Final Report
ME566
Winter Term 2020

Project: Electric AWD Sedan
Team 13: The Fast and the Electric

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Project Background

Motivation

The constant demand for cleaner fuel sources and lower emissions in today's world makes Hybrid Electric Vehicles (HEV) and Battery Electric Vehicles (BEV) a top priority for most automotive companies. They offer a variety of benefits in terms of fuel efficiency, cost effectiveness, and lower impact on the environment.

In the past, the sale of BEVs and HEVs was limited due to poor performance and charging infrastructure. However, over the years the automotive industry has overcome all such barriers to the point where electric vehicles can compete with some of the best high-performance vehicles. Vehicle range has improved significantly, and charging time has been reduced drastically. This offers an appeal to electric vehicles as people not only have some high-performance vehicles with zero fuel costs, but they also have the sense of joy about protecting the environment.

Furthermore, electric vehicles have far fewer losses and significantly better emission profiles than Internal Combustion Engines (ICE). There are fewer moving parts, no possibility of transmission belt failures and no necessity for oil changes. Overall, electric vehicles are the cleaner, more efficient and the better alternative to vehicles driven on engines. All it needs is the public appeal and the required performance to see a higher population shift towards EVs. That is what this project intends to offer.

Competitor Benchmark

When setting a baseline to compete with, in the electric vehicle segment, it is important for any OEM to investigate the Tesla Model 3. Having become the bestselling electric vehicle in the US market and having won the best-selling luxury vehicle title on the market in 2018, Tesla model 3 has become the leading standard of all the electric vehicles on the market. A vehicle that has outsold many of its internal combustion competitors during its production The Tesla Model 3 is the vehicle that is transitioning people to electric vehicles. Having a direct all-wheel drive vehicle architecture, it carefully considers cost without sacrificing luxury and performance thus creating a unique segment for customers which makes it a more attractive vehicle to optimize. For any automotive company looking to get into this vehicle segment, it is important to understand how the Tesla Model 3 operates and how to compete with it.

Another competitor to consider, that recently joined the electric segment, is the Porsche Taycan. Compared to traditional direct drives most electric vehicles use, the Taycan uses a two-speed transmission to improve the performance of the vehicle. Electric drive motors operate more efficiently than traditional internal combustion engines, so a direct driven powertrain is more practical, but it is also important to consider they have optimal operating ranges. Utilizing a multi-speed transmission like the Taycan can improve the electric vehicle's performance capabilities.

Having taken these two vehicles as inspiration, we envision improving the Tesla Model 3 platform by utilizing a multi-speed transmission to further improve economy and performance. Overall a vehicle with this improvement could challenge the best-selling electric vehicle on the market.

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Project Goal

The goal of this project is to design a high performance, all-wheel drive battery electric vehicle. The vehicle would need to have a high-top speed and acceleration, while also being economically viable for the average consumer. The vehicle would be a direct competitor to some of the best battery electric vehicles on the market such as the Tesla Model 3 and the Porsche Taycan. The novelty is to use an optimized multi-transmission system to drive the motors.

The model utilizes “Lecture 3 EV model” (EV_V1) as the baseline and modifications would be done to incorporate the dual motor, torque optimal allocation control strategy and the multi-transmission system. Drive unit efficiency maps will be drawn to get an accurate representation of the losses and potential performance improvements in the system, which would then be used to get the optimization parameters.

The scope of the projects extends to continuously optimize the performance of the model. Comparison of performance metrics such as horsepower, torque, top speed, acceleration, range, and efficiency will be done against the Tesla Model 3 AWD performance to prove why the novel BEV is likely to be a consumer preference. A V-development strategy will be used to model and optimize the system. Different design and control options need to be investigated before developing models for each system, which would then be compared with the baseline. Once the ideal model is decided based on the first part of the V-development, the focus will be shifted towards improving each result. Final performance testing, validation and optimization will be done using the EPA mandated city and highway cycles.

Project Research

Three different sources were researched to better understand and improve the baseline model, each of which were key in the vehicle's modeling development. Below is a brief summary of the strategies from these resources.

Torque Optimal Allocation Strategy of AWD Vehicles

The torque optimal allocation strategy focuses on the energy efficiency of the system as the optimization goal, proposes a dynamic allocation method to realize the torque distribution of electric vehicle all-wheel drive power systems, analyzes and verifies the adaptability of this optimization algorithm in different urban passenger vehicle working cycles. The difference of the efficiency distribution of the two shaft motors in the power system affects the energy consumption negatively. The proposed method can effectively solve this issue, while also realizing the flexible distribution of torque and improving the power, economy, and stability of the vehicle.

Efficiency maps of electrical machines

This review focuses on the calculation, modeling, and interpretation of efficiency maps for electrical machines. It is calculated using a finite-element analysis-based mapping of losses, torque, and flux-linkage as a function of current and speed. Three example machines are considered for this study and in each machine the key losses are observed to see how they impact the overall efficiency map. These key loss terms can be estimated by analysis of the electrical machine and its control and are different in the constant torque and field-weakening operating regions. Finally it is shown that the power loss of a machine operating at a given torque, T and speed, w, can be represented as the sum of the terms of the form $P_{loss}(T,w)=\sum k_{mn} T^m w^n$, where m and n are integers.

Electric vehicle with multi speed transmission

The last review explores the different types of multi speed transmission systems used in electric vehicles. It specifically references the effects multi speed systems can have on both the dynamic and economic performances. This is mostly because even though electric motors have high torque generation capabilities, they are often inefficient over wide speed ranges and driving conditions. Among the major improvements documented in the article when studying these multi speed systems, the biggest contributions were found in gradeability (up to 86% higher) and top speed (up to 90% higher) when compared to single speed systems. Another topic discussed is the contributions of multi speed systems to energy and the economic aspect of the vehicle. Improvement in energy efficiency is challenging for electric vehicles but it can be improved through optimization techniques.

Baseline Modeling

In order to create the initial Simulink model for this electric all-wheel drive vehicle architecture, the team started with the EV_V1 model as a baseline. This model has key components needed to simulate the powertrain of a base electric vehicle. Only slight modifications were needed in order to turn it into an all-wheel drive vehicle and evaluate the key performance metrics established within our project scope. The EV_V1 model can be seen in **Figure 1**.

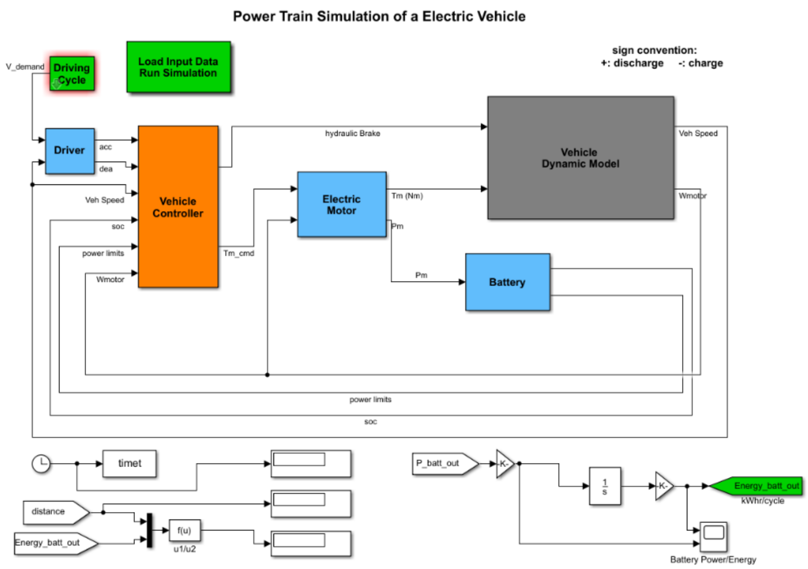

Figure 1: EV_V1 Model

The key performance characteristics of competitor vehicles in this market segment were also benchmarked as targets and for comparison purposes to our baseline model results as shown in **Table 1**.

Table 1. Tesla Model 3 Metrics

Metrics	
Power (horsepower)	450
Torque (lb-ft)	472
Top Speed (mph)	162.2
Acceleration* (s)	3.2
Efficiency (MPGe)	118

*time to go 0 mph to 60 mph

The first key change to the model is the addition of a second electric motor, where the purpose of each of these is to propel the front and the rear drives separately. In this case, the two motors considered for the analysis were a high torque switched reluctance drive motor at the front and a low torque induction at the rear. This follows the same methodology as the Tesla Model 3. This motor set-up already balances cost and performance.

After modeling the two motors, torque demand needed to be split between each drive system. A primary focus of the project revolves around the dual motors torque allocation control strategy. However, for the baseline modeling, it was assumed the torque demand coming out of the vehicle controller is split evenly to both motors. This assumption was acceptable to further develop the rest of the model.

The next improvement made was the modeling of electric drive motor efficiency. The electric motor efficiency maps are modelled inside the “Switch Reluctance” (SR) and “Induction motor” blocks. The original EV_V1 model from class assumed constant motor efficiency as an input, however, to maximize the vehicles metrics, a unique efficiency map was implemented into the vehicle model. Based on the class and the literature review referenced above, it is evident that efficiency maps and proper motor control are key elements to maximize the efficiency of the system. By creating an electric motor efficiency map, it is possible to simulate the electric motor losses through all the possible torque and engine speed points. All the efficiency values were calculated in Matlab and integrated in the Simulink model. The Matlab portion of the program creates the efficiency maps (for both the Induction and the Switched Reluctance motors) shown in **Figure 2**. The Simulink model uses the efficiency map to calculate the dynamic power usage. The Matlab program also calculates this in parallel in order to validate the results of the Simulink model. Also, it is assumed that the efficiency for motoring vs. regeneration conditions will be identical, which, may not be.

