A VEHICLE SYSTEMS APPROACH TO EVALUATE PLUG-IN HYBRID BATTERY COLD START, LIFE AND COST ISSUES

A Record of Study

by

NEERAJ SHRIPAD SHIDORE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF ENGINEERING

May 2012

Major Subject: Engineering

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Approved by:

Chair of Committee,	Mehrdad Ehsani
Committee Members,	Shankar Bhattacharyya
	Karen Butler-Purry
	Reza Langari
	Aymeric Rousseau
Head of Department,	Robin Autenrieth

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Major Subject: Engineering

ABSTRACT

A Vehicle Systems Approach to Evaluate Plug-in Hybrid Battery Cold Start, Life and Cost Issues. (May 2012)

Neeraj Shripad Shidore, B.E., University of Pune;

M.S., Texas A&M University

Chair of Advisory Committee: Dr. Mehrdad Ehsani

The batteries used in plug-in hybrid electric vehicles (PHEVs) need to overcome significant technical challenges in order for PHEVs to become economically viable and have a large market penetration. The internship at Argonne National Laboratory (ANL) involved two experiments which looked at a vehicle systems approach to analyze two such technical challenges: Battery life and low battery power at cold (-7 °C) temperature.

The first experiment, concerning battery life and its impact on gasoline savings due to a PHEV, evaluates different vehicle control strategies over a pre-defined vehicle drive cycle, in order to identify the control strategy which yields the maximum dollar savings (operating cost) over the life of the vehicle, when compared to a charge sustaining hybrid. Battery life degradation over the life of the vehicle, and fuel economy savings on every trip (daily) are taken into account when calculating the net present value of the gasoline dollars saved.

The second experiment evaluates the impact of different vehicle control strategies in heating up the PHEV battery (due to internal ohmic losses) for cold ambient conditions. The impact of low battery power (available to the vehicle powertrain) due to low battery and ambient temperatures has been well documented in literature. The trade-off between the benefits of heating up the battery versus heating up the internal combustion engine are evaluated , using different control strategies, and the control strategy, which provided optimum temperature rise of each component, is identified.

DEDICATION

I dedicate this work to my wife, Shweta. This work would not have been possible without her strong resolution and support to see me attain this degree, and the sacrifices she has had to make, the patience she has had to show through the last several years.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Ehsani, for allowing me to pursue this degree in the distance education format, while providing constant guidance, encouragement and support throughout the process. I would also like to thank my committee members, Dr. Bhattacharyya, Dr. Butler-Purry, and Dr. Langari, for their support.

Thanks go to the staff and management of Argonne National Laboratory, for allowing me to pursue my internship and complete my Doctor of Engineering degree. I would especially like to thank Mr. Aymeric Rousseau for agreeing to be my internship supervisor for the duration of the internship, and being flexible and supportive throughout the process. Thanks are also due to my colleagues who participated in the studies that are included in this document – Jason Kwon, Anant Vyas, Eric Rask and Forrest Jehlik. This work would not have been possible without their contributions. I also owe a sense of gratitude to all my colleagues at Argonne National Laboratory, who are too numerous to list, for making every work day fun and challenging.

Finally, thanks to my wife Shweta for her patience, sacrifice and support, and my daughter Meher for bringing a smile to my face all day long. I thank my parents and my sister for their encouragement, as well.

NOMENCLATURE

ANL	Argonne National Laboratory
PHEV	Plug-in Hybrid Electric Vehicle
NPV	Net Present Value
CS	Charge sustaining
CD	Charge depleting
Mpg	Miles per gallon
FE	Fuel economy in mpg
FC	Fuel consumption, in L/100 km
EV	Electric vehicle or electric vehicle operation of a PHEV/HEV

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CHAPTER I

INTRODUCTION TO THE INTERNSHIP SITE – ARGONNE NATIONAL LABORATORY

Argonne National Laboratory [1] is one of the U.S. Department of Energy's oldest and largest national laboratories for science and engineering research. Argonne has roughly 3,200 employees, including about 1,000 scientists and engineers, three-quarters of whom hold doctoral degrees.

Research at ANL centers around three principal areas which are described below.

ENERGY

Energy Storage: Argonne research includes energy storage systems for electric-drive vehicles, with an overall goal of a green-energy grid enabled by electrical energy storage development, prototype and manufacturing process engineering, stationary storage and grid management, and electric transportation systems.

1. Alternative Energy and Efficiency: Argonne is developing advanced alternative energy sources to promote energy independence through improved chemical fuels, advanced bio-fuels, solar energy systems, and improvements in engine , combustion and fuel dynamics.

This record of study follows the style of *SAE Journal of Engines*.

2. Nuclear Energy: Argonne develops advanced reactor and fuel cycle systems – including fast reactor and fuel cycle technologies and advanced modeling and simulation methods for the same. There is a strong focus on innovative nuclear energy systems, which enable the safe and sustainable generation of nuclear energy.

BIOLOGICAL AND ENVIRONMENTAL SYSTEMS

Argonne produces integrated molecular-scale, hydrological, economic and social computational models to enable regionally focused ecological and climate assessments through metagenome analysis, discovery of protein specimens in the hydrological system, weather and climate prediction on a regional, national and global level, and linking of the weather prediction to economic assessment of the region under consideration.

NATIONAL SECURITY

Argonne develops critical security technologies which help identify, prevent and reduce the impact of threats to the national security. Mathematical and computational sciences, research into biology, chemistry, nuclear safety and a study of overall energy security are involved.

TRANSPORTATION TECHNOLOGY R&D CENTER

The Transportation Technology R&D Center (TTRDC) at ANL broadly covers the ‘energy’ research. At the TTRDC, research is performed on advanced batteries, hybrid and plug-in electric vehicles, advanced engines, alternative fuels, vehicle systems, smart grid, recycling, applied materials and hydrogen fuel cells.

ANL researchers at the TTRDC help improve processes, create products and markets, and provide cost effective transportation solutions in support of Department of Energy (DOE) goals. The research results are used to assist the auto industry in the development and optimization of their advanced technologies, and help the DOE benchmark petroleum displacement, current technologies and future transportation goals. Research from TTRDC has won many awards including R&D 100 awards, discover awards, and distinguished study awards. Numerous patents have been filed by TTRDC in the above mentioned research areas.

VEHICLE SYSTEMS RESEARCH AT TTRDC

The vehicle systems research at TTRDC is divided into three areas:

1. Vehicle systems modeling and simulation: ANL's Powertrain System Analysis Toolkit (PSAT) is the primary software simulation tool to support DOE activities in the area of advanced vehicle technologies. PSAT is used by more than 400 users worldwide, including vehicle manufacturers (OEMs and suppliers), government laboratories, research institutes, and academia. Researchers in the vehicle systems group also perform studies for DOE, and in collaboration with private industry and academia, in the field of advanced vehicle systems.

2. Advanced Vehicle Benchmarking: ANL's Advanced Powertrain Research Facility (APRF) enables benchmarking of advanced vehicle technologies, like hybrid vehicles, plug-in hybrid vehicles and hydrogen or bio-fueled vehicles. Using the facility's two wheel drive and four wheel drive dynamometers and

state of the art instrumentation and emissions analysis units, vehicle performance, fuel economy, energy consumption and emissions are measured. The APRF is one of the only facilities in the US capable of advanced ‘in-situ’ instrumentation (for example: contactless engine torque sensor), and SULEV emissions measurement capability. This facility is extensively used by US and international OEMs to perform testing and advancements on prototype OEM vehicles, and more recently by after-market PHEV manufacturers as well. This facility is also used by DOE to benchmark the latest technology in vehicles.

