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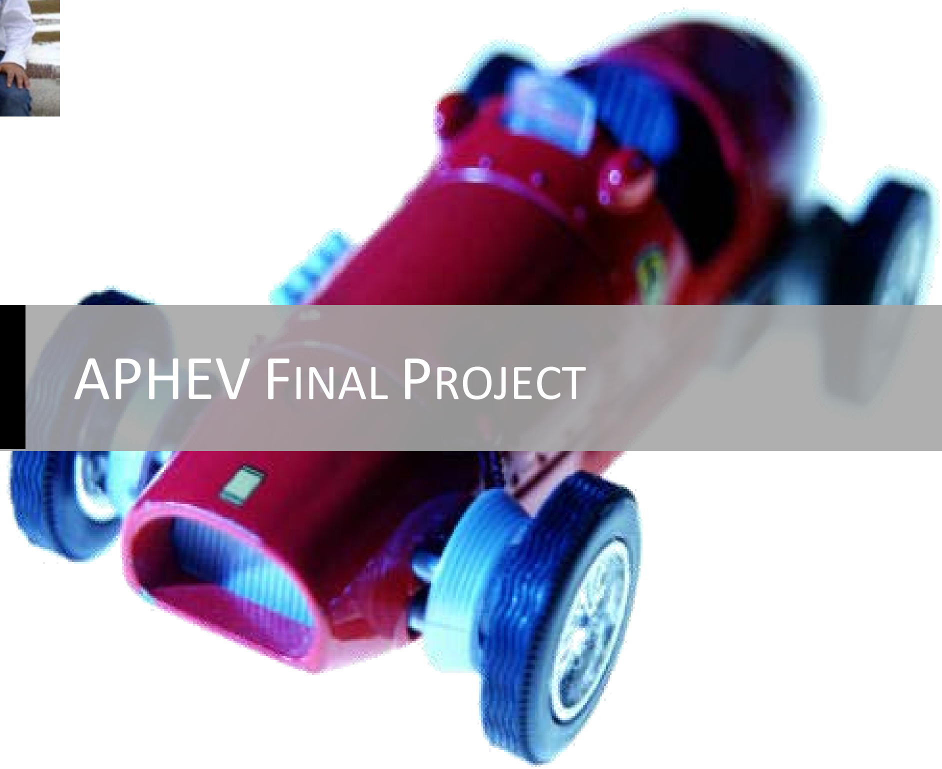

WEEK 04 APHEV FINAL PROJECT

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(A)Introduction

Table A.1 provides EPA sticker data for PHEV Chevy Malibu developed from 2010 Chevy Malibu with 2.4 Liter gasoline engine. PHEV developed in this project, has a 2L downsized gasoline engine with of 3.9 kW-hr Lithium ion battery and 45 KW electric motor. Technologies like regenerative braking, engine start stop, advanced engine control for efficient operation, which will be discussed later in this report, are added to reduce fuel consumption with optimum performance. PHEV designed, provides city MPG (EPA sticker) of 39 MPGe and highway MPG (EPA sticker) of 29 MPGe as compared to baseline 2010 Chevy Malibu with city and highway economy of 22 MPG and 30 MPG respectively. 0-100 MPH performance of designed PHEV is 33 seconds as compared to 29 seconds for baseline Chevy Malibu. Table A.1 provides EPA sticker values of designed Chevy Malibu PHEV.

Table A.1- Vehicle Sticker

Vehicle Type: (PHEV)		
$26,024		
Fuel Economy		
PHEV		
City	39	(MPGe)
Highway	29	(MPGe)
Combined	35	(MPGe)
Fuel/Energy Consumption		
Gasoline	2.76	(gal/100 miles)
Electric	5.64	(kW-hr/100 miles)
Blended	2.32	(gal_e/100 miles
Range		
Electric/Blended (CD)	42	(miles)
Gasoline (CS)	480	(miles)
Total (CD+CS)	522	(miles)
CAFE Composite FE		
Combined	39	(MGPe)
Annual Fuel Cost		
Cost	1600	($)

(B) Vehicle Baseline Results

In week 1 of project sensitivity analysis is performed on different model parameters including proportional gain Kp, integral gain Ki, co-efficient of drag Cd and rolling resistance. The model is tuned for maximum 2 errors within 3 mph for all drive cycles including UDDS, HWFET, US06. It is observed that fuel consumption is sensitive to Kp and Ki.

