Advanced Propulsion for Hybrid Electric Vehicles Final Project Week 1

Tune MTU HEV Model to 2010 Malibu Baseline
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1 Introduction and problem description

A 2010 Chevy Malibu is analyzed and the details of analysis are presented in this report. A vehicle model in Simulink is presented as a part of the problem statement. This effort is to ascertain the subtlety associated with each parameter that is to be tuned and document intricacies associated with different parameters. The details of IC engine, transmission, driver behavior, friction braking system, battery system and LVD are modeled mathematically in Simulink. As the vehicle is fixed; IC engine, transmission, braking and battery are fixed in this analysis and the parameters that require tuning are proportional and integral gains in different subsystems, transmission shift logic and other parameters which do not directly change designed parameters on any of the subsystems.

2 Tune Driver for Drive Cycles

The driver is tuned to ensure that it maintains the vehicle speed such that the City, Highway and US06 drive cycles has two or less counts of speed error and maximum error is less than 3 mph. Charts of the metrics (maximum speed error) as a function of tuning are developed.

Optimization is done to determine K_p (proportional gain) and K_i (integral gain) values which provide minimum (less than 2) count of error within maximum limit of 3 mph. Six iteration tests are performed for UDDS (city) and HWFET (highway) to determine K_p and K_i, corresponding K_p and K_i values of these iterations can be seen in Table 1. The result of optimization study is presented in following charts. Y axis represents various performance metrics and fuel consumption while x axis represents corresponding test with trial K_p and K_i values for UDDS and HWFET cycle as stipulated in Table 1.

Table 1 Optimization of Driver gains

Number of iteration	K_p	K_i	Maximum error(mph)	Number of errors	Fuel consumption(gallon)	Fuel economy CAFE (Vehicle)
Test 1 UDDS	0.10	0.03	4.80	162	0.29	25.89
Test 2 UDDS	0.20	0.02	1.70	0	0.29	25.81
Test 3 UDDS	0.50	0.05	1.04	0	0.29	25.67
Test 4 UDDS	1.00	0.10	0.52	0	0.29	25.61
Test 5 UDDS	5.00	0.50	0.15	0	0.29	25.46
Test 6 UDDS	10.00	5.00	0.05	0	0.32	23.14
Test 1 Highway	0.10	0.03	5.55	86	0.50	40.81
Test 2 Highway	0.20	0.02	1.32	0	0.50	40.83
Test 3 Highway	0.50	0.05	1.87	0	0.50	40.85
Test 4 Highway	1.00	0.10	1.02	0	0.50	40.78
Test 5 Highway	5.00	0.50	0.38	0	0.51	40.55
Test 6 Highway	10.00	5.00	0.03	0	0.59	34.76
Test 1 US06	1.00	0.10	2.46	1	0.25	32.01
Test 2 US06	5.00	0.50	2.1	1	0.255	31.38

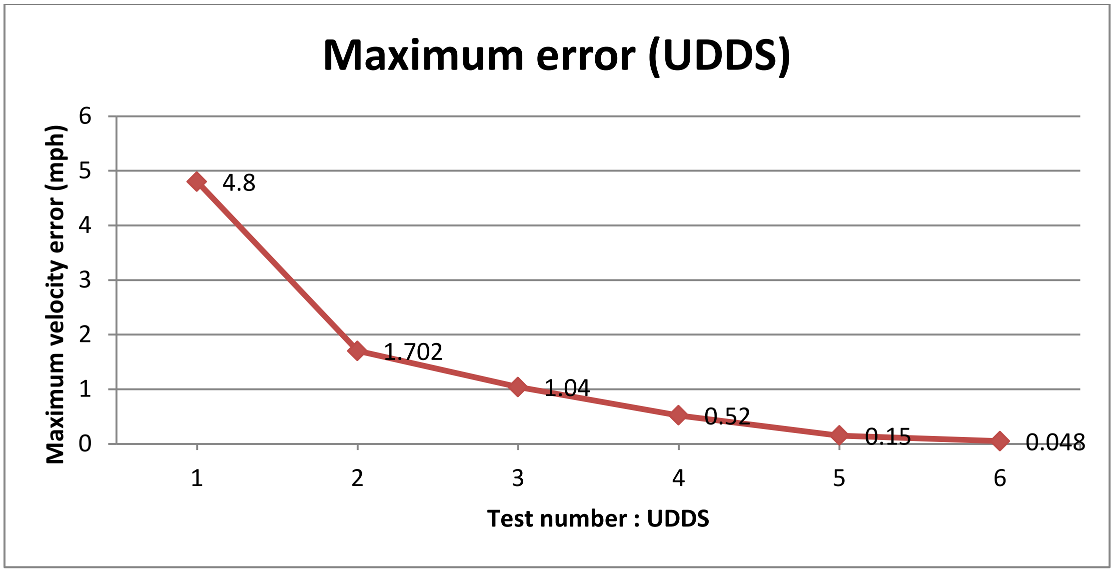

Figure 1 Maximum error (UDDS)