3. Component and powertrain subsystem benchmarking: Advanced powertrain components and subsystems (e.g. batteries, engines) are evaluated in a systems context using component in the loop (CIL) technology. Real components are evaluated in virtual vehicle environments for impact of vehicle strategies on component life and performance, as well as impact of component technology for vehicle fuel economy and performance. ANL is the only laboratory capable of CIL experiments. ANL has transferred the CIL technology to numerous companies and other national laboratories, as well.

The author has performed work in the Vehicle Systems Area of TTRDC, Argonne National Laboratory.

CHAPTER II

INTERNSHIP PROJECT- IMPACT OF PHEV CONTROL STRATEGY ON THE NET PRESENT VALUE OF GASOLINE SAVINGS OF A PHEV*

INTRODUCTION

Much insight into the energy management of currently available aftermarket PHEV conversions has been gained with chassis dynamometer benchmarking [1] and fleet testing [2] of aftermarket PHEVs. Numerous studies have focused on optimum energy management of PHEVs to achieve one or more of the following goals:

1. Maximize overall system efficiency [3], [4] over a certain daily travel.

2. Maximize utility factor (U.F.) weighted fuel economy [5].

3. Mitigate the impact of cold engine starts on emissions [6].

Another important factor that should be considered in deciding the energy management is battery life. Along with battery safety, this remains one of the significant technical barriers to the successful introduction of PHEVs into the market [7].

This study considers the impact of different energy management strategies on battery life and fuel economy. For a given vehicle, the energy management strategy that maximizes the Net Present Value (NPV) of dollar savings of a PHEV over its lifetime when

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compared to an HEV is identified. For each vehicle level control strategy, 'equivalent' battery life (over the life of the vehicle) is estimated based on battery utilization. An NPV evaluation of different control strategies would help identify the control strategy leading to the optimum tradeoff between maximizing fuel displacement (maximum EV mode operation and therefore reduction in battery life) and long battery life (minimum EV mode operation, but low fuel economy savings) (Figure 1).

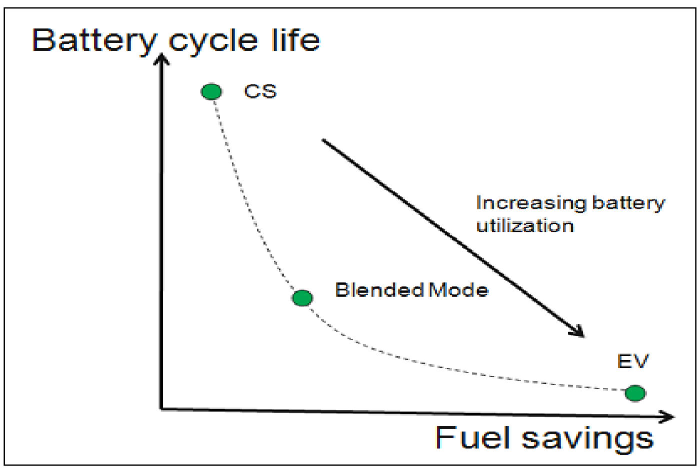


Figure1: Trade-off between PHEV Battery Cycle Life and fuel savings based on Battery Utilization

It should be noted that the NPV dollar savings are based solely on the gasoline dollar saved over the life of the vehicle, minus cost of electricity. Initial battery cost is a part of the vehicle cost, and is therefore not included in the comparison. The NPV of dollar saved should be compared to vehicle price differential to ascertain a PHEV's attractiveness.

BATTERY LIFE

PHEV battery life depends on battery utilization in the vehicle, and the state of the battery when the vehicle is not in use. An example of the latter would be the battery conditions like state of charge (SOC), temperature, when the vehicle is parked overnight and the duration for which the battery is in this condition, the grid charging profile of the battery, etc [8]. The impact of non-vehicle related factors on battery life is accounted for by the calendar life and shelf life [9]. The USABC target for calendar life is 15 years [10]. Battery life is significantly impacted by the large swings in battery SOC, battery temperature rise, initial battery temperature and battery RMS current when the battery is used in a PHEV [11], [12], and [13]. The cycle life of a battery is defined as the number of deep discharge cycles the battery can be subjected to, before the battery capacity and power decrease to a certain level (normally assumed to be 80%) [9]. If the battery capacity and power fall beyond this lower limit, the performance of the vehicle is impacted. The USABC target for PHEV battery cycle life based on a 70% SOC swing is 5000 deep discharge cycles [10]. Recent cycle life test results on individual cells and modules have indicated that in laboratory settings, the target cycle life can be achieved [14].

In an actual vehicle, the number of deep discharge cycles, before the battery capacity reduces by 20%, might be much lower than the cycle life results under standard temperature and humidity conditions. Environmental impacts, and the cell voltage at which the battery is stored overnight, bring down this 'equivalent cycle life'. Based on limited cycle life and calendar life tests, it is impossible to correctly estimate this equivalent cycle life. Therefore, for this experiment, three different equivalent cycle life scenarios are assumed for a 20% decrease in usable capacity based on a 60% SOC swing: 1000, 1500, and 3000 deep discharge cycles.

DESIGN OF EXPERIMENT

Multiple vehicle factors impact fuel and electrical consumption in a PHEV (Figure 2). Since the purpose of this study is to evaluate the impact of energy management on battery life and fuel economy, all other system level factors, except for energy management, are constant. The vehicle travels a given distance on a fixed drive cycle with different energy management strategies.

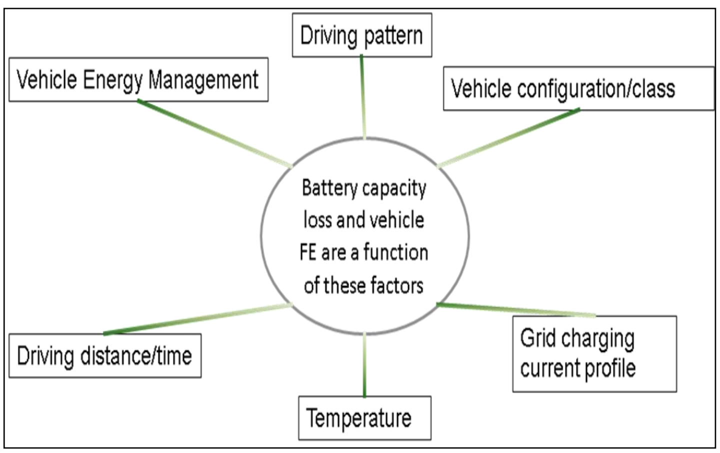


Figure 2: Several factors simultaneously impact Battery Utilization in a vehicle

The vehicle parameters that are kept constant throughout the experiment are:

Midsize power split vehicle with a vehicle test mass of 1921 kg. This includes cargo and driver mass of 136 kg, battery mass of 100 kg, and additional mass for the two electric machines and power electronics.

Drive cycle: LA92. This cycle has been selected as it represents approximately real world driving conditions.

Initial battery temperature: 25 °C.

Battery charged overnight to the same initial SOC (90%) using battery management system (BMS) controlled charging profile, which is also the starting or the initial SOC for each ‘run’.

Initially, the NPV calculations are done for the different energy management strategies for a fixed daily distance of 40 miles, 300 times a year, for 15 years, to identify the energy management that is optimum for both battery life and fuel savings. As stated in the above section, these NPV calculations are performed for three different equivalent battery cycle lives – 1000, 1500, and 3000 cycles for a 60% SOC swing. Later, the driving distance is also varied, to account for the impact of distance on the choice of the optimum energy management strategy.

Table 1 provides information on the power split powertrain used in the emulated vehicle; Table 2 lists the battery specifications for the 41 Ah Li-ion Johnson Control-SAFT pack used for the experiment.