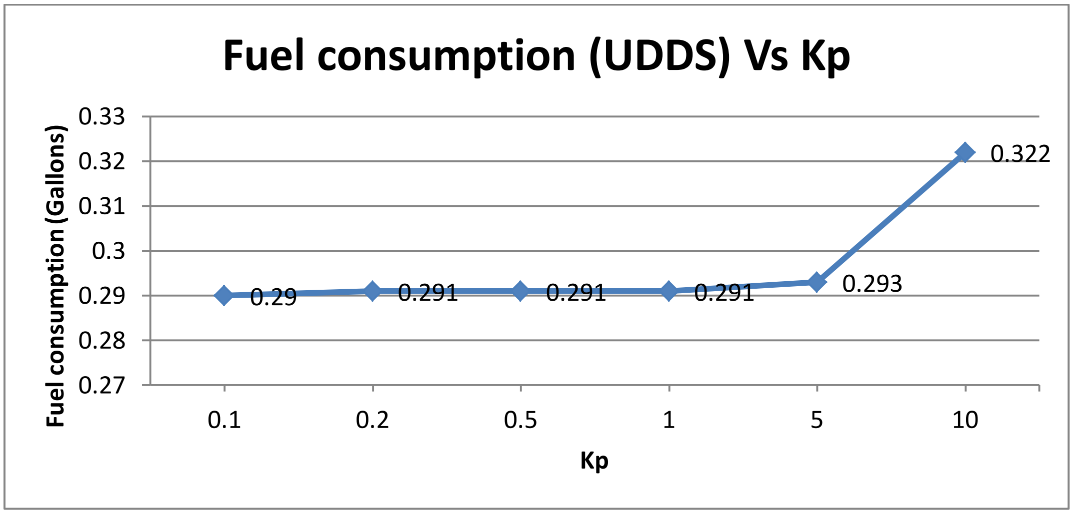

Figure 1 Fuel Economy variation with Kp

Figure 1 shows increase in fuel consumption with increase in Kp values. Based on this analysis Kp value of **1** provided optimum fuel consumption with zero error for UDDS. Analysis is done for HWFET and US06 and a Kp of 1 provided a zero error and hence, finalized. Similarly Ki is obtained as 0.1. Co-efficient of drag is selected as 0.25 which is an achievable value (Toyota Prius has Co-efficient of drag of 0.25). Analysis of fuel consumption for PHEV in HFET drive cycle reveals that electrification has little impact on fuel consumption reduction, hence there is need for less aerodynamic drag for reduction in highway fuel consumption. Table B1 summarizes sensitivity of Kp, Ki, Cd and Rolling resistance on fuel consumption (City/Highway) and performance.

Table B1. Sensitivity analysis used to determine final baseline model parameters

Model Parameter	Level of Change (%)	Hwy ΔFC (%)	City ΔFC (%)	Accel Δ (0-60) (%)
Kp	10	0.023	0.067	0
Ki	10	0.022	0.0074	0
Cd	10	1	0.5	0
Rolling Resistance	10	1	1	0
Upshift Threshold Mult	0	0	0	0
Downshift Threshold Mult	0	0	0	0

Table B2. Model Parameters tuned to match baseline model

Model Parameter	Base Model	Tuned Model		(Unit)
		Value	Percent Change	
Kp	**0.1**	1	90	(-)
Ki	**0.025**	0.1	75	(-)
Cd	0.38	0.25	34	(-)
Rolling Resistance	0.008	0.0072	10	(-)
Upshift Threshold Mult	1	1	0	(-)
Downshift Threshold Mult	1	1	0	(-)
BSFC Mult	1	1	0	(-)
Vehicle Mass	3414	3243	5	(lbm)
Engine Accessory Loss	17.2	17.2	0	(N-m)

Table B3. Results of tuning in comparison to base model and vehicle performance

Performance Factor	Actual Vehicle Data	Base Model	Tuned Model	% Diff	(Unit)
Highway Sticker FE	30.00	27	29	5.42	(MPG)
City Sticker FE	22.00	17	20	19.41	(MPG)
Acceleration (0-20mph)	1.9	3.3	2.5	-32	(s)
Acceleration (0-60mph)	9.7	13	11	-18.18	(s)
Passing (60-80)	6	14	11	-18.18	(s)

Table B3 contains results of tuning performed in Week 1 and compares fuel economy and performance with base model. It indicates that there is significant improvement in fuel economy and performance after tuning model parameters.

(C) Vehicle Design Selection

Table C1. Vehicle Technology Design Selection

Design Attributes	City FC (Gallons per 100 miles)	HWFET FC (Gallons per 100 miles)	FC impact(City) (%)	FC impact(Highway) (%)	Cost[1] ($)	Weight (Kg)
Base Vehicle	4.65	2.62	-	-	-	-
Hybrid technology	3.38	2.31	38	12	3125	67
CI engine technology	3.15	2.09	38	21	2393	NA
Engine Start Stop	4.37	2.59	6	1	NA	NA
Advanced Engine Control	2.28	2.71	51	-3.33	NA	NA