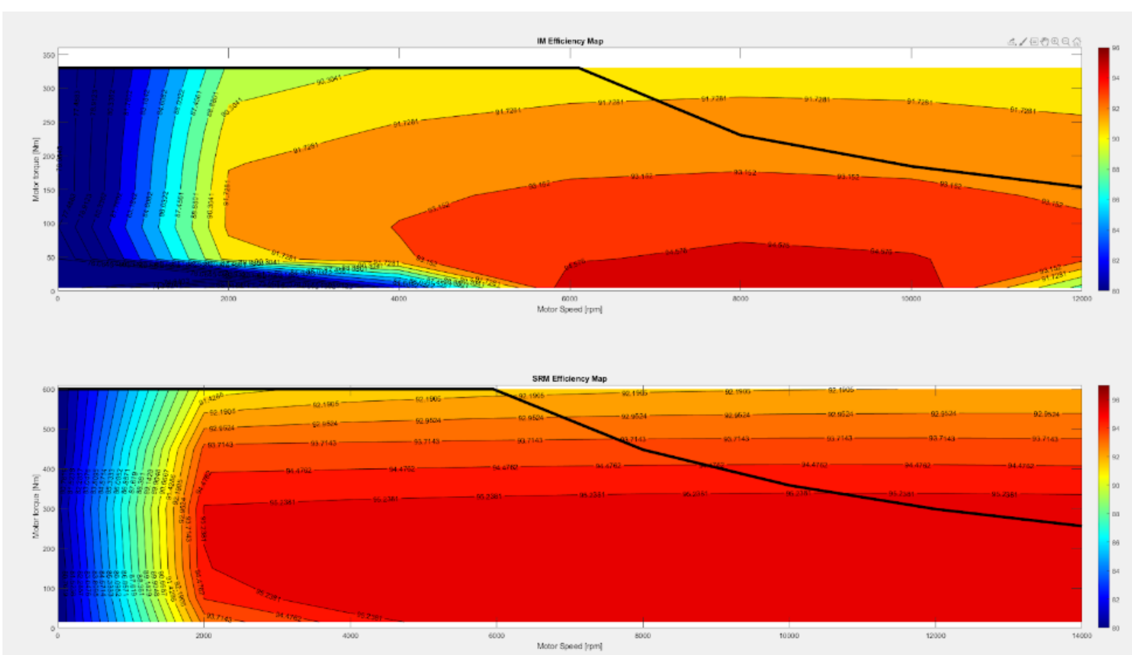

Figure 2: Efficiency Maps

Having added the additional electric motor and the efficiency map calculation, the last step is to run the baseline model and understand the results. In order to evaluate all the key performance characteristics when running the simulation, we developed a simple performance cycle. This performance cycle is a step input speed reference that evaluates the performance metrics like max speed, acceleration, torque, and power. Additional display blocks were added to the model to read power, torque, speed, and efficiency metrics including scopes to understand patterns and behaviors.

The baseline model of our electric vehicle and the key areas of improvement are highlighted in **Figure 3**. **Table 2** is our baseline model performance metrics results.

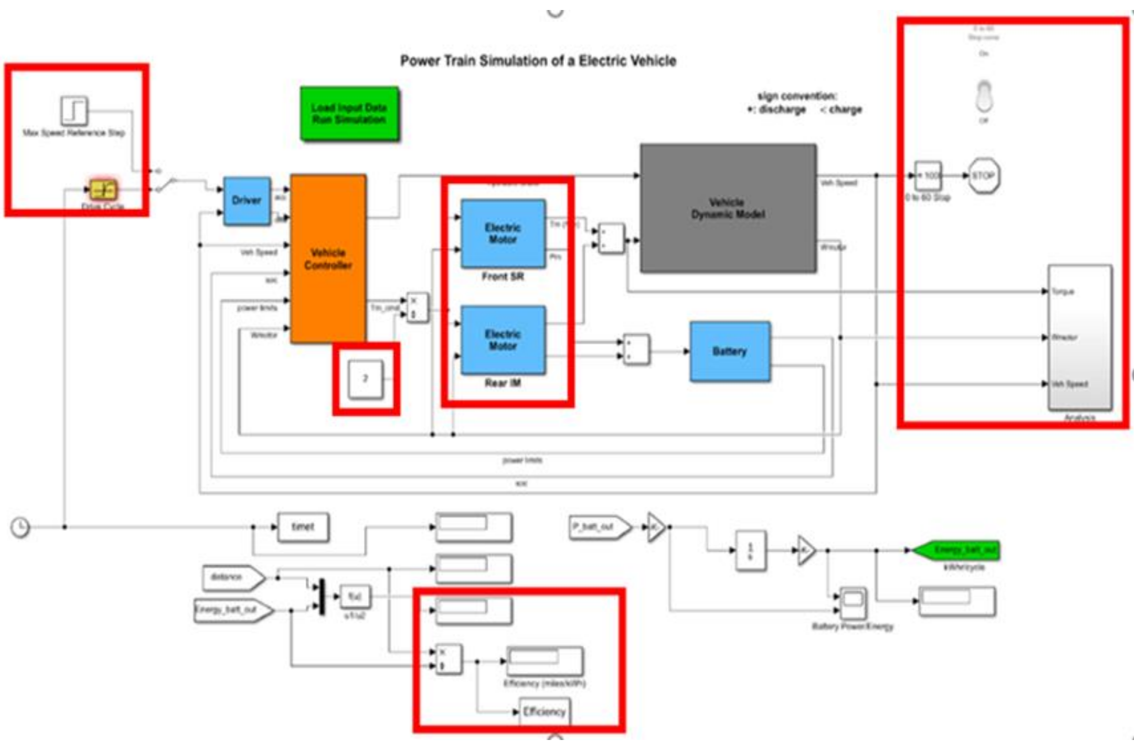

Figure 3: Baseline Model

Table 2. Baseline Model Initial Metrics

Metrics	
Power (horsepower)	238
Torque (lb-ft)	608
Top Speed (mph)	145
Acceleration* (s)	5.45
Efficiency (MPGe)	91

*time to go 0 mph to 60 mph

Transmission Development

Transmission Controller

To further improve upon the electrical all-wheel drive performance model, it was necessary to study the effects of an electric motor transmission.

In the background research, it is evident that incorporating a transmission will improve acceleration, top speed and gradeability when compared to a direct drive electric vehicle. The multi-speed transmission system allows for improved torque optimization and speed operating ranges. Since the vehicle in consideration is a passenger EV, having a two-speed transmission is enough to obtain the benefits without significantly increasing the cost of the vehicle. This can only be done if the transmission is optimized to reduce battery size.

It is important to optimize the gearbox controller by implementing a control strategy to maximize performance and efficiency. The initial gearbox model did not have a controller meaning that the vehicle would only constantly run on either first gear or second gear. These results were compared to see how performance shifts occurred between just running on first gear and second gear. The addition of the second gear yielded higher performance metric results with improvements to acceleration, top speed, power, and torque.

Two additional controls strategies were identified and tested in MATLAB to optimize the operation of an electric motor transmission. The first was an efficiency comparison controller which was modeled as shown in **Figure 4** to assign an optimization strategy for gear shifting. A K_high and K_low values were assigned to the high gear and low gear. The control strategy was based purely on the motor speed and the efficiency of the motor was used as the optimization parameter. Based on higher efficiency values obtained, the corresponding K_high or K_low that yielded this value was written as K_factor_out.

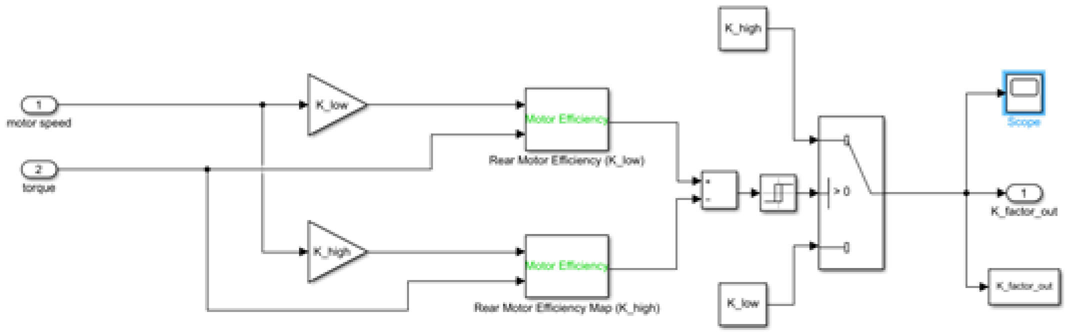

Figure 4: Transmission controller

This K_factor_out is then input to the vehicle and determines whether the vehicle should run on the high gear or the low gear. The best way to see these results are in a transmission shift map. **Figure 5** shows the transmission shift map results on the highway cycle.

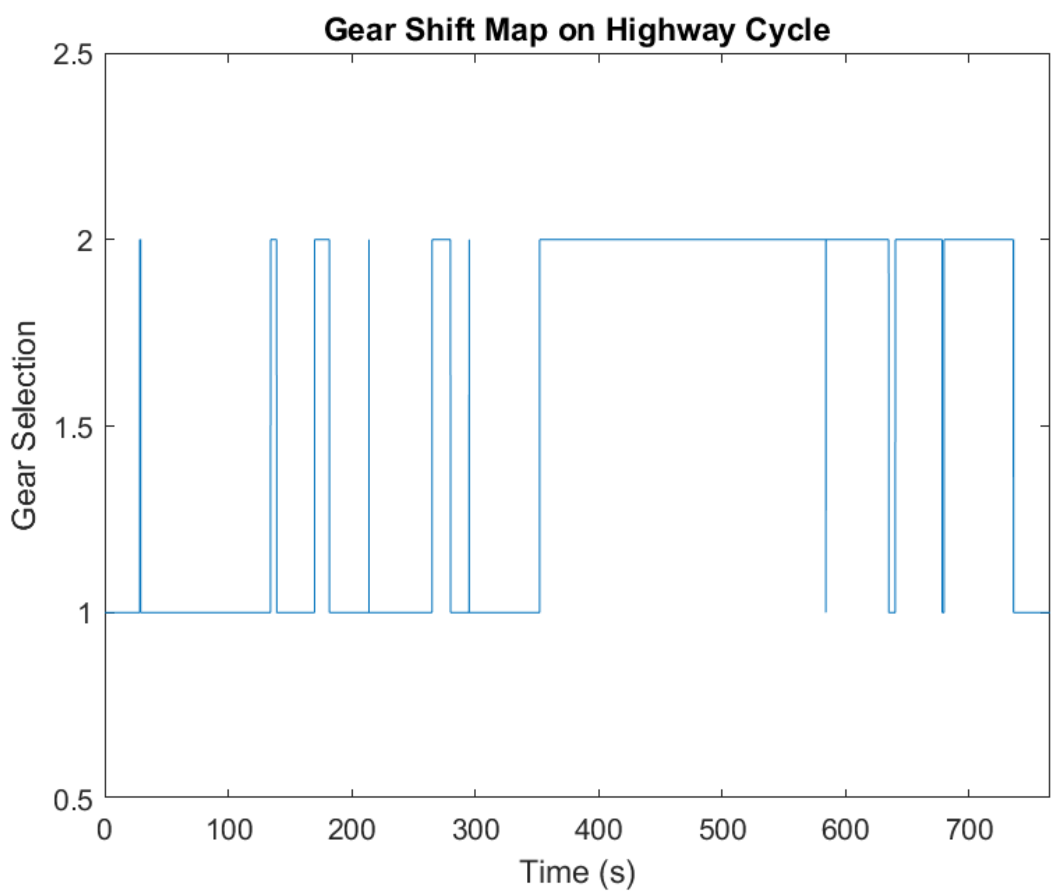

Figure 5: Gear Shift Map

Looking at these results, we see the transmission controls are almost instantaneous. A time delay was used to help prevent constant shifting. These shift results improved upon the baseline model which operates in a single gear. Specifically, this improves on performance metrics such as power, torque, top speed, and acceleration. While this control strategy is ideal in terms of motor efficiency and performance, it is not a realistic control strategy. There are many instances where sudden downshifts occur, which is undesirable to the driver.