Table 1: Vehicle Powertrain Specifications

Parameter	Value
Engine power (kW)	90
Motor power (kW)	80
ESS power (kW)	60 kW at 50% SOC for 30 seconds (physical battery)
Battery energy (kWh)	10.66
Total vehicle test mass (kg)	1,921

Table 2: Battery Specifications

Battery capacity	41 Ah at C/3 rate
Battery nominal voltage	260 V
Peak power	60 kW at 50% SOC for 30 seconds

The assumption on equivalent battery cycle life (1000, 1500, and 3000 cycles) is for an SOC swing of 60%. With a smaller SOC swing during driving, the battery cycle life would improve dramatically. Lower SOC swing would also possibly result in lower battery temperature rise, and favor the cycle life of the battery. With comparable temperature rise during usage, the equivalent battery cycle life is a strong function of battery SOC. If the equivalent battery cycle life, for 60% SOC swing is ‘x’, then the battery equivalent cycle life for lower SOCs is a non-linear function of ‘x’, as shown in Figure 3 below. The curve below has been approximated from the data published before in [11]. Since there is insufficient PHEV battery data, the curve is an approximation, however, the approximation is sufficiently accurate for the cost analysis that is to follow.

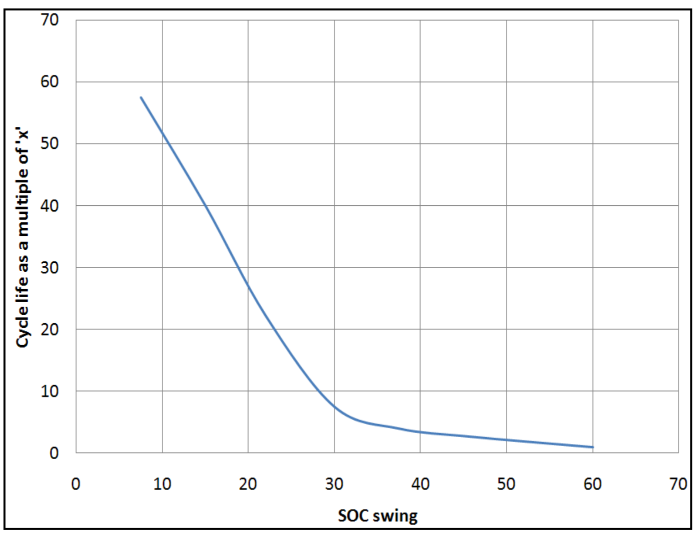


Figure 3: Relationship between SOC swing and increase in cycle life

Even though the battery attains end of life status (20% decrease in usable capacity) after 'x' number of 60% SOC swing deep discharge cycles, where x = 1000 or 1500 or 3000 deep discharge cycles, there is sufficient capacity and power left in the battery so that the fuel economy of the PHEV would still be better than a charge sustaining hybrid. Therefore, from NPV savings perspective, there would be continued gasoline savings even though the battery has reached end of life, the CD range of the vehicle would decrease due to a reduction in the usable capacity of the battery. From cycle life testing of the SAFT VL41M cells at Southern California Edison [15], it has been observed that capacity fade is a linear function of # deep discharge cycles. Although this relationship is expected to be highly non-linear as a substantial capacity fade is seen, for the current study it is assumed that the capacity fade continues to be linear even after the battery has reached 'end of life'. With an assumption of 300 uses per year, and one overnight charging event, the vehicle life in terms of number of deep discharge cycles is 300*15= 4500 deep discharge cycles, assuming a vehicle life of 15 years. Figure 4 shows the battery capacity assumptions as they relate to battery life, used for this analysis.

For the powertrain specified above, the dollar NPV savings over the vehicle life will be calculated for four different energy management strategies. For each case, the engine is started at a different threshold of wheel power demand. The four power thresholds that result in four different energy management strategies are 20 KW, 25 kW, 30 kW and 40 kW. For the vehicle, generator speed limits are high, and therefore generator speed limit does not influence the engine -ON decision. The vehicle energy management issues an engine -ON signal solely based on wheel power demand. Each energy management strategy results in a particular fuel consumption and battery SOC swing, over a constant distance of 40 miles. As stated earlier, it is assumed that the equivalent battery cycle life is proportional to the SOC swing, and temperature rise is fairly constant across the different energy management scenarios. In order to verify that the energy management strategies do yield a comparable battery temperature, and to record the SOC swing of a real battery, a virtual vehicle with the above powertrain configuration was created in PSAT [16] and a real battery of the rating specified in Table 2 was subjected to the energy management strategies using BIL principle.

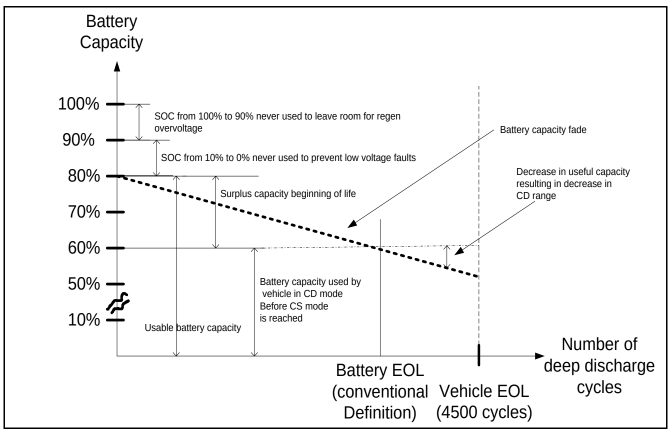


Figure 4: Battery capacity assumptions for the analysis before and after end of life

BIL is used to record utilization data of a real PHEV battery in a virtual vehicle (defined above) over different energy management strategies with the virtual vehicle defined above. For each energy management strategy, fuel economy numbers are also obtained for the virtual vehicle. Based on the battery utilization data obtained, battery cycle life is estimated and used for the cost analysis with the fuel economy numbers. The detailed process is shown in Figure 5.

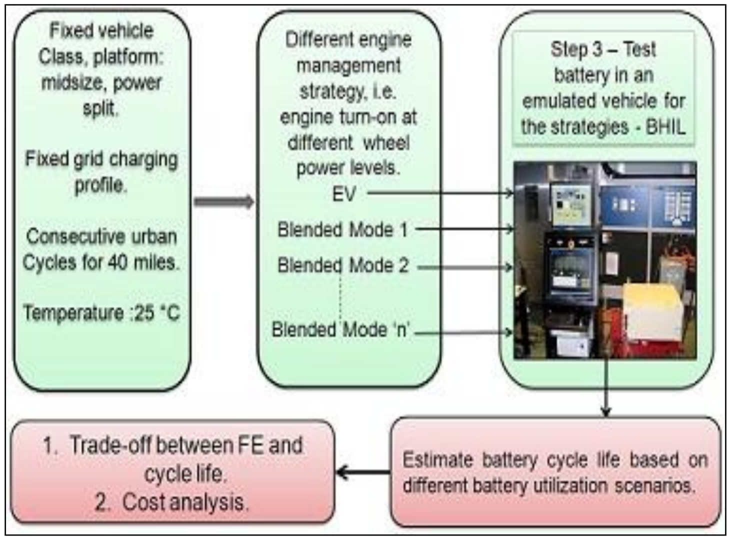


Figure 5: Experiment Process

BATTERY IN THE LOOP

Figure 6 shows the block diagram for Battery IL. Battery IL is used for battery focused PHEV studies, without the need for a real vehicle.