Table C1. Contains various technologies assessed in project for reducing fuel consumption. Hybrid technology with engine start stop and engine control is selected considering emission concerns of CI technology. For design selection in order to reduce fuel consumption, advanced technology as mentioned in Table C1 and reduction in fuel consumption by their introduction over base vehicle is assessed. For hybrid technology battery and motor are designed for PHEV application. Design comparison of three battery technologies namely lead acid, Nickel Metal Hydride and Lithium Ion is performed. 3.9 kW-hr Lithium Ion Battery is found to be suitable for PHEV application when compared to 1.5 KW-hr NiMH and Lead Acid Battery. It is observed that Lithium-ion battery with large capacity of 3.9 KW-hr provides more range for operation in charge depleting mode and hence, suitable for PHEV application. 5 KW-hr Lithium-ion battery is used in Toyota Prius (Hymotion) PHEV[2]. Three motors have been compared for a Hybrid Electric Vehicle application. Motor with maximum torque of 143 Nm (0-3000 RPM) and maximum power of 45 KW (3000-7000 RPM), along with addition of hybrid power train, engine

[1] Assesment of Technology for Improving LDV Fuel Economy, NAE report
[2] Testing and Analysis of Three Plug-in Hybrid Electric Vehicles SAE 2007-01-0283

start stop controller logic and advanced engine control strategy, is selected to meet the performance and regeneration requirements of PHEV. Control strategies are discussed in next section. Table C1 includes cost and weight increase details with addition of hybrid technology. Final cost of PHEV Chevy Malibu is about **$26,024** with a mass of **1636 Kg**.

(D) Vehicle Controllers

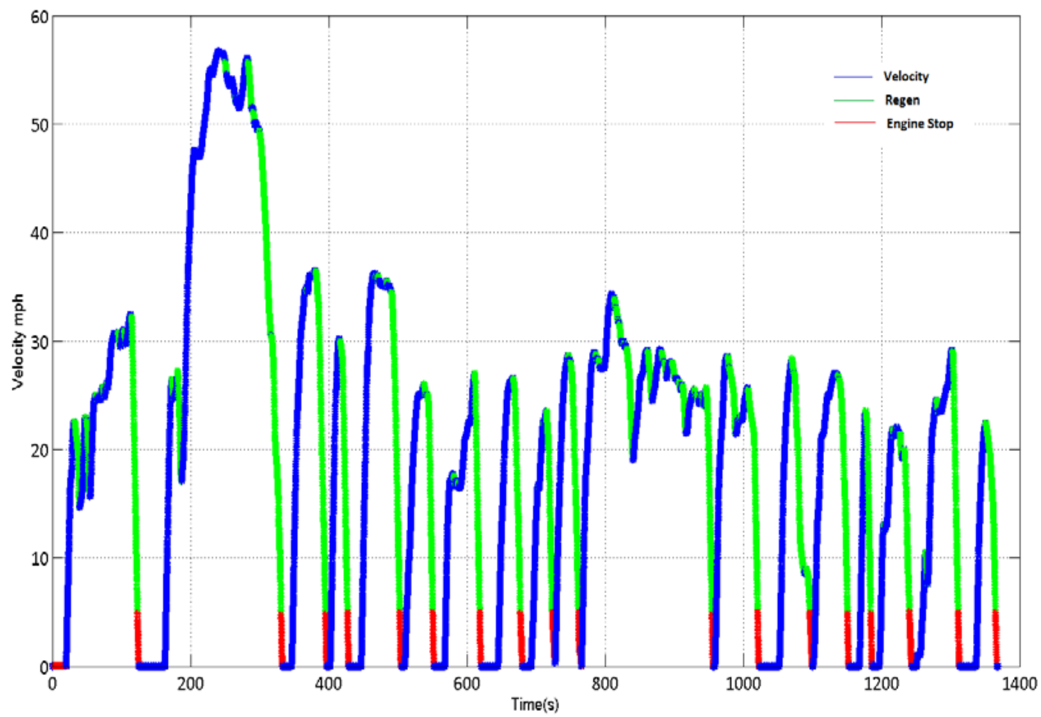

Figure 2 Active Controller Components During UDDS cycle

It is evident from this figure that, there is a lot of potential for regeneration in UDDS (city cycle). Vehicle model actually possesses controllers in order to activate these components on a specific drive cycle. Different types of controlling strategies with their respective FC reduction are shown in the following table.

Table D1 FC reduction achieved by employing different strategies

Control strategy	FC reduction (%)
Engine start-stop	6
Torque blend	16
Engine speed optimization	13
No regeneration below 5 mph	-3%

The values above represent FC reduction potential in the case of UDDS cycle, and these values differ in case of highway. As the possibility of regeneration and engine start-stop is meager in case of HWFET, these values are lower for highway driving. Also, FC reduction percentage is negative in the case where there is no regeneration below 5 mph. This control strategy has to be employed because regeneration torque is lesser when compared to braking torque and it diminishes as speed decreases and at speeds below 5 mph, regeneration torque has to be neglected for efficient braking. Also, it is evident that torque blend, which is the essence of hybridization, has maximum potential and hence the technology is beneficial for urban style of driving.

