At these points, the Control system has to switch on the engine and motor will be off until the SOC increases due to regenerative braking. Hence by designing test cases when the SOC is less and greater than 0.3 we will be able to verify the correct working of the Control System.

4.3.2.1 Test case 1(SOC > 0.3)

Figure 38 shows the $T_{req}$ by the HEV over the UDDS cycle. It is observed that at points when the HEV is decelerating the $T_{req}$ is negative hence; this torque can be used for regeneration of SOC. In addition, at points when the speed in zero the engine is idling and the requested torque is a fixed nominal value. This shows that the Control System is correctly calculating the requested torque.
Figure 38 Plot of Requested torque by the HEV over the UDDS cycle

Figure 39 shows the $T_e$ and $T_m$ over the UDDS. It can be seen that since the input SOC is always greater than 0.3 at all points of the drive cycle, the motor will always be able to run and produce a torque output. However sometimes when the requested torque becomes exceedingly high the $T_m$ alone is not sufficient hence, the engine is on at these points and runs at its optimum torque.

Figure 39 Plot of $T_e$ and $T_m$ by the HEV over the UDDS cycle when SOC $> 0.3$
Figure 40 shows the gear ratios over the UDDS cycle. It is observed that as the HEV starts to gain speed the gear ratio decreases until it reaches its maximum speed and then it decreases as the HEV speed increases. This makes sense as consider a scenario when you start a car its idling now hence you want to run it at 1st gear i.e. maximum gear ratio when you want to increase speed you change gears to 2nd, 3rd and so on hence you decrease gear ratios. It is also observed that when the vehicle is decelerating the gear ratio is low, as at this point you want to extract maximum braking torque.

![Figure 40 Plot of gear ratios of the HEV over the UDDS cycle](image)

**4.3.2.2 Test case 2 (SOC < 0.3)**

In this test case the $T_{req}$ and $i_n$ will be same as above test case as we still run the HEV over the UDDS cycle. But, Since the SOC is below the minimum the motor can never give a positive output torque, however the motor can still regenerate and hence when the HEV speed is decreasing the $T_m$ will be negative. This is observed in Figure 41 which shows the plot of $T_m$ over the UDDS cycle when SOC <0.3

![Figure 41 Plot of $T_m$ by the HEV over the UDDS cycle when SOC<0.3](image)
Figure 42 shows the Plot of $T_e$ by the HEV over the UDDS cycle when SOC<0.3. It is observed that since the motor can no longer provide any positive torque the engine always has to be on most of the times and switches of only when the HEV is decelerating. This is also intuitive and this shows that the Control System works correctly.

5.0 Assembly and Verification of the Overall HEV

When the entire system was assembled, connections were made between the subsystems. The mechanical input shaft was coupled with the electrical drive with an ideal differential model with a 50/50 torque split. The velocity of the vehicle is used in the control system, and is sent as a variable sensed from the longitudinal movement of the vehicle. A clutch was added to decouple the engine from the entire drivetrain when it is not required by the control system. This clutch is activated by the control system requiring more torque than the electric motor will output. The overall assembly of the individual components of the HEV is shown in Figure 12.
Since individual components were working as expected three test cases were designed for the HEV
1. Track the UDDS cycle to measure the fuel efficiency
2. Request the HEV to follow a step input to test the acceleration of the HEV
3. Measure the maximum speed from test 2.

5.1 Test 1
The plot of the HEV speed vs. the UDDS cycle speed is shown in Figure 44. It is observed that the HEV follows the cycle. Hence, we are convinced that the model is behaving in a way that is acceptable. Figure 45 shows the SOC over the simulation, it is observed that the initial SOC is set at 0.6. This value is chosen, as we want to utilize the battery over a range of 0.8-0.2 where the open circuit voltage and the resistance of the battery is constant. Further starting at a very high SOC does not truly test the efficacy of the Control System and does not simulate conditions close to reality, as we cannot always expect the battery to be fully charged. Hence, 0.6 SOC was chosen. It is also observed from Figure 45 that the SOC drops initially as a high torque is needed by the HEV and then the SOC increases gradually due to regenerative braking.