The virtual vehicle – which is a real time simulation model of the vehicle described in the earlier section, subjects the battery through power profiles, as it follows a preset drive trace (the LA92). The high voltage DC power supply (ABC-170) sinks and sources current from and to the battery. Feedback from the battery (SOC, temperature, cell voltage, and power restrictions as a function of temperature and SOC) are communicated to the virtual vehicle controller in real time, to be used as a part of the energy management. This feedback loop from the battery makes battery HIL different from conventional testing of batteries/modules/cells. For example, the vehicle controller is reading SOC as a feedback variable from the battery. If the vehicle controller detects a low SOC, the controller will use the engine more often as the vehicle follows the vehicle speed trace. The virtual vehicle follows standard dynamometer cycles, such as the UDDS or the highway drive cycle. Similarly, the vehicle controller continuously monitors the battery module temperature as a feedback variable. It also controls the battery cooling loop and the virtual vehicle, so as to maintain the battery temperature within prescribed limits and to achieve other control strategy goals.

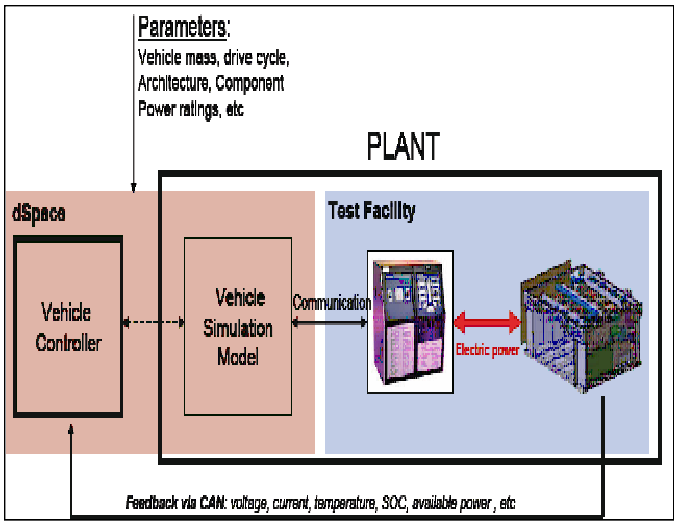


Figure 6: Block diagram of battery HIL

The PSAT vehicle model is modified for CAN, Serial, and Analog/Digital I/O before targeting to the dSPACE system. Battery power constraints (as a function of temperature and SOC), provided by the battery manufacturer, are incorporated into the PSAT blocks. The power constraints cannot be stated because the information is proprietary. Safety interlocks are also added to the virtual vehicle [17].

Battery HIL has been used for the following experiments (Figure 7):

1. Impact of vehicle parameters on battery utilization and battery behavior, e.g., energy management strategies at cold ambient for quick rise in battery temperature.

2. Impact of battery conditions on vehicle performance parameters, e.g., impact of cold battery conditions on vehicle AER [18].

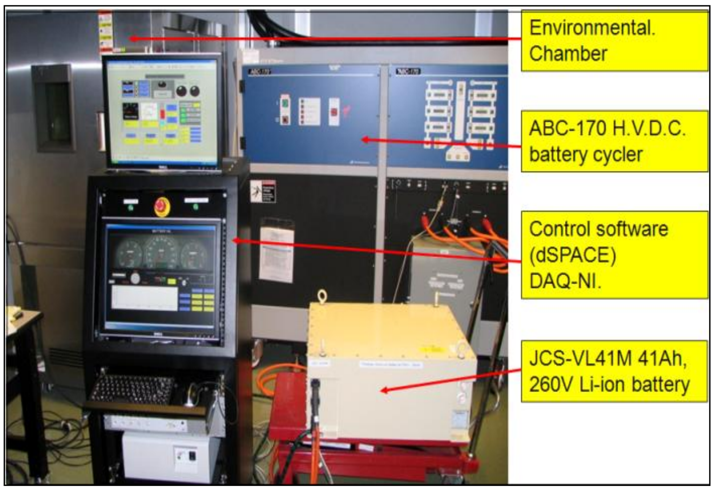


Figure 7: Battery HIL set-up at Argonne National Laboratory

3. Evaluation of hybrid energy storage systems for PHEVs [19].

4. Apples-to-apples comparison of battery technologies.

5. Standard USABC tests for battery capacity, power, etc.

HIL TESTING RESULTS FOR BATTERY UTILIZATION FOR DIFFERENT ENERGY MANAGEMENT STRATEGIES

Table 3 summarizes the vehicle, energy management strategy, drive cycle for this analysis.

Table 3: Vehicle Powertrain Specifications, Energy Management Strategies

Vehicle	Midsize powersplit, vehicle mass 1921 kg
Drive profile	40 miles of LA92 cycles
Energy management	Engine turns on based on wheel power demand threshold — the threshold is varied to have different battery utilization and engine fuel consumption. Engine turn-on thresholds based on wheel power demand are: 20 kW, 25 kW, 30 kW, and 40 kW. Engine operates close to best efficiency when ON.
Battery temperature	Battery initial temperature of 25°C
Battery SOCs	Initial SOC ~ 90% for each test; charge-sustaining at 30% SOC

In order to use the assumption that the equivalent cycle life is mostly dependent on SOC swing (Figure 3), it is important to measure the temperature rise for 40 miles of LA92 driving for different energy management strategies. Table 4 shows the battery utilization data for the different energy management strategies. It should be noted that being a liquid cooled battery, the temperature rise (CAN signal from the BMS) is small, and comparable between different strategies. The highest RMS current is close to 1 C. The initial SOC for the experiment is close to 90%, and the initial battery temperature of 25°C. Table 4 also shows the electrical (Wh/mi) and fuel consumption (L/100 km) for the different energy management strategies. In general, PHEV performance is plotted as a plot of L/100 km versus Wh/mile, to have a sense of the electrical and gasoline consumption (Figure 8). The fuel consumption numbers are from an engine model, and therefore cold start conditions have been ignored. In the cost analysis section, the NPV calculations will be on a separate Y axis, with Wh/mile on the X axis.

Table 4 – Battery utilization for different Energy Management Scenarios

Wheel power for engine turn – ON	Delta SOC*	Temp Rise** (°C)	I-RMS (A) (CD +CS) modes	Wh/mi	L/100 km
20 kW	30%	2.78	33.08	79.95	4.52
25 kW	48%	3.41	40.80	127.92	3.55
30 kW	60%	4	47.65	154	3
40 kW	60%	3.93	45.46	155	3.2

**Mean temperature – Initial temperature; *Initial SOC of ~ 90% - (final SOC at the end of 40 miles of driving).

Based on the battery utilization, battery cycle life is estimated in terms of number of deep discharge cycles up to end of life. As stated earlier, it is difficult to estimate battery cycle life because of lack of data (in the public domain). The HIL testing of the battery utilization reveals that battery temperature rise, RMS current are within limits of 1°C (41 Ah battery) and 5°C, respectively. The battery is always at the same initial temperature and SOC at the start of the test. Therefore, the major battery utilization factor that differs from one control to the other is the SOC swing. As stated in the earlier sections, equivalent battery life is therefore estimated based on the SOC swing, as shown in Figure 3. Accurate predictions will change the values in the cost analysis to follow, but will not change the conclusions significantly.