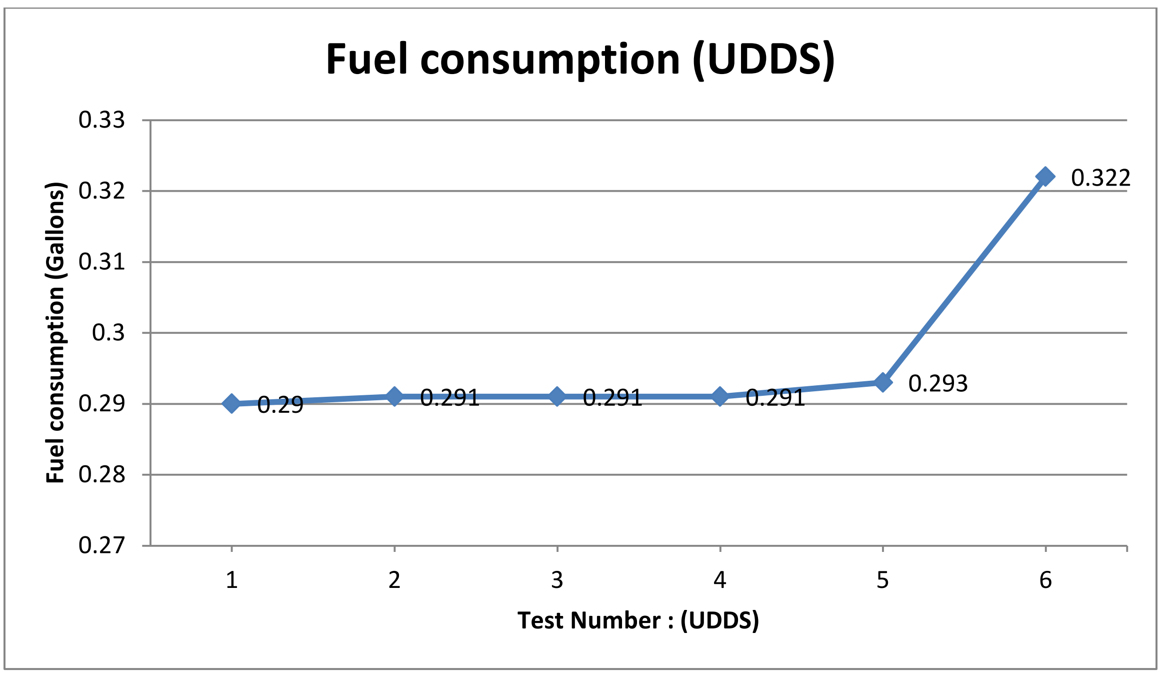

Figure 2 Fuel consumption (UDDS)