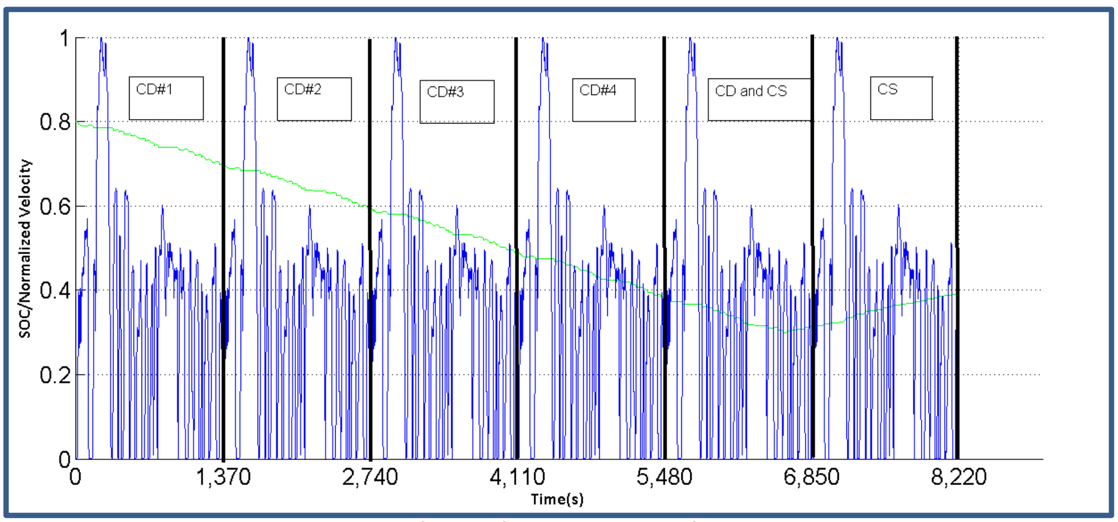

Figure 3 CD and CS Mode During UDDS cycle

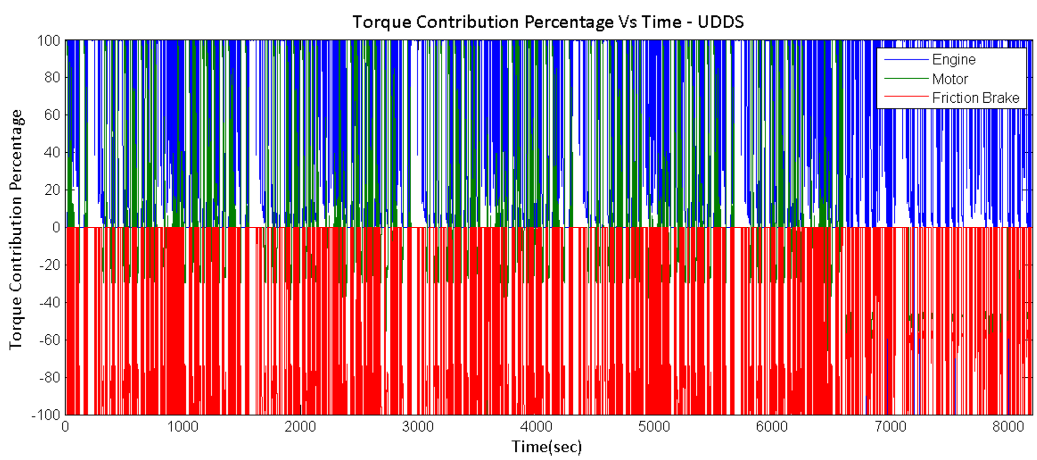

Figure 4 Motor Deactivation and SOC Control for UDDS

Figure 4 represents the activity of controllers over a range of drive cycles; in this case the range is limited to 5 UDDS cycles. It is evident from the first plot that battery SOC which starts at 0.8 falls to 0.3 (ΔSOC ~ 3% of FC energy) by about 4.5 cycles and the controller switches the motor off at this point. Until this point, vehicle can be assumed to travel in CD mode. After this point, regeneration helps improve SOC until it reaches 0.8 and the cycle continues. The second figure in Figure 3 denotes active components for the range of drive cycles. It is evident that motor is switched off exactly at the point when the battery SOC is less than 0.3 and active regeneration helps achieve increase in battery SOC.

Table D2. SOC Control and Battery Usage based upon a 13 A-hr / 3.9 kW-hr capacity battery.