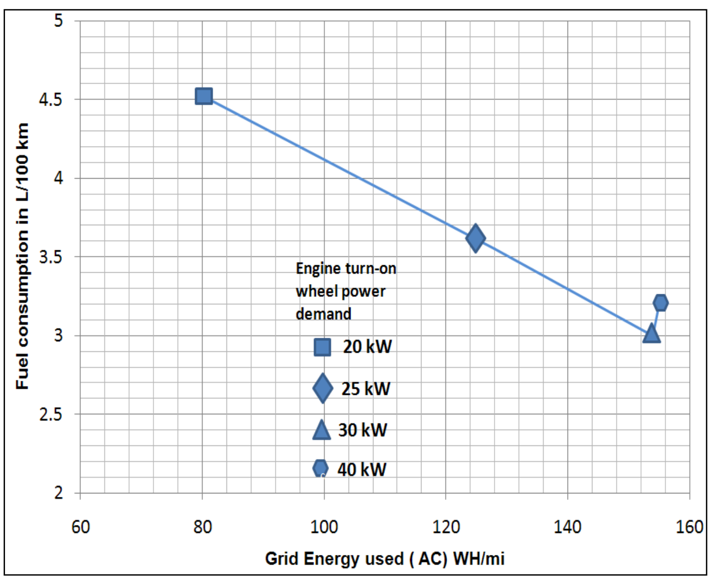


Figure 8: Fuel and electrical consumption for different energy management strategies

NET PRESENT VALUE CALCULATIONS

As stated in the introduction section, dollar NPV of gasoline savings minus electricity cost over the life of the vehicle is the best criterion for comparison of different energy management strategies over a representative drive cycle (LA92) for a given PHEV. This criterion for comparison takes fuel efficiency and battery cycle life into account. The NPV of gasoline dollar savings are fuel dollar savings in comparison to a charge sustaining gasoline vehicle of the same class, over the same cycle (LA92).

The calculations, which have been published earlier in [20] are shown in Figure 9, and the steps are as follows:

For a given energy management strategy (e.g., the engine turns on at 20 kW), Table 4 provides a fuel consumption value in L/100 km and a delta SOC value. After the test is complete (40 miles of LA92), the battery is charged back to its initial SOC of 90% by connecting it to the wall through a charger, with an efficiency of ~85% [21]. AC kWH required to charge the battery to its initial SOC are measured.

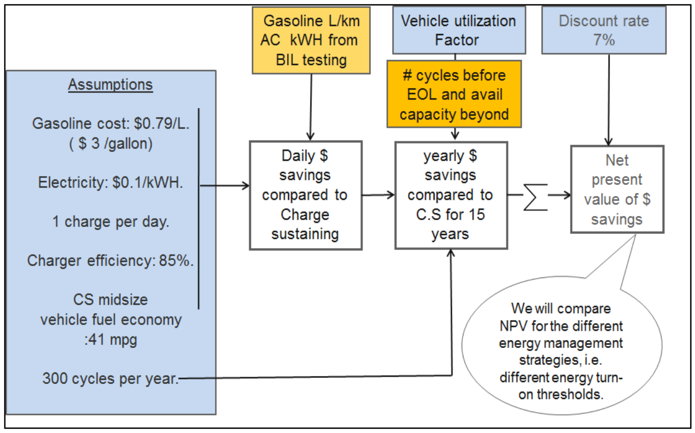


Figure 9: NPV of gasoline savings for each strategy without battery replacement

With an assumption on gasoline cost of 3 dollars per gallon and electricity at dollar 0.1/kWh, the dollar cost of traveling 40 miles LA92 with this control strategy is calculated. To calculate the daily gasoline savings compared to a CS vehicle, the dollar cost of driving a charge sustaining hybrid vehicle for 40 miles LA92 is subtracted from the above cost.

With 300 such uses per year, and an assumption of a single gird charging event overnight, the daily savings can be added up to calculate the yearly savings.

With a vehicle life assumption of 15 years or 150,000 miles (whichever is lower), these savings for each of the 15 years are calculated. In this calculation, the battery cycle life effect enters the picture. For example, in year 10, the battery might have already reached EOL and has a reduced CD range beyond year 10, while in year three, the battery is still above EOL and will result in higher dollar savings for year three. Also, the vehicle utilization factor is used for calculations in the later years. The vehicle utilization factor represents the lower use of vehicles in the later years of their life, when owners typically move to a newer vehicle for daily commutes. The reduction in the rate of vehicle utilization for older vehicles is adapted from the average use pattern of cars published by the National Highway Traffic Safety Administration (NHTSA) [22].The pattern published by NHTSA represents average annual usage. This can be converted to average daily usage, and reduction in daily vehicle usage can be estimated. Yearly savings for the 15 years are added together with a 7% discount rate assumption to obtain the NPVs of fuel savings over the 15 years for the 25-kW energy management case. The same analysis is repeated for the different energy management strategies.

The calculations for the NPV of gasoline dollar saved can be represented by the following set of equations:

1. The cost of gasoline dollars saved in the 'nth' year can be calculated as

$$\$\,gasoline\ saved_{\,n} = \left[\left(F.C_{hev} - F.C_{phev}\right) \times dtrip \times trip_{\,n}\right] \times gasoline\ cost\ \ per\ year \tag{1}$$

where

$\$\ gasoline\ saved\ n$ = gasoline \$ saved in the nth year

$F.C.hev$ = HEV fuel consumption per trip

$F.C.phev$ = PHEV fuel consumption per trip

2. The cost of electrical energy consumed by the PHEV in the 'n'th year can be calculated as

$$\$Electrical\ Energy_n = \frac{(\Delta\ kWh\ per\ trip \times trip_n)}{\eta_{charger}} \tag{2}$$

where

$\$\ Electrical\ Energy_n$ = Cost of electrical energy consumed in the nth year.

$trip_n$ = number of trips in the nth year.

$\eta_{charger}$ = Charger efficiency (constant value assumed)

3. Therefore, from equation 1 and 2, the future value of the dollar savings of the PHEV in the 'n' the year over a CS hybrid can be calculated as:

$$F.Vn = \$gasolione\_saved_n - \$Electrical\ Energy_n \tag{3}$$

where

$F.Vn$ = Future value of \$ saved in the nth year.

4. The future value is converted to present value using a discount rate (assumed 7% for this study), for the nth year:

$$P.V._n = F.V_n\,(1+d)^{-n} \tag{4}$$

where

$P.V._n =$ Present Value of \$ savings in the nth year

$d =$ discount rate

5. The net present value of dollar savings can be calculated by adding the present value savings of each year for 15 years of vehicle life or 150,000 miles, whichever is reached sooner:

$$N.P.V = \sum_{n=1}^{n=15} P.V._n \tag{5}$$

where

N.P.V = Net Present Value of \$ savings (operational cost) by using a PHEV instead of an HEV

COST ANALYSIS

The NPV analysis compares the gasoline cost saved over the life of the PHEV, for different control strategies. As can be seen from the explanation in the earlier section, NPV savings is a function of equivalent cycle life and gasoline savings per charge. Comparison of different control strategies for NPV analysis is done for three different equivalent cycle lives: 1000, 1500, and 3000 deep discharge cycles for a 60% SOC swing.

CASE 1: NPV SAVINGS COMPARISON FOR THE FOUR CONTROL STRATEGIES FOR FIXED DISTANCE

Figure 10 shows the NPV savings for the different control strategies for an assumed equivalent cycle life of 1500 cycles for an SOC swing of 60% (right hand side axis, yellow curve), against the Wh/mile on the X axis. The left hand side axis shows L/100 km on a 'per distance' basis (blue curve). The blue curve represents the electrical and fuel consumption for different energy management strategy. The shape of the green curve is a result of multiple factors which are presented in Table 5.

***Table 5 - Multiple factors which impact NPV savings for an Equivalent Cycle Life of 1500 cycles for an SOC swing of* 60%.**

Engine ON threshold	Wh/mile	L/100 km	SOC swing per charge	Equivalent cycle life (from Figure 3)	Vehicle years in which battery capacity less than 60% SOC (maximum used).	Does capacity fade impact CD range given that distance is 40 miles only?
20 kW	79.95	4.52	30%	11250	None	No capacity fade
25 kW	127.92	3.55	48%	3750	Years 13,14 ,15	No, capacity fade is minimal and daily distance is also low for years 13, 14, 15.
30 kW or 40 kW	154	3	60%	1500	Years 6-15	Yes, but impact reduced in years 12-15 due to reduced daily distance.