The next controller iteration focused on improving the shifting strategy utilizing motor map efficiencies and adding 12.5% shift delay between downshifts and upshifts. We developed a two-speed shift map for each electric motor.

In this model the first gear ratio to a value of nine and the second gear ratio to be six for both motors. This was determined by observing the efficiencies of discrete motor operating points in first and second gear. We found the switched reluctance motor ran more efficiently in first gear for higher throttle demands. The shift maps for each motor can be seen in **Figure 6**. The exact results used to develop this shift map can be seen in the appendix.

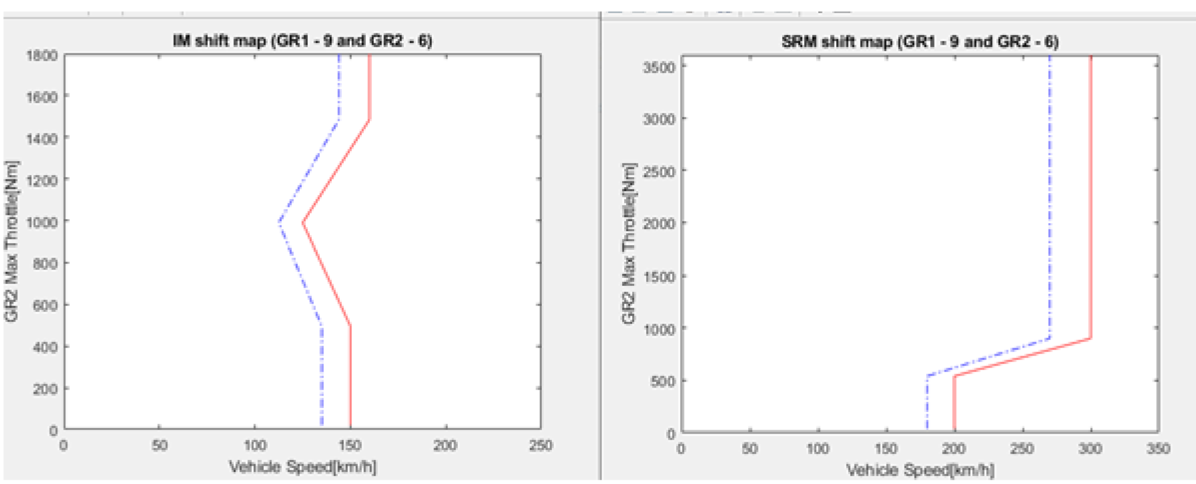

Figure 6: Transmission Shift Map

Define transmission location

In developing the first transmission model, we simply adjusted the torque and speed using a constant called "k_factor_out". The model would allow us to see two different gear ratios results. The Porsche Taycan has first gear final drive ratio of 8.05:1 and second gear final drive ratio of 15.6:1. This is approximately a 1:2 gear ratio between first and second gear. We assigned the k_factor_out constant a value of 2.

Next, we focused on the transmission location because the transmission can easily be integrated to the front or rear drive systems. For this, two models were developed. First, we looked at the effects of running first and second gears on the system and ultimately, we found out that a gearbox on the front drive system had no significant efficiency benefits. On the rear drive system, the gear ratio improved the performance metrics. These models were tested on the city cycle, highway, and performance cycle. The initial transmission model is shown in **Figure 7**.

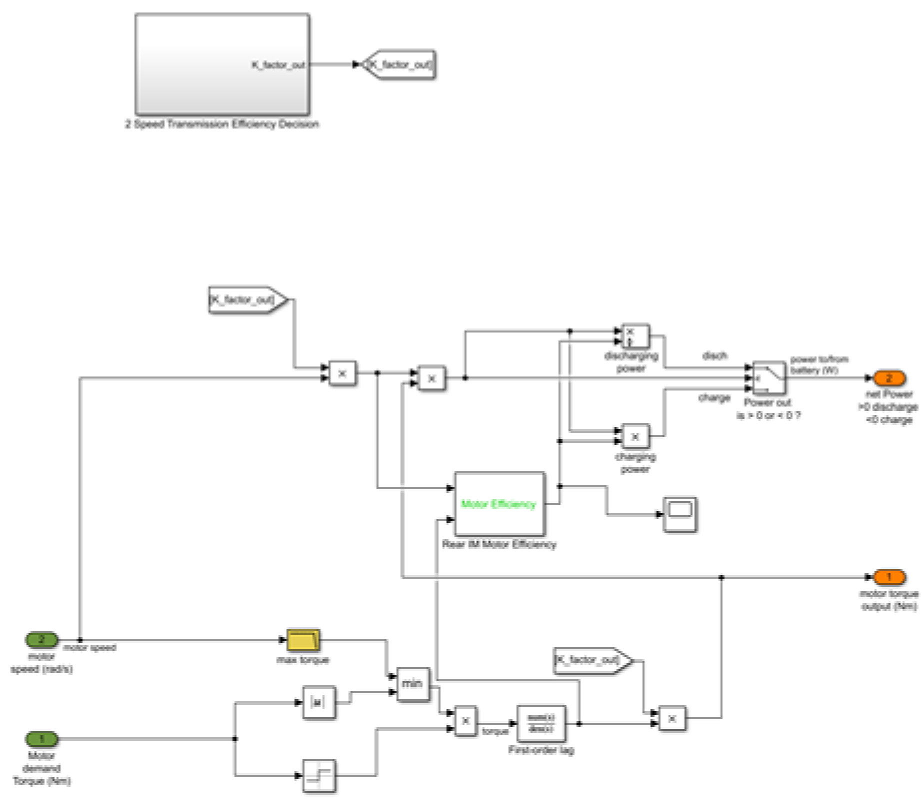

Figure 7: Motor with 2 speed transmission

This conclusively proves that the gearbox should be placed in the rear motor to obtain optimal results, and the gearbox has further potential for improvement if a control system is implemented.

Torque Allocation Development

In a traditional internal combustion all-wheel drive application, torque between the front and rear wheels are limited by vehicle architecture and powertrain integration. Most vehicles can divert its power bias between the front and rear wheels by using a system of clutches and differentials. This usually has limitations on the amount of power that can be delivered to the front and rear wheels.

Electric vehicles have a distinct advantage to control torque diverted between the front and rear motors. Knowing we can dynamically adjust the torque split between the front and rear motors, we have focused on optimizing the drive system to improve our model metrics.

In this next model improvement, the focus was improving the torque demand split between the front and rear motors. Before this point, a fifty-fifty torque split was used between the front and rear wheels. This can be seen in **Figure 8**. From the Torque Optimal Allocation strategy of AWD vehicles literature review we learned about a strategy focused on activation between the front and rear drive system. Instead, we wanted to focus on dynamically splitting the torque. We focused on a controls strategy to run the electric motors at their most efficient points. We developed a simplified dynamic programming control strategy to sweep through each motor torque, speed, and torque allocation split. This code can be seen in the appendix.

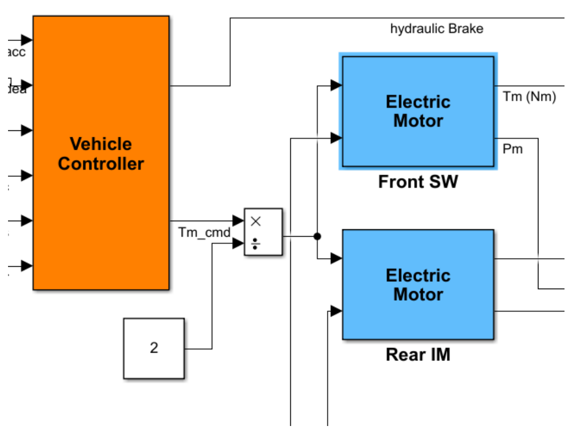

Figure 8: Torque Allocation Controller

We then took the matrix of data and looked at maximizing power, torque, and efficiency. We developed three different looks up tables to control the motors speeds and torque. These different tables would be different operating modes for the all-wheel drive system. When modeling, we only link in one torque allocation control strategy. This can be seen in **Figure 9**

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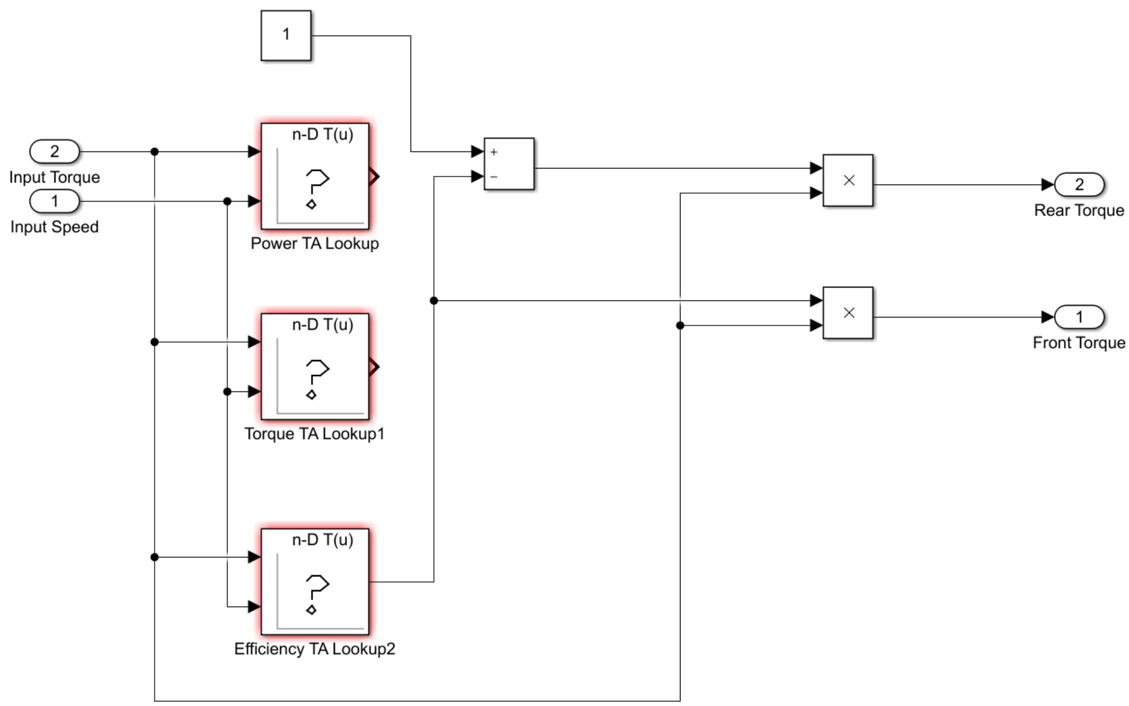

Figure 9: Torque Allocation Lookup Tables

Figure 10 is the torque allocation strategy to maximize output power. Torque allocation percent represents the torque split between the front and rear motors. The lower the percentage (close to zero), the more front wheel bias the vehicle is. The higher the percentage (close to one), the more rear wheel bias the vehicle is. We can see that as speed and torque demand increases, the rear induction motor is being utilized to provide additional power. This would be the least efficient way to run the vehicle but would allow us to maximize the performance of the all-wheel drive system.