Cycle	**Starting SOC**	**Ending SOC**	**Number of Cycles[3]**	**Fraction of FC[4]**
City CD	0.80	0.30	4.6	N/A
Hwy CD	0.80	0.30	51.4	N/A
US06 CD	0.80	0.30	13.0	N/A
City CS	0.31	0.39	1.0	1
Hwy CS	0.30	0.35	1.0	1
US06 CS	0.33	0.40	1.0	1

Table D2 is a simple representation of Figures 3 and 4 in terms of numbers. Here the numbers clearly suggest that hybrid technologies are very efficient for city driving conditions. As the more efficient, 'motor', operates more in the case of UDDS than HWFET, it results in higher MPGe. Also, battery depletion is lesser in case of highway driving. This is beneficial because power of E-motor (45kW) is lesser compared to that of an IC Engine and hence cannot propel the vehicle at higher speeds. Also at these speeds, IC engine is considerably more efficient.

Table E1. Overview of vehicle performance in comparison to the 2010 Malibu baseline vehicle, 2012 Toyota Prius, and a benchmark vehicle with Energi technology[5]

Performance Factor	Baseline 2010 Malibu	2013 Prius	Bench Mark Vehicle(Ford Fusion PHEV 2013)	Your Vehicle	(Unit)
Cost	$ 22520	$ 32000	$ 27200	$ 26204	($)
Mass	1539	1436	1688	1537	(kg)
Highway CS FE	30	51	44	29	(MPG)
City CS FE	21	49	41	33	(MPG)
Range CS	400	550	520	480	(Miles)
Highway CD FE	-	88	100	39	(MPGe)
City CD FE	-	102	108	29	(MPGe)
Range CD	-	11	21	42	(Miles)
Steady State (50 mph)	29.0	48.8	-	100.0	(mpg)
Steady State (62 mph)	31.0	37.0	-	56.3	(mpg)
Steady State (81 mph)	27.0	29.5	-	29.8	(mpg)
Steady State (93 mph)	27.0	24.0	-	23.0	(mpg)
Acceleration (0-20mph)	3.0	3.0	2.0	5.0	(s)
Acceleration (0-60mph)	12.4	12.0	8.5	15.0	(s)
Passing (60-80)	6.5	8.0	8.0	8.0	(s)

In Table E1, the vehicle designed is compared to various other vehicles. The effort was to improve the efficiency of baseline Malibu 2010 non hybrid vehicle and the new vehicle achieved the target with impressive FE numbers and not deteriorating performance. In comparison with the popular PHEVs in market, vehicle is priced on a slightly lower side. CS FE of the vehicle designed is lower when compared to Prius in both city and highway drive cycles. This can be attributed to the fact that Prius uses a 2.4L engine with a 60kW motor and a 4.5 kWh battery[6]. These numbers are significantly higher compared to the components provided to design PHEV. In fact, designed vehicle utilizes a 45 kW motor with a 3.9 kWh battery which does not provide comparable hybridization as in the case of Prius. In steady state driving of 50 mph, vehicle is most efficient because of the torque blend and engine optimization controller which

[6] http://en.wikipedia.org/wiki/Toyota_Prius_PHV

run at maximum possible efficiency for this speed. The charge depletion (CD) FE numbers are also lower in the case of designed vehicle because other vehicles are run completely on an E-motor during CD modes which considerably enhance FE. The designed vehicle does not have the capability to run completely on an E-motor, especially in a highway drive cycle and the battery discharged completely in half a drive cycle when an attempt was made to do so. Ford Fusion PHEV[7] with Energi technology is used as a benchmark vehicle because it utilizes a comparable 2.0L engine and an 88 KW motor (this is not comparable). Even in this case, a strong hybridization is possible and hence, FE economy numbers are much higher when compared to the designed vehicle.

From figure 5, the vehicle designed can be considered to be quite fuel efficient when compared to the baseline vehicle but needs to show appreciable increase in FE when compared to vehicles in the market. However, with constraints on motor power and battery capacity provided, it can be assumed that vehicle uses the available energy quite effectively.