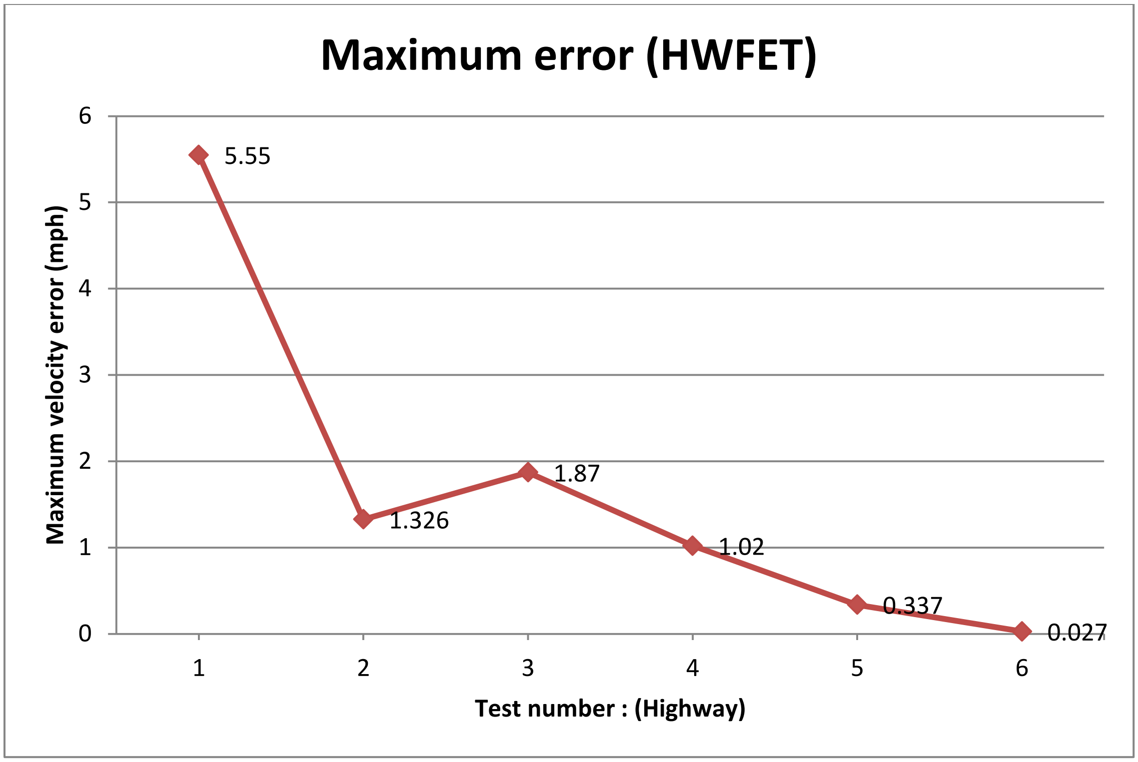

Figure 3 Maximum error (HWFET)

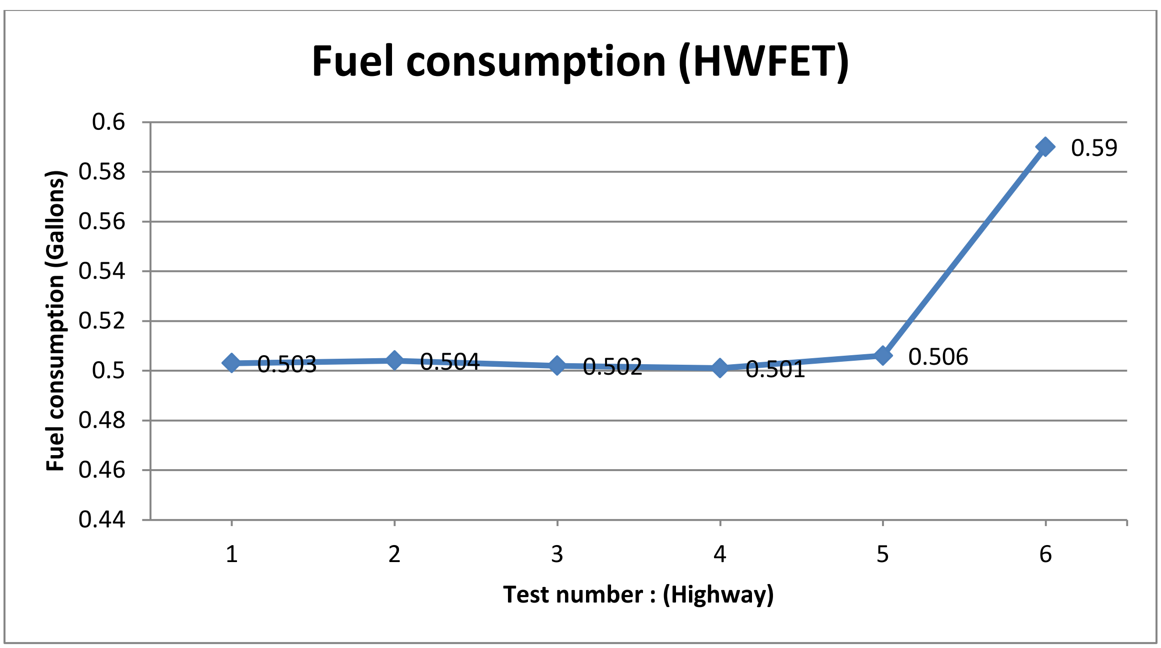

Figure 4 Fuel Consumption (HWFET)

For first test with Kp=0.1 and Ki=0.03 the maximum error is 4.8 mph and count of error is 162 for UDDS cycle and maximum error is 5.55 mph and count of error is 86 for HWFET cycle. This is not within the tolerance; hence next test is done with higher values of Kp and Ki. It is observed that test number four with Kp=1 and Ki=0.1 provides count of error as zero for both UDDS and HWFET cycle and maximum error of 0.52 mph and 0.337 mph for UDDS and HWFET respectively.