Figure 11 is torque allocation controls to maximize torque output. In this model, in a high torque demand situation. We can see that 80% torque allocation is to the rear drive motors. This torque split remains constant as motor speed increases. This is because of the fundamental properties of electric motors. Electric motors have instantaneous and constant torque. An 20/80 split favoring the rear drive is the best way to maximize torque output.

Figure 12 is the torque allocation to maximize motor efficiency. This plot operates very differently than torque and power plots. The control strategy utilizes the front drive motor as much as possible. The front drive motor operates more efficiently than the rear induction motor. Only at high motor speeds and torque demand, we begin to leverage the rear motor.

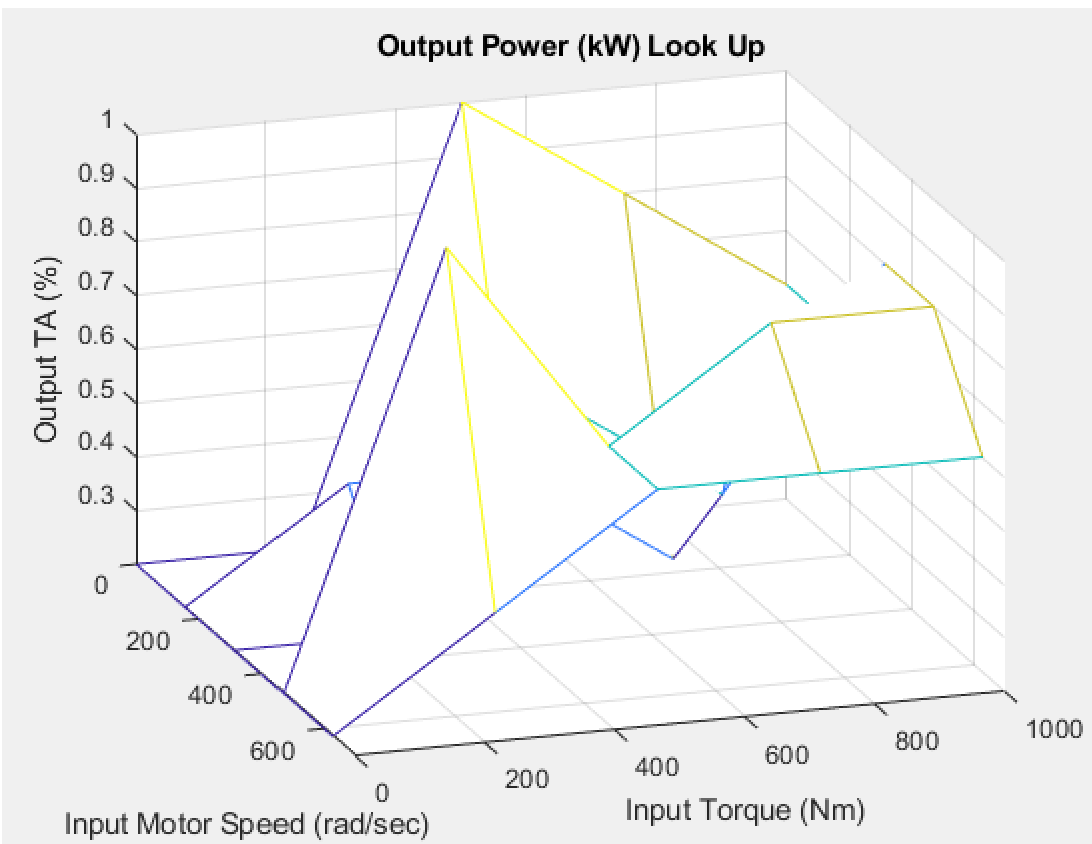

Figure 10: Torque Allocation Max Output Power

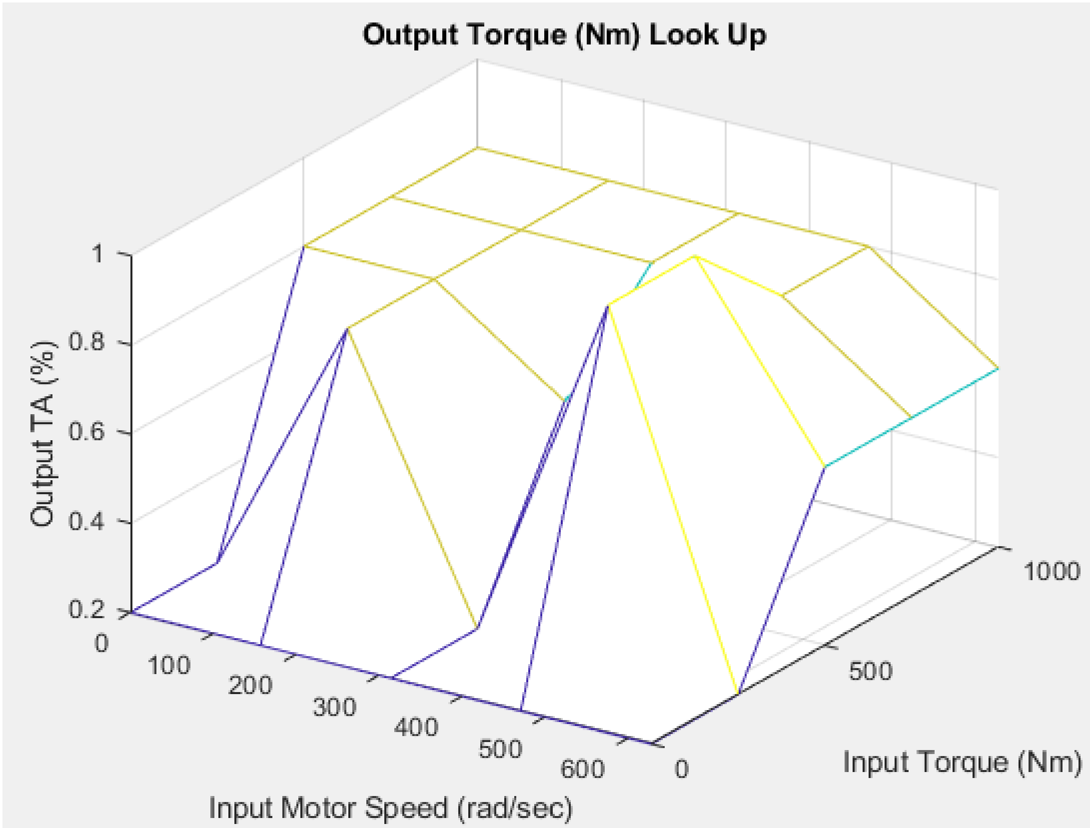

Figure 11: Torque Allocation Max Output Torque

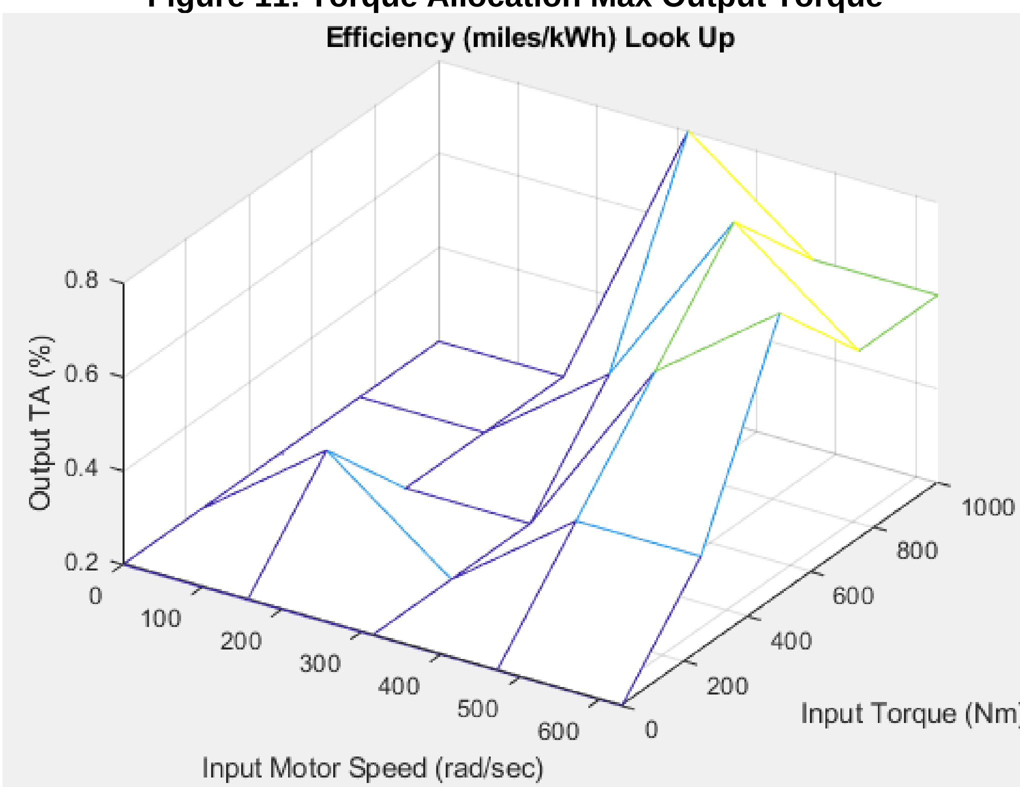

Figure 12: Torque Allocation Max Efficiency

For real world application, there may be challenges dynamically changing the torque allocation to each motor. Instead of dynamically changing torque split between the front and rear drive system, it may be better to keep the torque allocation split constant at certain operating torque and speed ranges. Then use a control system to transition to different operating torque allocation situations.

Results & Validation

The first set of results compare the model with the addition of the gearbox controller to the baseline model results. For this first iteration, the focus was only the low gear controls only. Once the low system controller design is determined, the model will be configured with the upper level controller options and will be compared to previous best results from the lower system controller as a percentage. The results obtained are based on 3 different drive cycles. The first is a performance cycle that is a full throttle application while the second and third cycle are the UDDC city cycle and HWFET highway cycle. Performance based results are obtained by running the performance cycle while the efficiency is based on averaged results of the city and highway cycles. The most optimized metrics were obtained for the efficiency comparison controller.