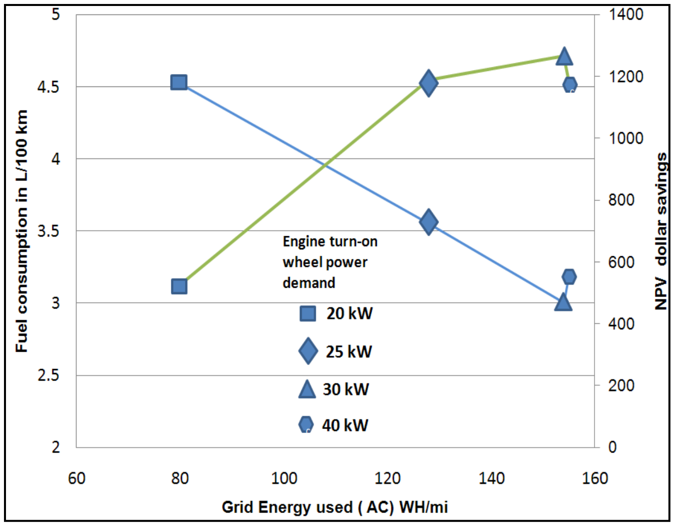


Figure 10: NPV savings for different energy management strategies, for 40 miles of LA92

Multiple factors impact the NPV savings as seen in Table 5 and Figure 10. When the engine turn on threshold is 20 kW, the daily SOC swing is low (30%), and the battery lasts more than the vehicle. Therefore, the low NPV savings are due to not utilizing the battery to its full CD capacity. For the 25 kW case, there is better battery utilization than the 20 kW case (SOC swing of 48% versus 30%), and equivalent cycle life is slightly less than vehicle life (3750 and 4500, respectively). The useful battery capacity does dip below 60% after 3750 cycles, however, the battery still has enough capacity to do an SOC swing of 48%, as required for that engine turn- ON power (Table 5). Therefore, even though the battery reaches 'End of Life' per definition, no impact on the vehicle level is observed. For the energy management where the turn on threshold is 30 kW, and 40 KW, the equivalent cycle life is 1500 cycles. Therefore, there is a drop in usable capacity until the vehicle reaches end of life. The rate at which capacity decreases per year is 4% or 0.4 kWh (1500 cycles for a 2 kWh or 20% capacity fade, therefore, 0.4

kWh per year /300 cycles). In the later years of the vehicle, (years 12-15), the vehicle daily distance traveled decreases, and therefore the severe negative impact of capacity fade is cancelled. Also, because the engine turns on at 30 kW and 40 KW respectively, there is a lot of gasoline savings in the initial years. Because of the discount rate used in the NPV calculations, the impact of capacity fade in the later years does not get as much weight as the high gasoline savings in the initial years. The NPV savings for the 30 kW case are higher than the 40 kW case because the 40 KW case has more CS operation: therefore, higher L/100 km gasoline consumption. From the NPV point of view, the battery capacity impact is the same for the 30 kW and the 40 kW cases.

To summarize, there is a sharp increase in NPV savings from the 20 kW case to the 25 kW case since the NPV savings are independent of battery life, and higher battery utilization increases NPV savings. When the 25 kW engine turn on threshold results are compared to the 30 kW case, the NPV savings still increase; however, the rate of increase is lower than the rate of increase between 20 and 25 kW case. Though higher engine turn-on threshold increases the savings, battery life has a negative impact and tapers the rise in savings. The battery impact itself is mild, since it occurs late in the vehicle life when daily driving distance reduces, and since the daily distance of travel is just 40 miles in the initial years as well. The battery capacity fade is only 0.4 kWh per year. Increased charge sustaining operation for the 40 kW engine turn ON case result in lower NPV savings as compared to 30 kW; the battery impact is identical for both cases.

Figure 11 shows the results if the equivalent battery life of 1000, 1500, and 3000 cycles is assumed, for a 60% SOC swing. The behavior of the curves for the 1000 and 3000 equivalent cycles can be explained in a manner similar to the above. For the case where the cycle life is 1000 for a 60% SOC swing, the 'end of life' is reached in 4 years of vehicle life, and therefore, by the 15 year of the vehicle, there is a huge degradation in battery capacity. Therefore, the NPV savings are lower for the 30 kW and 40 kW case when compared to the 25 kW case. Also, the rate of battery degradation is high (20% or 2 kWH in 1000 cycles, therefore 6% or 0.6 kWH per year, i.e., 300 cycles). When the battery cycle life is assumed to be 3000 cycles for a 60% SOC swing, the impact of battery capacity fade is seen only in the final 5 years of the vehicle. Decreased driving, slower rate of battery capacity fade (20% or 2 KWH in 3000 cycles, therefore 2% per year) after end of life, and discounting rate of 7% for NPV value calculations results in the 30 and 40 kW energy management strategies having higher NPV savings as compared to the 20 and 25 kW cases.

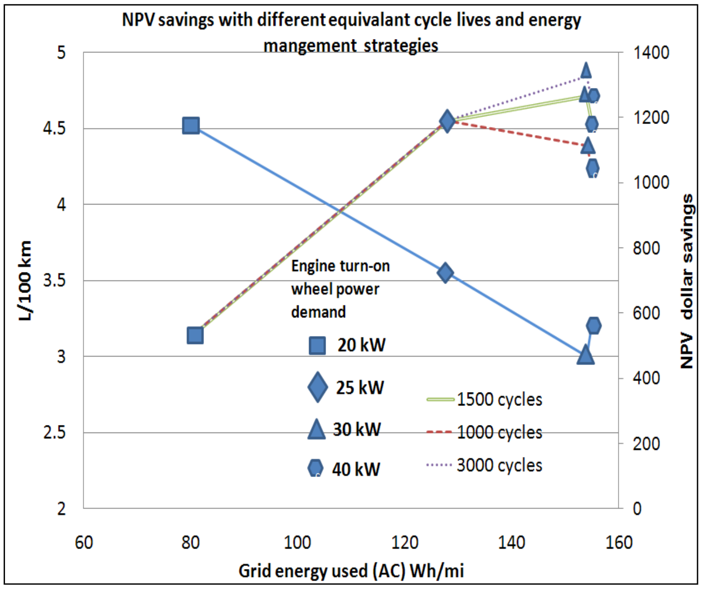


Figure 11: NPV savings for different energy management strategies for equivalent cycle lives of 1000, 1500, and 3000

It can be observed from Figure 11 that there is hardly any difference between the PHEV NPV savings of the 1500 and 3000 cycle life case. This would suggest that the NPV results are dominated by the daily gasoline savings, and not so much by battery life, even though the battery capacity fade is twice as fast for the 3000 cycles case as compared to the 1500 cycle case. This is again because of the factors mentioned earlier - graduate decrease in battery capacity, lower vehicle usage in later years negating impact of capacity fade, and lower NPV of dollar differences in the later part of the vehicle life, due to the discount rate. Another important factor that limits the impact of battery life is driving distance, which will be addressed later in the study.

<u>Impact of battery power fade with life</u>

Battery power also decreases with aging of the battery. Tests conducted on the VL41M [15] show that power fade is a linear function of number of deep discharge cycles. For the energy management strategies considered in this study, the engine turns on at 20, 25, 30, and 40 kW of wheel power demand. Therefore, as long as the battery has enough power to provide 20, 25, 30, and 40 kW of power, the impact of power fade will not be seen when driving the LA92 with the energy management strategies. However, the 0-60 times of the vehicle will significantly change with power fade, the vehicle response will be sluggish. It could be argued that the main reason for battery replacement might be vehicle performance degradation and not fuel economy degradation, provided the ECU does allow the vehicle to use all of the battery power. Therefore, a complete NPV comparison should consider a cost associated to performance degradation along with the calculations presented above. Due to time constraints, and due to the fact that the cost analysis here is focused on battery use for the LA92 cycle, the performance degradation was not considered.