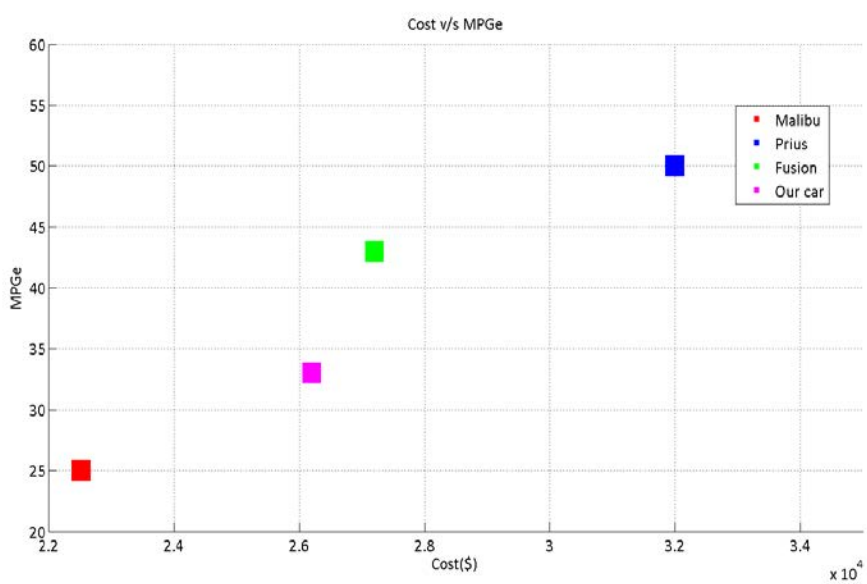

Figure 5 Cost v/s MPGe for vehicles being compared

[7] http://media.ford.com/images/10031/2013_FusionHybrid_Specs.pdf

(F) Summary and Conclusions

- A PHEV is successfully designed from a baseline Malibu with improved efficiency and without disturbing performance of the vehicle
- Kp and Ki have been tuned in the first week so that the errors in the drive cycle have been reduced. Also. Sensitivity of Kp and Ki on FC is tested. Transmission shift logic is slightly optimized so that the performance criteria are met without reducing FE
- In week 2, percentage FC reduction using different technologies have been compared against values mentioned in the NAE report. A CI engine has been designed to test the relevance of CI technologies in terms of hybridization. Also, possibilities for regeneration and application of engine start-stop technologies have been explored
- In week 3, motor and battery have been critically tested so that best configuration can be obtained for realizing maximum hybridization potential
- All the control strategies pertaining to the hybridization have been formulated in week 4. First, a linear torque blend algorithm has been used to optimally distribute the normalized torque request between IC Engine and E-motor. Next, the engine is optimized to operate at maximum efficiency points based on cost opportunity at different speeds and torque requests. Battery is then managed within the set limits of maximum and minimum SOC so that maximum regeneration energy can be tapped without losing battery capacity. Regeneration is clipped off below vehicle speeds of 5 mph as braking torque provided by motor in these speeds is very low
- Finally, by adding appropriate technologies and employing control strategies. a better performing (in terms of Fuel Economy) vehicle is obtained from the baseline, Chevy Malibu,

(G) Appendix

G1. Sizing of Motor based on maximum Regen Power

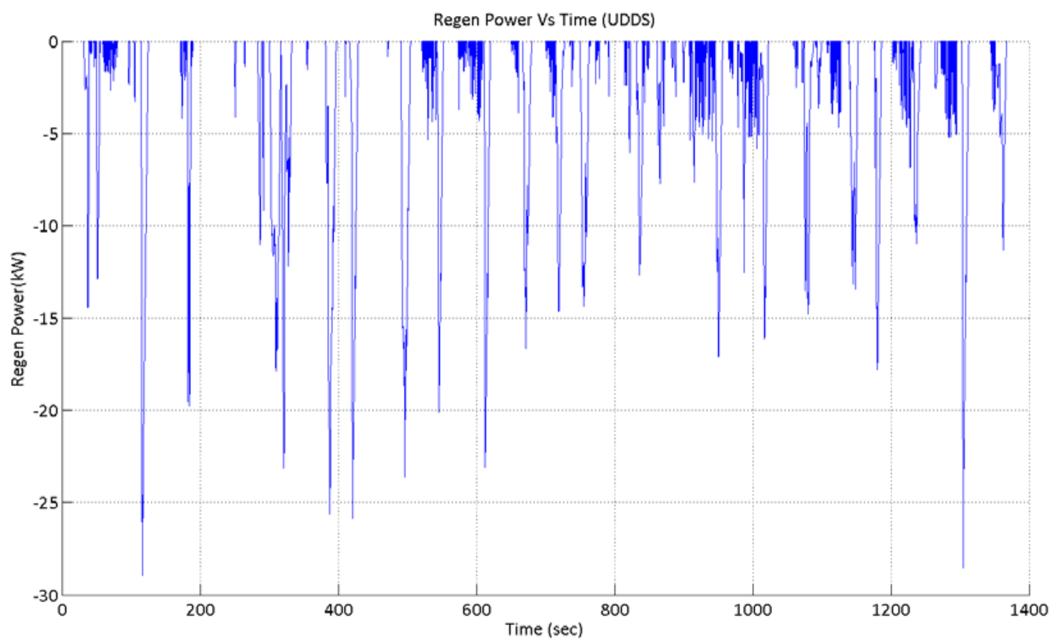

Figure 6 Regen Power Vs Time (UDDS)

From fig 6 it can be observed that for UDDS cycle maximum regeneration energy is possible between 28 Kw (approx). 45 Kw motor selected for PHEV application is thus found capable for absorbing maximum possible regeneration occurring for UDDS city drive cycle.