Torque Allocation Controller Results

Using the improved metrics obtained from the improved gearbox controller in combination with the torque allocation controls on the front and rear motor, two optimization lookup controllers were tested against these results. The first controller used was developed by searching optimal output metrics while sweeping input torque, input speed, and torque allocation into a model with the previous lookup gearbox controller installed. Thus, the Torque Allocation controller and gearbox controller are independent. Whereas, the second controller tested was developed by sweeping the same inputs while adding an input gear speed configuration. The two sets of lookup tables used in both optimization strategies were; Torque Allocation which is dependent on input torque and input speed, and the gearbox lookup is dependent on the amount of torque requirement going into the motor where the gearbox is connected to. The results obtained from these two optimization strategies are shown in **Table 3**.

Table 3. Torque Allocation Controller Results

Metrics	Baseline model	Torque Allocation	Torque Allocation w/ transmission controls
Power (horsepower)	363	420	420
Torque (lb-ft)	851	778	921
Top Speed (mph)	145	157	157
Acceleration* (s)	4.1	3.4	4.1
Urban Efficiency (MPGe)	94	94	94
Highway Efficiency (MPGe)	88	88	88

*time to go 0 mph to 60 mph

The differences between the two control strategies are not very significant as they have the same efficiencies across the different cycles, indicating they have nearly identical driving ranges. The torque allocation controller with the gearbox displayed a higher torque (921.lb-ft), while the one without the gearbox path had a better acceleration time (3.4 seconds). The percent differences between the two when compared to the baseline model are tabulated below in **Table 4**.

Table 4. Torque Allocation Model Iteration Improvements

Metrics	Torque Allocation (%)	Torque Allocation w/ transmission controls (%)
Power	15.6	15.1
Torque	-8.5	8.2
Top Speed	8.2	0
Acceleration	16.0	-16.0
Urban Efficiency	-0.3	-0.3
Highway Efficiency	0	0

Similar improvement of results was achieved in both controllers. The biggest trade-off between the two is a large improvement in acceleration for the upper level torque allocation and positive improvement in torque for the torque allocation and gearbox controller. The decision was to move on the gearbox path controller even though both have equal average improvements and no weighting toward specific metrics.

Transmission Controller Results

The three different control strategies illustrated in the transmission development section were simulated and the following results, in **Table 5**, were obtained. It is evident that the introduction of the gearbox itself allows for significant improvement, which enabled the selection of the best control strategy.

Table 5. Transmission Controller Results

Metrics	1st gear only	2nd gear only	Efficiency Comparison Controller	Shift Map Efficiency Controller
Power (horsepower)	238	363	345	363
Torque (lb-ft)	608	851	608	851
Top Speed (mph)	145	147	157	155
Acceleration* (s)	5.45	3.7	5.5	4.1
Urban Efficiency (MPGe)	94	53	64	94
Highway Efficiency (MPGe)	88	50.5	78	88

*time to go 0 mph to 60 mph

The Efficiency Comparison Controller was found to be significantly better than the baseline model. There was considerable improvement in performance metrics such as power and top speed. The acceleration time was the same as the baseline model. The efficiency was lower than the baseline model and there was a slight reduction in the driving range which can be attributed to the improved performance. This concludes that even though some of the performance metrics are compromised, the overall performance of the vehicle is enhanced. The percentage improvement or tradeoff is shown in **Table 6**.

Table 6. Transmission Iteration Improvements

Metrics	Efficiency Comparison Controller (%)	Shift map efficiency controller (%)
Power	45	52.7
Torque	-0	40
Top Speed	8.2	-1.3
Acceleration	0	-31.2
Urban Efficiency	-14.2	0
Highway Efficiency	-0.5	-40.5

It was reasonable to consider the shift map efficiency controller as the Efficiency Comparison Controller is based on ideal, instantaneous shifting. This bolsters the performance metrics and has higher efficiency than the shift maps but can cause discomfort to the driver, which can be undesirable. Implementing shift maps reduces the efficiency and range considerably but allows for even better performance than the Efficiency Comparison Controller.

Transmission Location Decision

Finally, the configured controller from the previous two test comparisons was tested on the front (switched reluctance motor) and rear (induction motor) to see which yields maximum improvement, which drove the gearbox location decision. The comparison of the various metrics comparing the two cases from the baseline are shown in **Table 7**.

Table 7. Optimized Transmission Location Results

Metrics	Transmission location on vehicle	
	Front	Rear
Power (horsepower)	418	418
Torque (lb-ft)	820	921
Top Speed (mph)	126	157
Acceleration* (s)	5.2	4.1
Urban Efficiency (MPGe)	94	94
Highway Efficiency (MPGe)	88	88

Again, very similar improvement results were seen when looking at the average, however there is a clear tradeoff between torque and power improvement and a decrease in acceleration time. Both locations yield neutral efficiency improvements. The decision was to keep the gearbox on the rear baseline (induction motor) to maintain improvement in acceleration time due to an already large improvement in torque and power from previous controllers.

Final Comparison to Baseline

Based on the implementation of all the control strategies highlighted above, the final vehicle model was compared across all metrics with the baseline. The results across all the performance metrics and their percentage improvements are shown in **Table 8**.

Table 8. Final Model Comparison to Baseline

Metrics	Baseline model	Final Design	Model improvements (%)
Power (horsepower)	237	418	75.7
Torque (lb-ft)	608	921	51.4
Top Speed (mph)	145	157	8.2
Acceleration* (s)	5.5	4.1	25.7
Average Efficiency (MPGe)	91	91	-0.1

*time to go 0 mph to 60 mph

There was a large increase in the power and torque of the system, leading to a much better acceleration time. This concludes that the model developed was significantly better than the baseline model with just a dual motor system without any control strategy.

Conclusions & Recommendations

Today the automotive industry is shifting toward a fully electric vehicle. We focused on how we could develop and improve one of the bestselling EV on the market, the Tesla model 3. It is one the bestselling electric vehicles on the market. When developing our model, we focused on following the V-development process to optimize an all-wheel drive electric vehicle. In our model we focused on accurately modeling the losses within the electric motors. We used the electric motor efficiency maps to develop our control strategy for the all-wheel drive system. We also created a realistic electric motor transmission control's strategy. The newly developed electric model is one that would appeal to the consumer market due to its high-performance metrics. It is a popular consumer demand for the vehicle to have a low acceleration time and a high-top speed, which is achieved in this vehicle model. Like anything most of our controls had tradeoffs in power or economy.

For future model development, we would focus on further improving the vehicle model and understanding our performance gains. Even though we saw good improvement in our performance. We expect the results could be more accurate. We also expected more efficiency improvements. We would look to further optimize and analyze the effects of vehicle parameters (like final drive ratio). Finally, to improve our controller results, we would spend more time developing a dynamic program controller. This could allow us to further integrate our economical and performance controls together. In making these changes, we believe we would have an efficiency metric similar the Tesla Model 3.

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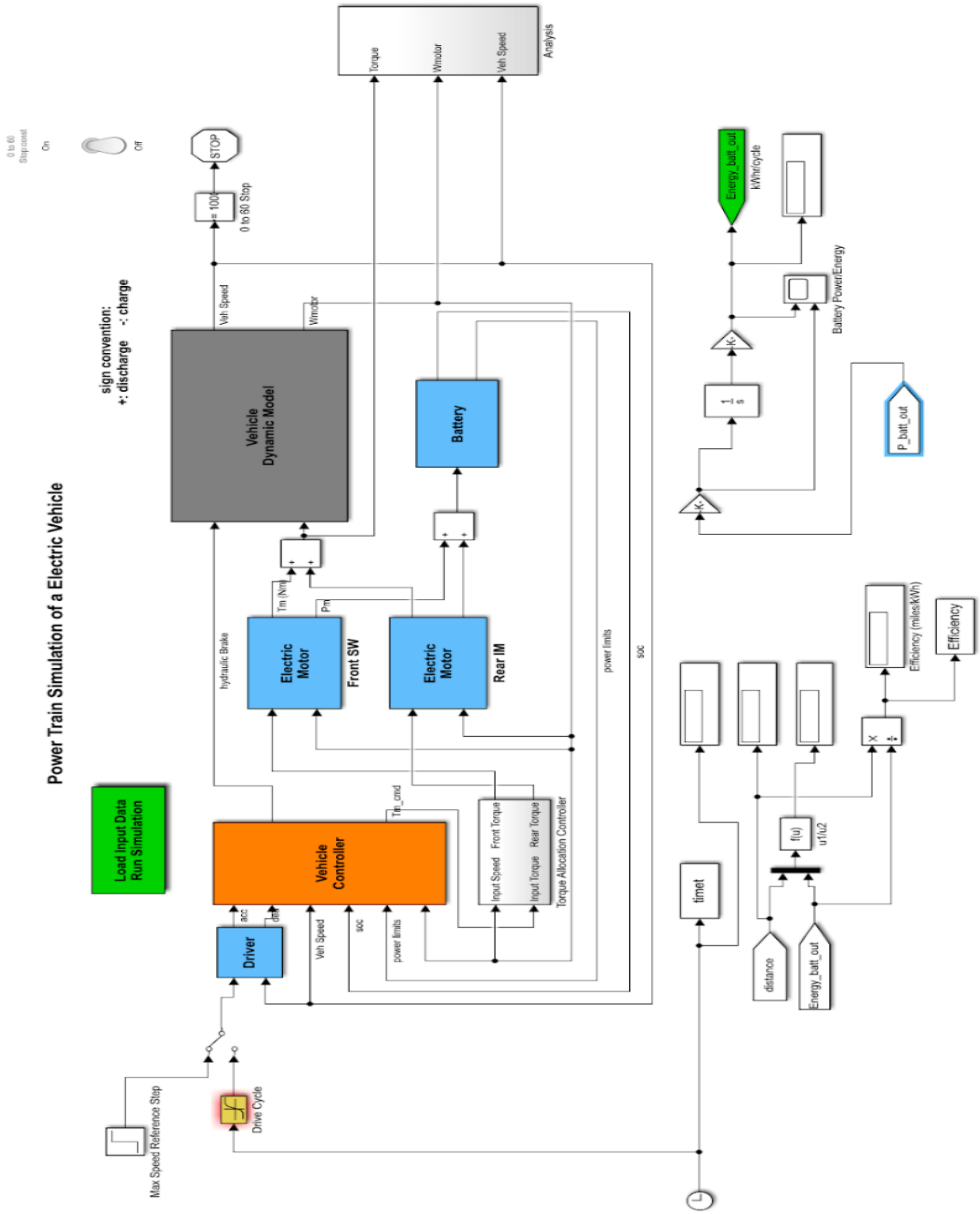
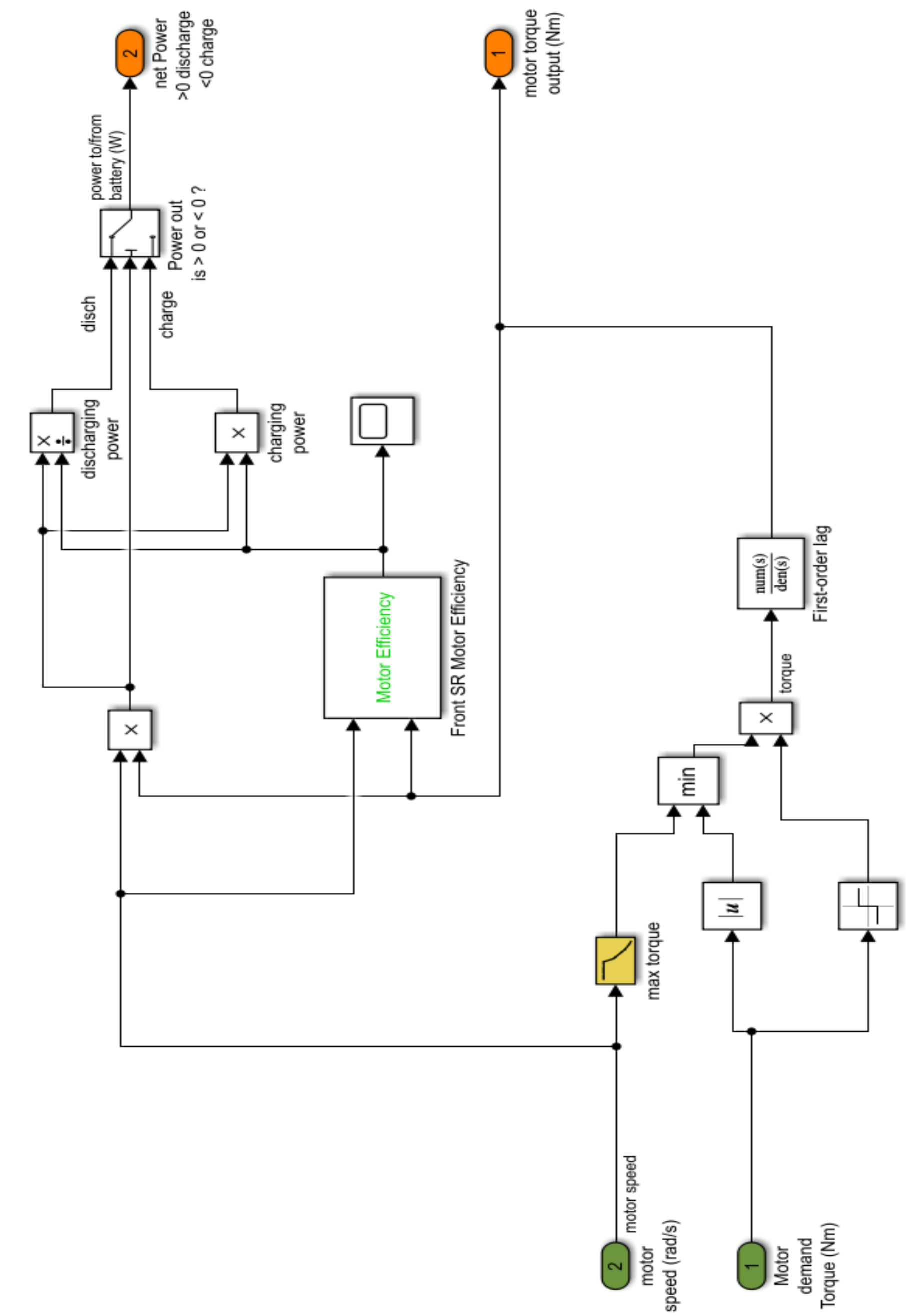
Appendix