Figure 45 shows the plot of fuel consumed by the vehicle over the entire UDDS cycle. It is noticed that the fuel efficiency increases drastically at the beginning and increases slowly at a later part of the UDDS as torque requested is less.
Figure 44 UDDS velocity and velocity of car

Figure 45 Plot of SOC over the UDDS cycle
5.2 Test 2

Along with increasing the fuel efficiency of the vehicle, the acceleration of the vehicle is equally important. Hence, a step command of a 120 MPH is given as input and the HEV is asked to track it. It is observed from Figure 47, which shows the plot of speed of HEV for step input, that although the HEV is able to reach a top speed the acceleration needs improvement.

5.3 Test 3

We measure the maximum speed from Figure 47. It is observed that the top speed the HEV can achieve is around 125 MPH, which is considered good for a HEV.

Apart from the overall simulation with optimum parameters, simulations were also conducted for cases when the important individual parameters of the vehicle are varied keeping all other parameter same. This include
1. Initial SOC if the battery
2. The battery capacity
3. The Maximum torque of the motor
4. The mass of the vehicle
5. The throttle position of the HEV
Figure 48 shows the plot of fuel consumed by the HEV over UDDS versus the initial SOC of the battery. This test is important, as most often in on road conditions one cannot expect a high SOC. Hence, the power that can be drawn from the motor is limited. These cases can decrease/increase fuel efficiency reported. It is observed from Figure 48 that reducing the initial SOC increases the fuel consumed.

![Plot of Fuel Consumed over UDDS vs SOC](image)

*Figure 48 Plot of Fuel Consumed over UDDS vs. initial SOC*

Figure 49 shows the plot of the battery capacity (Q) vs. the fuel consumed. This test determines the optimum size of the battery. A lower Q would charge and discharge the battery quickly hence, the effect of this parameter is important in reporting the optimum fuel efficiency. It is observed that decreasing the Q lower than 2 Ah drastically increases the fuel consumed.
Figure 50 shows the plot of maximum torque of motor vs. the fuel consumed. This case plays a crucial role in determining the size of the engine and motor. As, we consider that the motor delivers the extra torque when the engine is not able to at points of high speed in the UDDS cycle. It is seen that with decreasing maximum motor torque the fuel consumed increases.
Figure 51 shows the plot of fuel consumed over UDDS vs. the mass of the HEV. It is observed that the fuel efficiency increases with increase in mass. This makes sense, as a larger HEV requires more torque to follow the UDDS.

![Plot of Fuel Consumed over UDDS vs Mass of HEV](image1)

*Figure 51 Plot of fuel consumed over UDDS vs. Mass of HEV*

Figure 52 shows the plot of fuel consumed by HEV over the UDDS vs. throttle position of the engine. It is observed that with decreasing throttle position the fuel consumed decreases. However, we must note that we should not choke the engine at the cost of fuel efficiency.

![Plot of Fuel Consumed over UDDS vs Throttle Position](image2)

*Figure 52 Plot of Fuel Consumed over UDDS vs. Throttle position*
6.0 Lessons Learned

In the electric drive system, we were struggling for three parts: DC/DC converter modeling for fast simulation; closed loop controller for the DC motor; and the battery model.

We initially built an actual circuit of DC/DC converter in Dymola. However, due to the fast switching of the semiconductor switch, the simulation speed is too low. Based on discussion with professor, we decided to build a steady state model using signal current source and signal voltage source. This speeds up our simulation by a lot.

We spent a lot of time debugging the closed loop controller for the DC/DC converter to regulate the DC motor speed. The initial controller has two control loops and the control parameters highly depended on the circuit parameters, such as the motor and load characteristics. Finally, we decided using one control loop, which only controls the motor armature voltage. After verification, it shows that the motor speed is still under regulation.

The initial battery model we built has a changing open circuit voltage depending on the battery SOC. However, under fast charging or discharging conditions, we saw a weird large battery voltage. Since the battery open circuit voltage change is very small for the entire SOC range, we decided to use a simple constant voltage source in series with a small resistor.

We learned in the assignment that it is sometimes impossible for the physical system to follow sudden changes in its parameters, so assigning a delay for those changes can help the system to adjust to the required values of these parameters. Another thing was getting the engine to run properly. One of the problems was that we forgot to assign a damper for bearing friction to the engine, which made the engine run at extremely high speeds. Looking up the differential equation of motion was helpful to determine the missing part in the engine model.

We also learnt that for the control system part rather than using individual components or equations, using an algorithm worked best. Even so, we realized that Modelica/Dymola are significantly syntactically different from other Object Oriented Programming Languages and hence proper understanding was needed for correct implementation.