G2.Sizing of Battery based on cumulative regen energy

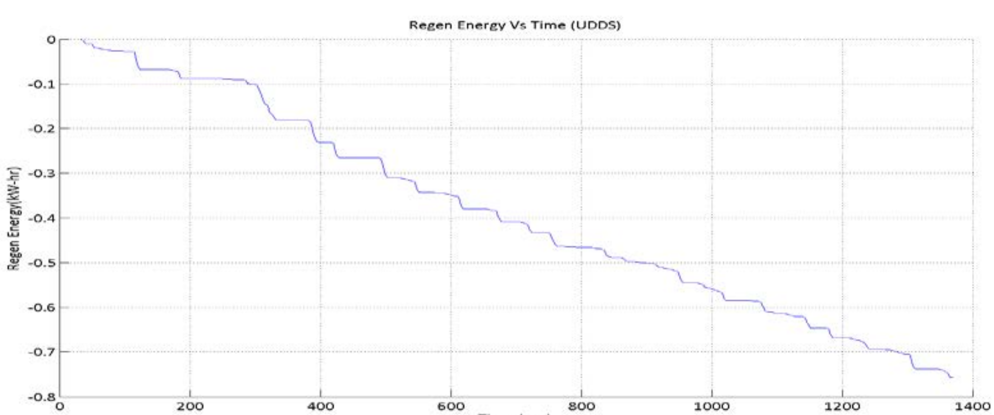

Figure 7 Regen Energy Vs Time for UDDS

From fig maximum regen potential of UDDS cycle is 0.75 Kw-hr. Lithium ion battery with 3.9 kW-hr energy capacity is thus found to be capable of absorbing maximum regen energy over one UDDS drive cycle.