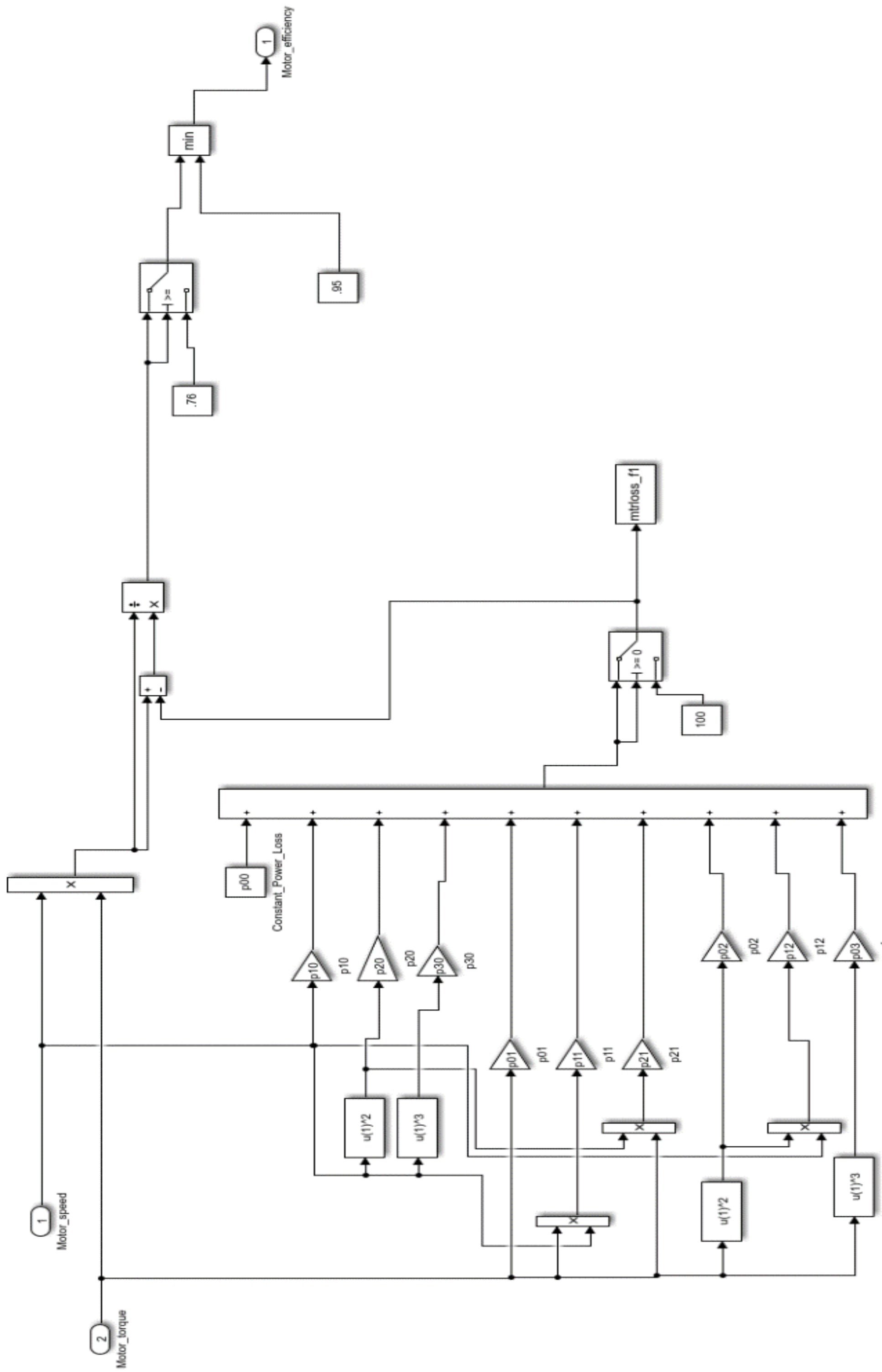
A. Final model Overview



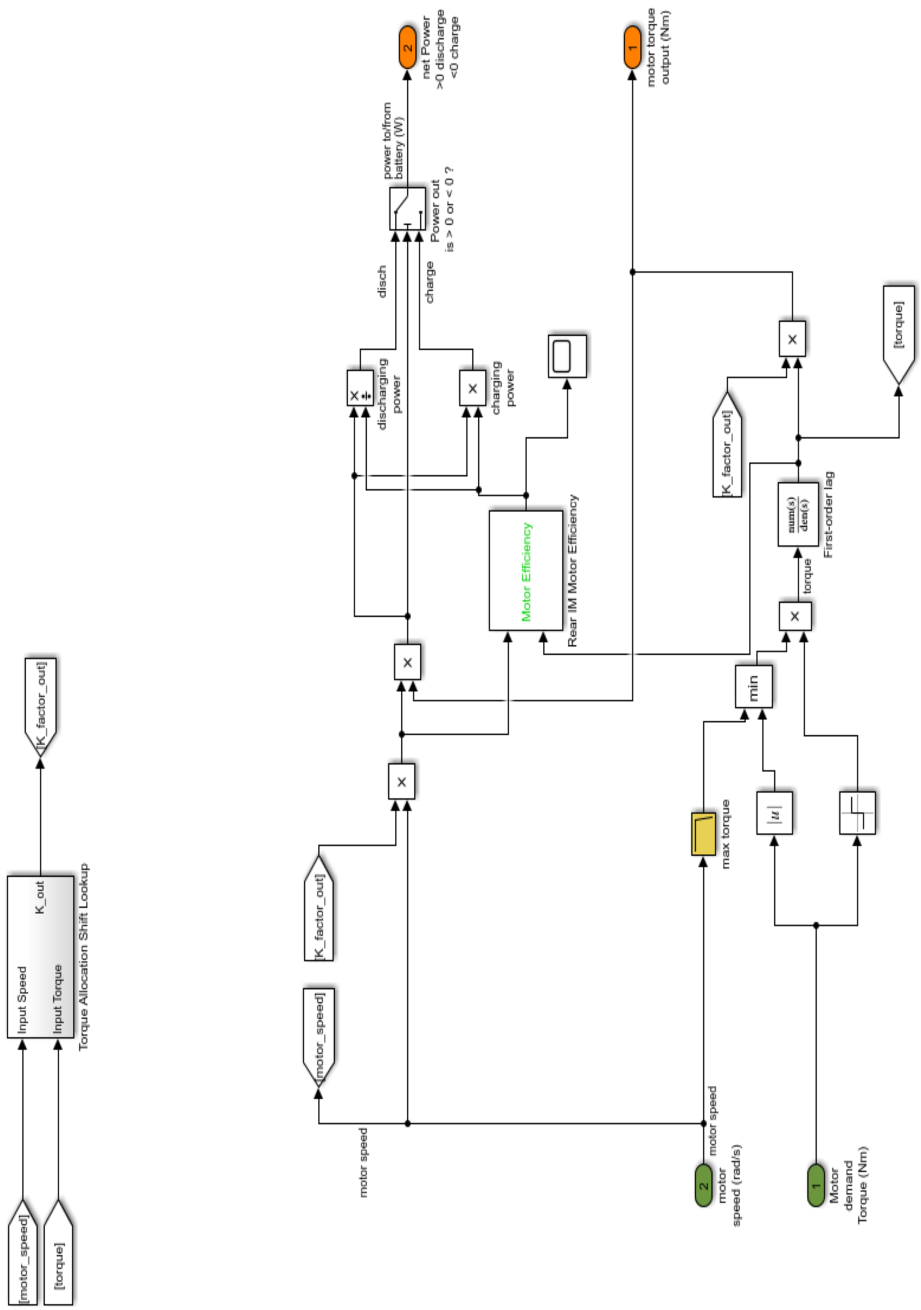
B. Front Motor model



C. Motor efficiency Model



D. Rear Motor Model



E. Matlab Simulation

```
% Run this file to see the results

clear all;                      % Initialize workspace
% close all;                    % Close graphic windows

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%load initialization data file
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 %bolt_ev_sim_data;
tesla_sim_data1;
disp('Data loaded sucessfully!');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Simulation initial conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ess_init_soc=0.6;        %initial battery state of charge (1.0 = 100% charge)

K_factor_in=2;           %K factor for rear transmision one speed operation
K_low=1;                 %K factor for low speed mode transmission
K_high=2;                %K factor for high speed mode transmission

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%% load driving cycle %%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
drivingcycle = 2; %1:EPA City cycle %2:EPA Highway cycle
switch (drivingcycle)
    case 1
        %load EPA cycle (compare the results of fuel comsuption
        load CYC_UDDS.mat; % Load driving cycle (EPA urban cycle)

        time_final = 1*length(cyc_mph(:,2));

    case 2
        %load EPA cycle (compare the results of fuel comsuption
        load CYC_HWFET.mat; % Load driving cycle (EPA highway cycle)
        time_final = 1*length(cyc_mph(:,2));
%     case 3
%         %load trapezoid cycle
%         load CYC_trapezoid_higher.mat;
%         time_final = 1*length(cyc_mph(:,2));

end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% All Control related parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% driver controller parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Kf_c = 1/10;
Kp_c = 30;
Ti_c = 60;
Tt_c = 65;
v_max_c = 100;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BATTERY CONTROL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% SOC boundaries
high_soc=0.95;  % highest desired battery state of charge
low_soc=0.10;   % below this value, the engine must be on and charge
stop_soc=0.10;  % lowest desired battery state of charge, avoid reaching this point
regstop_soc=0.9;  % reach this point, regenerative brake will stop


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Simulation and Results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
simulation_case=1; %1:normal simulation 2:fuel consumption with soc correction
switch simulation_case
    case 1
        time_step = 0.05;
        sim('initial_model1_front.slx');
        display('Simulation completed!');
%         prius_sim_plot;

    case 2
        time_step = 0.02;
        soc_init_index = [0.5 0.6 0.7];
        for simrun=1:length(soc_init_index)
            ess_init_soc=soc_init_index(simrun);
            sim('prius_rulebased_v1.mdl');
            display(['Simulation ',num2str(simrun),' completed!']);
            mpg(simrun)=distance_in_mile(2)/fuel_consum_in_g(2)*1000*3.8*0.75;

            figure;
            plot(timet,demand_spd,...
                'r:',timet,actual_spd,...
                'b-',timet,actual_spd,'g-.','LineWidth',2);
            set(gca,'fontSize',12,'fontWeight','bold')
            xlabel('time (sec)','fontWeight','bold','fontSize',12);
            title(['Main Results:  Total travel ',num2str(distance_in_mile(2)),...
                    ' Miles;  Fuel ',num2str(mpg(simrun)),' MPG.'],'fontWeight','bold','fontSize',12);
            hold on;
            [AX,H1,H2] = plotyy(timet,actual_spd,...
                timet,output_soc,'plot');
            set(get(AX(1),'Ylabel'),'String','Vehicle Speed (MPH)','fontWeight','bold','fontSize',12)
            set(get(AX(2),'Ylabel'),'String','State of Charge','fontWeight','bold','fontSize',12)
            set(H2,'LineStyle','-.')
            set(H2,'LineWidth',2)
            set(AX(2),'fontSize',12,'fontWeight','bold')
            % set(AX(2),'YLim',[0.45 0.9])
            set(gca,'fontSize',12,'fontWeight','bold')
            legend('Reference Speed','Actual Speed','SOC')
            grid;

            soc_dif(simrun)=output_soc(length(output_soc))-ess_init_soc;
        end
        mpg_final=interp1(soc_dif,mpg,0);
        figure;
        plot(soc_dif,mpg,'b-',soc_dif,mpg,'r*','LineWidth',2);
        set(gca,'fontSize',12,'fontWeight','bold')
        xlabel('difference of soc (final-initial)','fontSize',12,'fontWeight','bold');
        ylabel('fuel consumption (MPG)','fontSize',12,'fontWeight','bold');
        title(['fuel consumption after soc correction: ',num2str(mpg_final),' MPG'],'fontSize',12,'fontWeight','bold');
end

%% Metrics

Max_Power_hp=max(0.00134102*Max_Power )           %Max power (hp)
Max_Torque_lbft=max(0.7375621493*Max_Torque)      %Max torque (lb*ft)
Max_Speed_mph=max(Max_Speed)                      %Max speed (miles/hr)
Efficiency_miles_kwh=Efficiency(end)              %Efficiency (miles/kWh)
Time=timet(end)                                   %Time (sec)
```

F. Vehicle Parameters Matlab

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% electric motor parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
m_eff=0.9;