It can be observed from Figure 2 and Figure 4, which compare fuel consumption for six iterative tests in UDDS and HWFET cycles, that fuel consumption becomes sensitive to Kp beyond test 4 i.e. Kp = 1. There is a sharp rise in fuel consumption for higher values of Kp and fuel consumption tends to become maximum for test six with Kp = 10 and Ki=5. The reason for dependence of fuel consumption on Kp can be explained as follows: The Driver Sub model calculates error between required vehicle speed from drive cycle and actual vehicle speed from LVD subsystem. This error is multiplied by Kp which is proportional controller gain and product is sent as torque request for engine (or motor). Thus torque request is proportional to Kp and thus fuel consumption increases with increase in Kp beyond Kp = 1.

Considering above analysis we have selected Kp and Ki from test 4 as optimum value to obtain zero error (count) and minimum fuel consumption.

Optimized Kp and Ki values are further used for US06 cycle to check performance metrics are within tolerance limits. Number of errors is found to be 1 with maximum error of 2.46 mph which is within tolerance value of 3 mph.

Thus optimized proportional and integral gains for the vehicle model are K_p = 1 and K_i = 0.1.

3 Tune Base Parameters for Non-Hybrid Malibu

The model is tuned for base parameters of Malibu as per given data. Given data for Malibu is input in 'Student_Design_Parameter.m' file. ICE option 5 is selected to match given engine parameters. Transmission option 2 is selected to match given transmission parameters.

3.1 Optimization of Transmission-shift logic:

Table 2 Performance and Fuel Economy comparison through shift-logic variation

Transmission mode	HWFET		UDDS		Performance	
	Drive Cycle	Sticker	Drive Cycle	Sticker	PCF	0-100mph
Shift Logic 1	14.36	11	10.31	8	10.96	19.36
Shift Logic 2	38.25	27	25.04	20	12.93	39.24
Shift Logic 3	38.23	27	25.29	20	4.69	28.92

Table 2 presents a comprehensive comparison detail of change in performance and fuel economy for three different trials employed which involve a change in shift logic. Fuel economy is compared separately for highway and city cycles. Also, a parameter called Performance Compliance Factor (PCF) is defined, which quantifies the variation of simulated drive cycles with respect to shift logic. The mathematical details pertaining to calculation of this factor are presented in Appendix (4). The basic idea behind three shift logics is