G3. Regen Power Vs Vehicle Speed

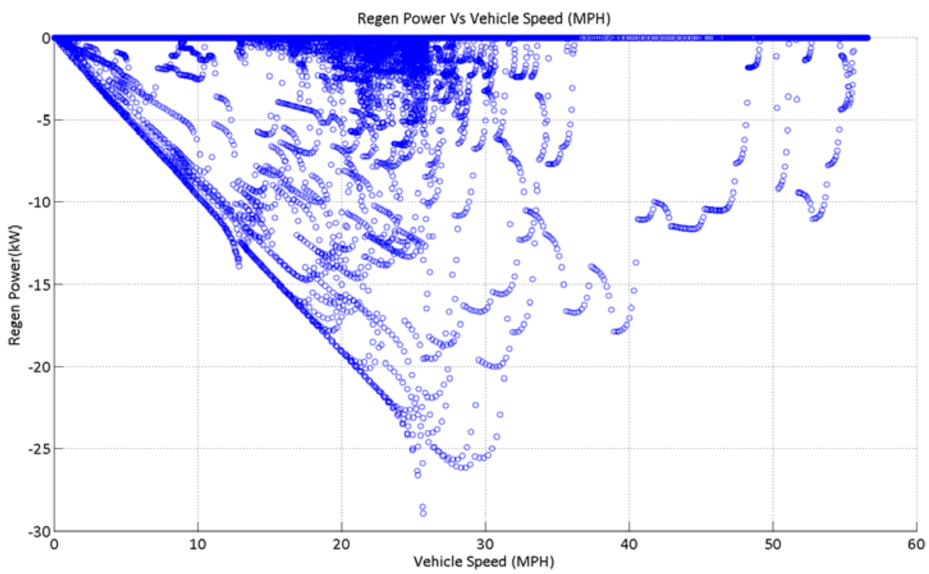

Figure 8 Regen Power Vs Vehicle Speed

Figure 8 shows that maximum regeneration occurs between 25 MPH and 30 MPH

G5. CD and CS analysis for US06 and HWFET

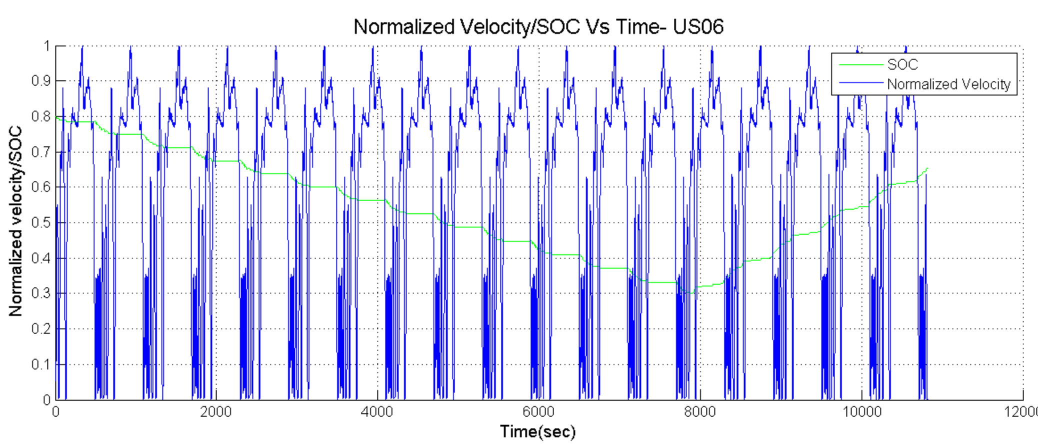

Figure 9 Normalized Velocity/SOC Vs Time- US06

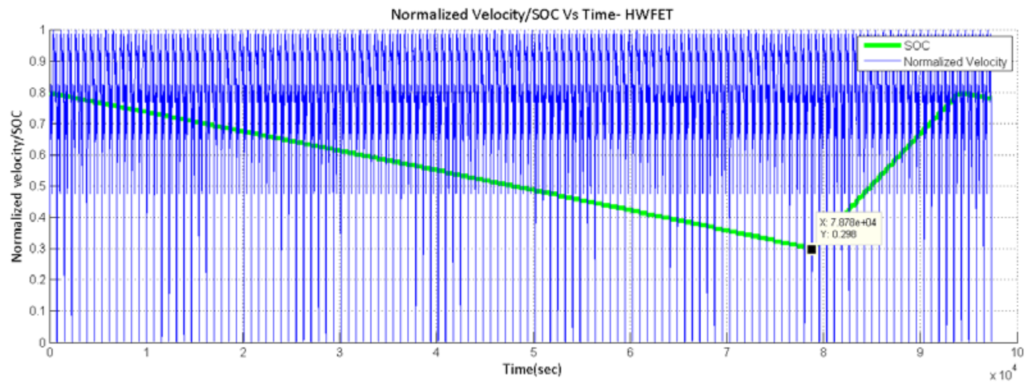

Figure 10 Normalized velocity/SOC Vs Time- HWFET

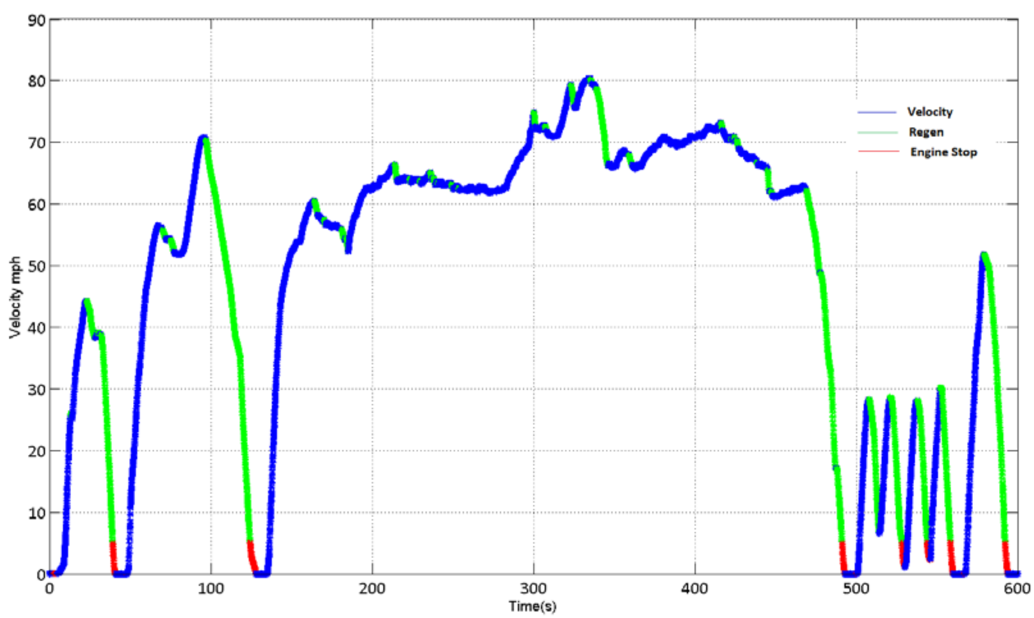

Figure 11 Regeneration/start stop potential-US06

G4.Cost analysis

Table G5. Cost Analysis

Technology added	Cost of new technology ($)
3.9 Kw-hr Lithium ion battery	850
45 Kw Electric motor	1050
Engine downsizing (2.4 l to 2 l)	555
Regenerative braking	240
Starter Alternator	-95
High voltage cables	80
Body for hybrid power train	180
Control Electronics	940
Total	3800