m_min_volts=200;        % minimum voltage for motor/controller set, V
% maximum continuous torque corresponding to speeds
m_peak_trq_SR = 660.28; %Nm  % SR motor specs from google
m_peak_trq_IM = 329.46; %Nm  % IM motor specs from google
m_peak_pwr = 310; %kW  %
m_map_spd = [0  100     250     500     1000    1500    2000    2500    3000    4000    4500    5500    6000    7000    8000    9000    10000]*(2*pi)/60;
m_max_trq_SR = min(m_peak_trq_SR, m_peak_pwr*1000./m_map_spd); % estimation by published peak torque and power
m_max_trq_IM = min(m_peak_trq_IM, m_peak_pwr*1000./m_map_spd); % estimation by published peak torque and power
m_max_gen_trq=-m_max_trq_SR-m_max_trq_IM; % estimate

% SR efficiency map
       ap00 =      -69.58  ;
       ap10 =      0.5123  ;
       ap01 =       11.22  ;
       ap20 =  -0.0007943 ;
       ap11 =    0.009736 ;
       ap02 =     -0.1665  ;
       ap30 =   3.794e-07  ;
       ap21 =  -4.587e-07  ;
       ap12 =   0.0003316  ;
       ap03 =   0.0006218 ;

% IM efficiency map coefficients
       p00 =      -215.8  ;
       p10 =       4.164  ;
       p01 =       3.368  ;
       p20 =   -0.009417  ;
       p11 =     0.04408 ;
       p02 =     -0.0178  ;
       p30 =   5.161e-06 ;
       p21 =   5.981e-06 ;
       p12 =   9.874e-05  ;
       p03 =   6.515e-05 ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% battery parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% reference seed ADVISOR data file:  ESS_NIMH6.m
ess_description='Spiral Wound NiMH Used in Insight & Japanese Prius';
% Assume fix temperature of the model
ess_fixtemp=25;
enable_stop=1;

% SOC RANGE over which data is defined
ess_soc=[0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1];  % (--)
% The following data was obtained at 25 deg C.  Assume all values are the same for all temperatures
ess_tmp=[0 25];  % (C) place holder for now

% LOSS AND EFFICIENCY parameters (from ESS_Prius_pack reference)
% Parameters vary by SOC horizontally, and temperature vertically
ess_max_kwhr_cap = 90; % kWhr, % Tesla website
ess_max_ah_cap=ess_max_kwhr_cap*1000/350*[1 1]; % (A*h), max. capacity / nominal voltage

% module's resistance to being discharged, indexed by ess_soc and ess_tmp
% The discharge resistance is the average of 4 tests from 10 to 90% soc at the following
%  discharge currents: 6.5, 6.5, 18.5 and 32 Amps
%  The 0 and 100 % soc points were extrapolated
ess_r_dis=[
        0.0377  0.0338  0.0300  0.0280  0.0275  0.0268  0.0269  0.0273  0.0283  0.0298  0.0312
        0.0377  0.0338  0.0300  0.0280  0.0275  0.0268  0.0269  0.0273  0.0283  0.0298  0.0312   ]*0.1; %estimated resistance for energy cell battery

% module's resistance to being charged, indexed by ess_soc and ess_tmp
% The discharge resistance is the average of 4 tests from 10 to 90% soc at the following
%  discharge currents: 5.2, 5.2, 15 and 26 Amps
%  The 0 and 100 % soc points were extrapolated
ess_r_chg=[
   0.0235       0.0220  0.0205  0.0198  0.0198  0.0196  0.0198  0.0197  0.0203  0.0204  0.0204
        0.0235  0.0220  0.0205  0.0198  0.0198  0.0196  0.0198  0.0197  0.0203  0.0204  0.0204   ]*0.1;

% module's open-circuit (a.k.a. no-load) voltage, indexed by ess_soc and ess_tmp
ess_voc=[
        7.2370  7.4047  7.5106  7.5873  7.6459  7.6909  7.7294  7.7666  7.8078  7.9143  8.3645
        7.2370  7.4047  7.5106  7.5873  7.6459  7.6909  7.7294  7.7666  7.8078  7.9143  8.3645
];

% LIMITS (from ESS_Prius_pack)
ess_min_volts=6; % 1 volt per cell times 6 cells lowest from data was 255V so far 8/26/99
ess_max_volts=9; % 1.5 volts per cell times 6 cells highest from data so far was 361V 8/26/99

% OTHER DATA (from ESS_Prius_pack except where noted)
ess_module_num=40;  %20 modules in INSIGHT pack, 40 modules in Prius Pack

ess_cap_scale=1; % scale factor for module max ah capacity
ess_res_scale_fun=inline('(x(1)*ess_module_num+x(2))/(x(3)*ess_cap_scale+x(4))','x','ess_module_num','ess_cap_scale');
ess_res_scale_coef=[1 0 1 0]; % coefficients in ess_res_scale_fun
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% vehicle parameters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
M_total = (4650+300)/2.2046; % kg curb + 300 lbs passengers
g_gravity = 9.81;
R_tire = 0.335; % meter 19 inch tire
A_frontal = 2.8; % m^2 estimated from vehicle specs (56 inch by 77 inch)
rho_air = 1.2;                  % Air density % kg/m^3
C_d = 0.24;                             % Aerodynamic drag coefficient, web claim
f_rolling = 0.018; % Rolling resistance range on efficient tires

% gear ratios
FR = 9.73;

%% TA Efficiency Lookup
d=5;                                               %Sweep dimension length (sim runs=d^3)

mtr_torque_Nm=linspace(0,1000,d);                 %motor torque (Nm)
mtr_speed_rad=linspace(0,6000*2*pi/60,d);         %motor speed (rad/sec)
torque_allocation=linspace(0,1,d);                 %Torque allocation percentage (TR=front motor, 1-TR=rear motor)

load('opt_output_efficiency_location112');
load('K_lookup_eff');
K_lookup_real_eff=K_lookup_eff.*ones(d,d);

load('opt_output_torque_location112');
load('K_lookup_tor');
K_lookup_real_tor=K_lookup_tor.*ones(d,d);

load('opt_output_power_location112');
load('K_lookup_pow');
K_lookup_real_pow=K_lookup_pow.*ones(d,d);
```

G. Electric Motor Efficiency Map Models and validation