CASE 2: NPV SAVINGS COMPARISON FOR THE FOUR CONTROL STRATEGIES FOR DIFFERENT DISTANCES

In Case 2, the NPV savings from the four control strategies are compared for different distances, over a range of 10 miles to 100 miles of daily driving. The vehicle life is 15 years or 150,000 miles of driving, whichever comes sooner. For example, if the daily distance consists of 100 miles of driving, and there are 300 such uses per year, then yearly distance covered is 30,000 miles, and the vehicle would reach end of life in 5 years. However, the number of battery deep discharge cycles would still be 300*5= 1500 cycles. Therefore, one can imagine that in such a case, the battery would still last the entire vehicle life without any capacity fade. As daily distance increases, the battery discharges from the initial SOC of 90% to the final SOC of 30% in CD mode, and then covers the rest of the distance in CS mode. An important assumption in the above reasoning is that the battery temperature rise does not increase with distance, i.e. the battery temperature reaches equilibrium with the ambient due to the cooling loop, and since increased distance forces increased CS mode of operation, the battery utilization is low for the CS part of the journey.

For the comparison of energy management strategies for different distances, it is assumed that the equivalent battery cycle life for a 60 % SOC swing is 1500 deep discharge cycles. For the different engine control strategies, (engine turn ON thresholds of 20 kW, 25 kW, 30 kW and 40 kW), the battery will be discharged to a different depth of discharge for a given distance. If the vehicle drives the given distance every day, this will result in a cycle life based on the distance covered; since the battery discharges to a different SOC for each strategy, each strategy results in a unique cycle life. For example, in Figure 12, the 20 kW engine turn ON strategy results in a certain SOC swing as a function of distance. Therefore, for each distance, there is an estimation of equivalent cycle life. Using the equivalent cycle life for each distance, and the fuel consumption numbers for the energy management strategy (CD and CS), the NPV, for that control strategy and distance can be calculated.

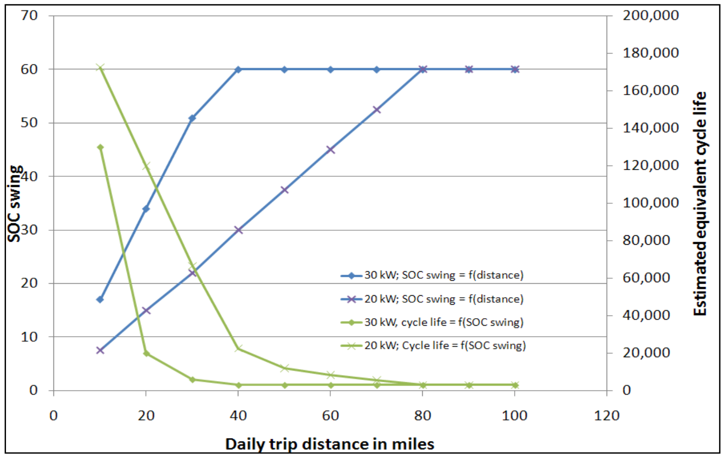


Figure 12: SOC swing and corresponding cycle life as a function of distance, for two different energy management strategies

The dollar NPV savings, for a 25 kW engine turn -on strategy, with and without battery life effects, is shown in Figure 13.

From the curve, it can be seen that the highest NPV savings are obtained for the distance where the vehicle uses its full battery CD capacity (60%) and covers the least distance in CS mode. For the 25 kW case, the NPV savings are highest for the distance traveled of 50 miles. For longer distances, the CS distance traveled goes on increasing in proportion to the CD distance traveled, and therefore the NPV savings decrease. As noted earlier, the maximum vehicle life is defined as 15 years or 150,000 miles, whichever comes earlier. For very low daily distances, such as 10 miles and 20 miles, the vehicle miles traveled over its life are less than 150,000, and therefore the NPV savings are low. Also, the battery utilization for the low distance cases is low, resulting in lower NPV savings.

The orange curve shows the NPV savings with an assumption of infinite battery life, and the blue curve shows NPV savings with a battery life assumption of 1500 cycles, if the SOC swing for the distance is 60%. The reason for battery life effect on the NPV savings can be analyzed by studying Table 6.

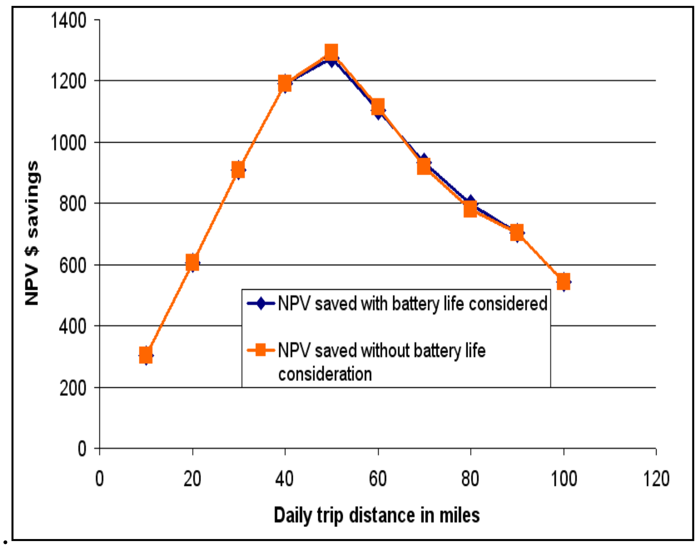


Figure 13: NPV savings for a 25 kW engine turn ON strategy over different distances

Table 6: Impact of Battery Life on NPV saved, for different daily distances

Daily distance in miles	SOC swing per use	Vehicle life in years; the minimum of 150,000 miles and 15 years - whichever is earlier.	Equivalent battery cycle life as a function of SOC swing per use. (Battery capacity fade impacts NPV savings if # battery cycles greater than this cycle life number.)	Battery cycles over vehicle life = vehicle life in years * 300 battery cycles /year	Impact of battery life on NPV savings?
10	12	15	75000	4500	No
20	24	15	25000	4500	No
30	36	15	9000	4500	No
40	48	12.5	3750	3750	No
50	60	10	1500	3000	Yes
60	60	8.33	1500	2499	Yes
70	60	7.14	1500	2142	Yes
80	60	6.25	1500	1875	minimal
90	60	5.5	1500	1650	minimal
100	60	5	1500	1500	No

Consider the daily driving distances of 10 to 40 miles. With a wheel power demand of 25 kW, at which the engine turns ON, the battery SOC swing is less than 60% (Column 2). Therefore, using Figure 3, the equivalent battery cycle life (Column 3) is greater than the vehicle life expressed as number of deep discharge cycles (Column 5). The vehicle life in years is multiplied by 300 (and therefore # deep discharge cycles per year) to calculate the vehicle life as number of deep discharge cycles. Since the battery life is greater than vehicle life, the battery does not see an 'end of life' and therefore battery capacity fade has no impact on NPV savings.

Consider the last row in Table 6, where the daily distance is 100 miles. In such a case, the vehicle life of 150,000 miles would be reached in 5 years, and therefore, the number of deep discharge cycles the battery would go through (300 uses per year, 1 deep discharge cycle per use) is 300*5= 1500; i.e., vehicle life in terms of number of deep discharge cycles would be 1500 cycles, which is exactly the battery cycle life for a 60% SOC swing. Therefore, the battery does not reach EOL before the vehicle, and battery capacity fade impact is not seen on NPV savings.