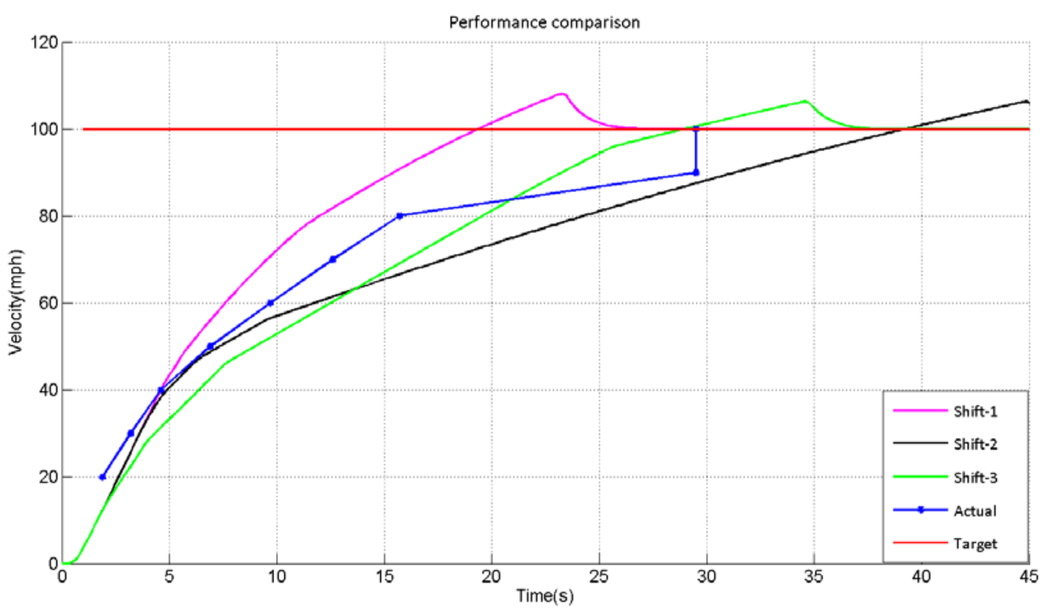

Figure 5 Graphical comparison of performance through different shift logics

- Shift Logic 1: This mode can be described as a 'Performance mode' where prime emphasis is laid on reaching the 100mph mark. Lookup tables provided with the model which include Upshift/Downshift tables are not used while in this mode. Engine runs until it reaches its maximum RPM, otherwise, maximum power in every gear until the maximum gear (gear 4). As desired, the vehicle reaches 100mph in about 19.3s. However, compliance to the desired performance parameters (as presented in Table 5 of the problem statement) is low in this case which is reflected by PCF. Also, as engine revs up most of the time to attain maximum power, fuel economy suffers a major blow. This can be seen in Table 2 and also from the performance comparison graph which also presents a comparative detail of different shift logics
- Shift Logic 2: This mode uses one of the upshift threshold tables presented in the Trans_tech.m files provided with the model. On the fuel economy front, it can be assumed that this mode is relatively more fuel efficient when compared to the previous shift logic. However, this mode has performance compliance issues. It can be seen that, this mode, is not only extremely incompliant but also its 0-100mph value is about 38.2s which is about 10s beyond the required threshold of 29s. Hence this mode cannot be used for the model
- Shift Logic 3: It has been recognized by iterating over the upshift threshold tables presented, that by running the vehicle in a lower gear only at very low speeds (0-15mph) and switching to higher gears beyond the speed range mentioned, a break-even can be achieved between compliance, 0-100mph time and fuel economy. This lead to iteratively developing a set of upshift thresholds which lead to Shift Logic 3 which is as close as one can get to achieving maximum fuel economy without suffering from performance deviation issues. This fact can also be appreciated from the table where the green plot (Shift-3) is clearly the closest follower of desired performance. This logic also helps achieve very impressive fuel economy numbers.

In the view point of parameters described in table 2, Shift Logic 3 is recommended for this vehicle.

3.2 Optimization of coefficient of drag Cd

The vehicle model with optimized transmission logic for fuel economy and performance is now further optimized for co-efficient of drag. Table 3 Provides optimization data.

Table 3 Cd optimization

Coefficient of drag	UDDS sticker	HWFET sticker
0.3645	20.06	27.34
0.3463	20.08	27.43
0.3281	20.11	27.56

Based on above analysis 0.3281 is selected as optimized value.

3.3 Optimization of coefficient of rolling resistance

Table 4 provides iteration details of optimization of coefficient of rolling resistance. Based on this data coefficient of rolling resistance is selected as 0.0072.

Table 4 Rolling resistance optimization

Rolling resistance coefficient	UDDS sticker	HWFET sticker
0.008	20.11	27.56
0.0076	20.18	27.73
0.0072	20.24	27.82

3.4 Optimization of Alternator gain factor in IC engine sub-system

The vehicle model with optimized transmission logic, coefficient of drag and co-efficient of rolling resistance is now optimized for alternator factor to achieve optimum fuel economy.

Table 5 Alternator gain factor optimization

Alternator gain factor	UDDS sticker	HWFET sticker
10	20.24	27.82
5	20.24	28.13
1	20.24	28.44

Based on this data Alternator factor of 1 is selected as optimum value.

In order to achieve sticker target for highway fuel economy, coefficient of drag now further reduced to 0.3098 to achieve HWFET sticker value of 29 mpg and UDDS mpg of 20 mpg.

4 Summary and conclusions

In this report, sensitivity of different parameters on performance and fuel economy have been tested by iteratively optimizing different values in the Simulink model presented as a part of the problem statement. The flow of the report depicts the actual flow of tasks performed to achieve an optimal fuel economy without losing on performance. To restate, firstly, Kp and Ki gains have been adjusted in order to obtain enhanced drive cycle compliance with UDDS, HWFET and US06. While performing this task, it has been observed that fuel economy is extremely sensitive to Kp and Ki.

Secondly, transmission logic has been explored and it is found to be a major factor concerning both performance and fuel economy. Various shift logic configurations have been tested; details of three of these configurations are presented in the report. It has been recognized that performance and economy have contrasting requirements when it comes to transmission logic. Hence, there exists a tradeoff between fuel economy and performance in terms of transmission shift logic.