```
%% IM efficiency map

       p00 =      -215.8  ;
       p10 =       4.164  ;
       p01 =       3.368  ;
       p20 =   -0.009417  ;
       p11 =     0.04408 ;
       p02 =     -0.0178  ;
       p30 =   5.161e-06 ;
       p21 =   5.981e-06 ;
       p12 =   9.874e-05  ;
       p03 =   6.515e-05 ;

mtr_speed=[6 12000/6:12000/6:12000];
mtr_torque=[5 350/7:350/7:350];
mtr_speed_rad=mtr_speed.*(2*pi/60);
mtr_power1=zeros(8,7);
mtr_loss1=zeros(8,7);

for j=1:7
    for i=1:8
        mtr_power1(i,j)=mtr_torque(i)*mtr_speed_rad(j);
        mtr_loss1(i,j)= p00+p10*mtr_speed_rad(j)+p20*mtr_speed_rad(j)^2+p30*mtr_speed_rad(j)^3+...
              p01*mtr_torque(i)+p11*mtr_speed_rad(j)*mtr_torque(i)+p21*mtr_speed_rad(j)^2*mtr_torque(i)+...
              p02*mtr_torque(i)^2+p12*mtr_speed_rad(j)*mtr_torque(i)^2+...
              p03*mtr_torque(i)^3;

    end
end

mtr_loss1(mtr_loss1<0)=100;
mtr_eff_f=min(96,(mtr_power1-mtr_loss1)./mtr_power1.*100);
mtr_eff_f(mtr_eff_f<50)=76;

mtr_eff3=reshape(mtr_eff_f,[8,7]);


K=330/350;
mtr_torque=mtr_torque.*K;

figure(1)
subplot(2,1,1)
[C,h]=contourf(mtr_speed,mtr_torque,mtr_eff3,20);
clabel(C,h)
colorbar
colormap(jet(256));
lim=caxis;
caxis([80 96]);
hold on

% b1=[350 350 350 350 270 210 130 115];
% c1=[0 2000 4000 4500 6000 8000 10000 12000];
b1=[330 330 330 330 330 193e3/(2*pi*8000/60) 193e3/(2*pi*10000/60) 193e3/(2*pi*12000/60)];
c1=[0 2000 4000 4500 6100 8000 10000 12000];

plot(c1,b1,'-k','LineWidth',4);
ylabel('Motor torque [Nm]');xlabel('Motor Speed [rpm]');
ylim([0 360]);
title('IM Efficiency Map');
```

```
%% SRM efficiency map
       ap00 =      -69.58   ;
       ap10 =      0.5123   ;
       ap01 =       11.22   ;
       ap20 =  -0.0007943 ;
       ap11 =    0.009736 ;
       ap02 =     -0.1665   ;
       ap30 =   3.794e-07   ;
       ap21 =  -4.587e-07   ;
       ap12 =   0.0003316   ;
       ap03 =   0.0006218 ;

mtr_speed=[6 14000/7:14000/7:14000];
mtr_torque=[5 25 50:50:200];

mtr_speed_rad=mtr_speed.*(2*pi/60);

mtr_power1=zeros(6,8);
mtr_loss1=zeros(6,8);

for j=1:8
    for i=1:6
        mtr_power1(i,j)=mtr_torque(i)*mtr_speed_rad(j);
        mtr_loss1(i,j)= ap00+ap10*mtr_speed_rad(j)+ap20*mtr_speed_rad(j)^2+ap30*mtr_speed_rad(j)^3+...
              ap01*mtr_torque(i)+ap11*mtr_speed_rad(j)*mtr_torque(i)+ap21*mtr_speed_rad(j)^2*mtr_torque(i)+...
              ap02*mtr_torque(i)^2+ap12*mtr_speed_rad(j)*mtr_torque(i)^2+...
              ap03*mtr_torque(i)^3;

%
    end
end

mtr_loss1(mtr_loss1<0)=100;
mtr_eff_f=min(96,(mtr_power1-mtr_loss1)./mtr_power1.*100);
mtr_eff_f(mtr_eff_f<50)=80;

mtr_eff3=reshape(mtr_eff_f,[6,8]);

K=600/200;
mtr_torque=mtr_torque.*K;
subplot(2,1,2)
[C,h]=contourf(mtr_speed,mtr_torque,mtr_eff3,20);
clabel(C,h)
colorbar
colormap(jet(256));
lim=caxis;
caxis([80 97]);
hold on
% b1=[200 200 200 150 65 50 42 36 30];
% c1=[0 2000 3000 4000 6000 8000 10000 12000 14000];
b1=[600 600 600 600 600 375e3/(2*pi*8000/60) 375e3/(2*pi*10000/60) 375e3/(2*pi*12000/60) 375e3/(2*pi*14000/60)];
c1=[0 2000 4000 4500 5950 8000 10000 12000 14000];
plot(c1,b1,'-k','LineWidth',4);
ylabel('Motor torque [Nm]');xlabel('Motor Speed [rpm]');
ylim([0 610]);
title('SRM Efficiency Map');
```

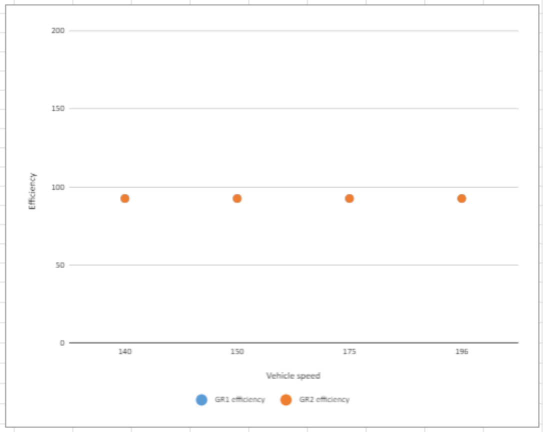
H. Torque Allocation Look-up Tables Matlab Code

```
%% Sweeping input TA, speed, and torque

run ev_sim_init2

runtime=3;

d=5;                                              %Sweep dimension length (sim runs=d^3)

mtr_torque_Nm=linspace(0,1000,d);                %motor torque (Nm)
mtr_speed_rad=linspace(0,6000*2*pi/60,d);        %motor speed (rad/sec)
torque_allocation=linspace(0,1,d);                %Torque allocation percentage (TR=front motor, 1-TR=rear motor)


for i=1:d
    input_motor_torque=mtr_torque_Nm(i);
    for j=1:d
        input_motor_speed=mtr_speed_rad(j);
        for k=1:d
            TA=torque_allocation(k);

                    sim('output_opt_lookup_formation_sim2.slx');
                    output_power(i,j,k)=mean(output_veh_power);
                    output_torque(i,j,k)=mean(output_motor_torque);
                    efficiency(i,j,k)=output_efficiency(end);
        end
    end
end

%Vehicle output power
[opt_output_power,A]=max(output_power,[],3);
opt_output_power_location2=A*1/k;
figure(1)
mesh(mtr_speed_rad,mtr_torque_Nm,opt_output_power_location2)
ylabel('Input Torque (Nm)'), xlabel('Input Motor Speed (rad/sec)'), zlabel('Output TA (%)')
title('Output Power (kW) Look Up')

%Vehicle output torque
[opt_output_torque,B]=max(output_torque,[],3);
opt_output_torque_location2=B*1/k;
figure(2)
mesh(mtr_speed_rad,mtr_torque_Nm,opt_output_torque_location2)
ylabel('Input Torque (Nm)'), xlabel('Input Motor Speed (rad/sec)'), zlabel('Output TA (%)')
title('Output Torque (Nm) Look Up')

%Vehicle output efficiency
[opt_output_efficiency,C]=max(efficiency,[],3);
opt_output_efficiency_location2=C*1/k;
figure(3)
mesh(mtr_speed_rad,mtr_torque_Nm,opt_output_efficiency_location2)
ylabel('Input Torque (Nm)'), xlabel('Input Motor Speed (rad/sec)'), zlabel('Output TA (%)')
title('Efficiency (miles/kWh) Look Up')

%sim('lookup_table_test.slx');
save('opt_output_power_location2','opt_output_power_location2')
save('opt_output_torque_location2','opt_output_torque_location2')
save('opt_output_efficiency_location2','opt_output_efficiency_location2')
```

I. Transmission Shift map development

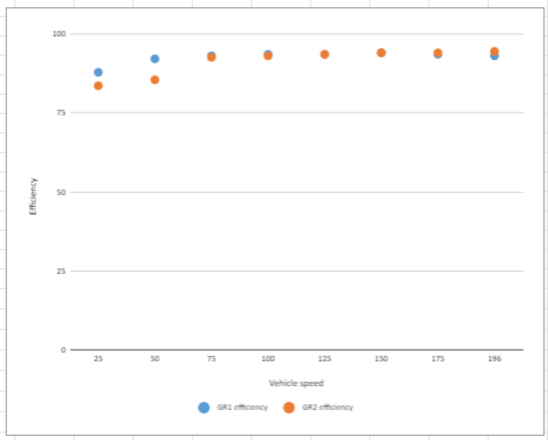
100% Throttle

Vehicle speed	GR1 efficiency	GR2 efficiency
140	92.63	92.63
150	92.63	92.63
175	92.63	92.63
196	92.63	92.63



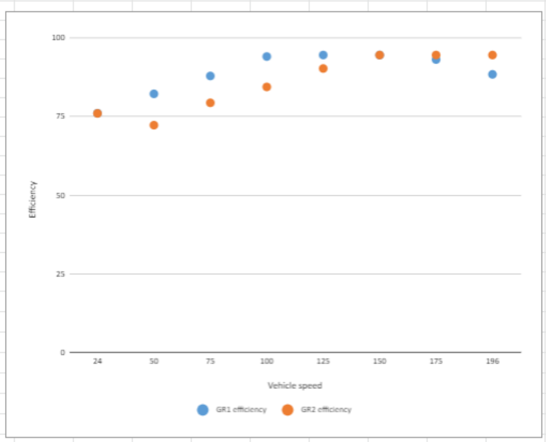
50% Throttle

Vehicle speed	GR1 efficiency	GR2 efficiency
25	87.89	83.63
50	92.16	85.52
75	93.1	92.63
100	93.58	93.1
125	93.58	93.58
150	94.05	94.05
175	93.58	94.05
196	93.1	94.53



15% Throttle

Vehicle speed	GR1 efficiency	GR2 efficiency
24	76.05	76
50	82.21	72.26
75	87.89	79.36
100	94.05	84.4
125	94.53	90.26
150	94.53	94.53
175	93.1	94.53
196	88.4	94.53



J. Efficiency Map