Consequently, coefficient of drag and rolling resistance have been optimized by reducing their respective values by about 15% to achieve sticker fuel economy targets of Chevy Malibu 2010-

non hybrid/baseline. It has also been recognized that these resistance factors have a very small impact on city FE numbers but improve highway FE numbers, substantially.

Lastly, within the IC engine subsystem, alternator gain factor has been changed to a minimum value as it has been identified that it was set to a very high value of 10.

By performing all the optimization tasks as mentioned above, a city FE of 20 mpg and a highway FE of 29 mpg and a 0-100 mph value of 29s has been achieved. In the next section, an overview of important parameters for an optimized and a non-optimized model has been presented as a conclusive remark.

Table 6 Comparison of optimized and non-optimized parameters

Important vehicle parameters	Non optimized UDDS	Non optimized HWFET	Optimized UDDS	Optimized HWFET
Distance Traveled (Vehicle) (miles)	7.55	20.53	7.45	20.51
Fuel Consumption (Engine) (gal)	0.29	0.52	0.28	0.50
Fuel Consumption (Battery) (gal)	0.009	0.01	0.007	0.008
Fuel Consumption (Total) (gal)	0.31	0.53	0.29	0.51
Fuel Economy (Engine) (mpg)	25.32	39.22	26.27	40.66
Fuel Economy (Total) (mpg)	24.60	38.49	25.66	40.03
Speed Max Error (Vehicle) #	3.20	2.50	0.50	0.30
Speed Contrl Errors(Vehicle) #	50.50	4.00	0.00	0.00
Speed Acc Metric (Vehicle) #	53.70	6.50	0.5	0.30
Sticker mpg	19.52	27.50	20.30	28.559
Max tout	1369	1544.00	1369	1544
Cycle_Vehicle_Distance_Traveled_miles	7.55	20.53	7.45	20.51
Cycle_Vehicle_Average_Speed_mph	19.86	47.86	19.60	47.83
Cycle_Engine_Fuel_Consumption_kg	0.84	1.47	0.80	1.42
Cycle_Engine_Fuel_Consumption_l_100km	9.29	5.99	8.95	5.78
Cycle_Engine_Fuel_Economy_mpg	25.32	39.22	26.27	40.66
Cycle_Vehicle_Speed_Control_Maximum_Error	3.15	2.53	0.46	0.27
Cycle_Vehicle_Speed_Control_Errors_Total_No	50.50	4.00	0.00	0.00

Appendix

1. Calculation for Transmission logic of shift logic 1 (Performance mode) in Table 1:

   Shift logic 1 is developed to obtain maximum performance from given tuned model for non-hybrid Malibu. From given Engine parameters for standard 2.4 L, 169 hp engine maximum horse power of 169 hp is obtained at 4500 RPM. From available gear ratios maximum operating speed for each gear is derived as follows. This allows extracting maximum performance from engine to achieve minimum time to reach from zero to hundred mph.

   Maximum vehicle speed for 1st gear, N1 = 4500 / (Nt1 * Nd1)

   Where Nt1 is first gear ratio and Nd1 is differential gear ratio.

   N1 value thus obtained is converted from RPM to radians and then to mph using formula

   Linear velocity = Radius of wheels * Angular velocity (Radians/sec)

   similarly maximum velocities for remaining gears are calculated to implement transmission logic for performance mode.

2. EPA Sticker city value $= \frac{1}{0.003259 + \left(\frac{1.1805}{\text{FTP FE}}\right)}$
3. EPA sticker highway value $= \frac{1}{0.001376 + \left(\frac{1.3466}{\text{HFWET FE}}\right)}$
4. **Performance Compliance Factor (PCF)**

This factor is used to appreciate the variation of a simulated drive cycle with respect to the actual performance values. It is obtained by calculating root mean squared (RMS) error between simulated values of velocity and actual value of velocity at each point of time for which the value of actual velocity is available. It has to be realized that this factor does not take into account how good the vehicle performs, as it is possible to have a very high PCF for a vehicle with good performance characteristics. PCF provides a quantitative measure to check if the model is compliant with empirical results. Lower values of PCF indicate higher compliance.

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Area	Points	Score
Cover Sheet	5	
Introduction	5	
Results and Discussion	80	-
Summary and Conclusions	10	
Total =	**100**	