For the daily distances in between 50 to 90 miles daily, the number of cycles the battery is subjected to (Column 5) is slightly greater than battery cycle life of 1500 cycles over 60% SOC swing. The maximum number of cycles that the battery is subjected to is 3000, that is twice of the cycle life of 1500. With a capacity fade rate of 20% over 1500 cycles, 3000 cycles would result in a 20% drop in useable capacity of the battery. But the impact on NPV savings is not significant. Again, as daily distance increases, the number of cycles the battery is subjected to goes on reducing, and short vehicle lives help in reducing the impact of battery capacity fade. If Figure 13 is observed closely, it can be seen that the orange curve deviates from the blue curve only for the distances of 50 miles to 90 miles.

To summarize, battery life has no impact when the daily distance traveled is less than CD range, since the low SOC swing results in long battery life. If the daily driving distance is very large (80/90/100 miles), the impact of battery capacity fade is again low since the short vehicle life (in terms of number of years) results in minimum battery fade. The NPV savings for such distances are lower because of the long CS operation. The impact of battery capacity fade can be seen for distances in between (i.e., 50 miles to 70 miles for the above case); however, the impact depends on rate of battery capacity degradation.

Figure 14 compares the NPV savings for energy management strategies of 25 and 30 kW. For each curve, the maximum NPV savings are obtained for the distance at which the vehicle uses its full battery CD capacity (60%) and covers the least distance in CS mode. For the 25 kW case, the NPV savings are highest for the distance traveled of 50 miles, and for the 30 kW case, the NPV maximum NPV savings are for a distance of 40 miles. For distances lower than 40 miles, the higher battery utilization of the 30 kW case results in higher NPV savings. For distances greater than 50 miles, for example for a distance of 80 miles, the CD to CS distance ratio of the 25 kW case is higher than the CD to CS ratio of the 30 KW case. Therefore, since for the 30 kW case a larger portion of the 80 miles daily travel is covered in CS mode, the NPV savings are lower than the 25 kW case.

Therefore, it can be seen that based on the daily distance traveled, one strategy can be preferred over another.

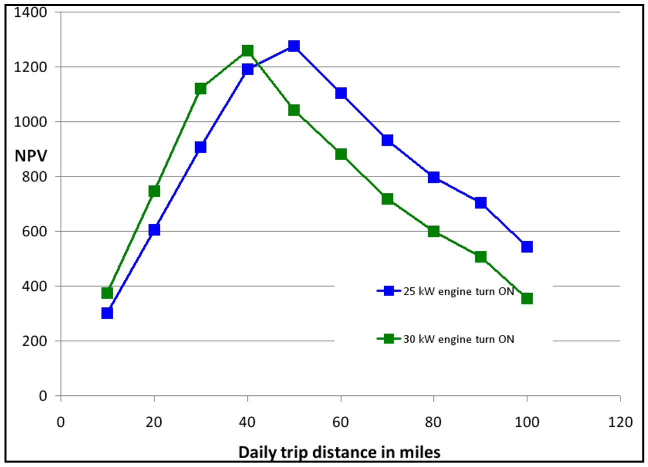


Figure 14: NPV savings of 25 kW and 30 kW engine turn -ON strategies for different daily distance traveled

SUMMARY OF THE EXPERIMENT

This study identifies the impact of energy management strategy on battery life and gasoline savings of a PHEV. NPV calculations of gasoline dollar saved by a PHEV over its vehicle life, when compared to a CS hybrid, are calculated for different energy management strategies, with an attempt to identify the optimum energy management from a battery life and gasoline savings' perspective.

Battery HIL is used to identify energy management strategies that result in comparable temperature rises for a liquid cooled VL41M pack in a virtual power split vehicle, so that battery ' equivalent cycle' life is a function of SOC swing per use. In order to account for battery life degradation due to non-vehicle related external factors like storage energy level, temperatures etc, three 'equivalent' cycle lives are chosen for the NPV calculations.

The different energy management strategies are initially compared for a fixed driving distance of 40 miles of the LA92 cycle. It is observed that the optimum energy management strategy (that gives the highest NPV savings) varies with the 'equivalent' cycle life assumption; the strategy that provides for maximum petroleum displacement per day might not be the most optimum strategy. This study analyses the impact of battery life on the NPV savings for the fixed distance cases.

The control strategies are compared for NPV savings for distances ranging from 10 miles to 100 miles of daily driving. The gasoline saved per trip has a larger impact on NPV savings as compared to battery life. This is because battery life impacts the savings only in a small range of distances, as described in the section earlier. Even in this range, the impact is small. It is also observed that different energy management strategies provide maximum NPV savings at different distances traveled.

FUTURE WORK

The analysis above is subject to assumptions on gasoline and electricity costs. The NPV savings will change significantly with changes in either of the above, or changes in consumer charging behavior, number of charges per year, etc. Therefore, it is important to perform a sensitivity analysis of the NPV calculations for the above factors. As mentioned in this study, degradation of battery power would have vehicle performance implications, and therefore, a cost should be associated to the performance degradation and added to the NPV calculations. With further data about the behavior of battery capacity and power with aging, the assumptions on battery life in this study could be refined, and a more NPV analysis is possible. The work in this study is based off a battery that was produced in 2006, and with the constant improvement in battery technology, the relationship between battery cycle life and SOC swing might be different. Therefore, the study could be conducted again for a different battery technology. If battery temperature rise can be incorporated into the battery life estimation, the study can be extended to even larger variations in energy management, and would lead to more accurate NPV comparisons.

CHAPTER III

INTERNSHIP PROJECT- PHEV ENERGY MANAGEMENT STRATEGIES AT COLD TEMPERATURES WITH BATTERY AND ENGINE TEMPERATURE RISE CONSIDERATIONS*

INTRODUCTION

Impact of cold temperature on PHEV fuel efficiency has been previously published, for chassis dynamometer tests [23] as well as on – road testing [24]. Seasonal temperature variations in the northern cities in continental United States and around the world have established the significance of this cold temperature impact [23]. This is due to the restriction on battery power by the Battery Management System – BMS) to preserve battery life [25] by preventing lithium plating on the anode due to a reduction in the intercallation process. Restriction in battery usage results in lower regenerative braking and lower propulsion power by the battery, causing a decrease in the fuel savings expected from PHEV operation. As the electrochemical reactions slow down at low temperature(Arrhenius law) , higher activation energy is required for charging and discharging , which is reflected as an increase in internal impedance of the battery. This may cause a decrease in usable capacity of the battery, based on the SOC swing allowed in the charge depleting (CD) mode of operation. Due to the above reasons, there is a lot of emphasis on improving the battery temperature by using thermal management techniques. Several methods have been proposed to increase battery temperature, which include thermal preconditioning [26], keeping the battery warm though over-night charging, active heating of the battery through heating channels [27]. Recent publications by Argonne National Laboratory and others have shown that there is a significant penalty on PHEV fuel economy at cold engine temperatures due to low engine efficiency [28], [29]. Therefore, there is an incentive to increase the engine temperature in a PHEV operation, as well.

Numerous studies have focused on optimum energy management of PHEVs to achieve one or more of the following goals:

1. Maximize overall system efficiency [30], [31] over a certain daily travel, at normal ambient conditions.

2. Maximize utility factor (U.F.) weighted fuel economy [32].

3. Mitigate the impact of cold (at normal ambient temperatures) engine starts on emissions [33].

4. Maximization of Net Present Value (NPV) savings of a PHEV [34].

The intent of this study is to see if different vehicle energy management strategies cause a difference in battery warm-up time, engine warm-up time, and the result of this difference in on PHEV fuel and gasoline consumption over a fixed distance. While previous studies have established that charge-depleting operation until the end of driving distance (no charge sustaining operation) is the preferred energy management strategy for optimizing PHEV powertrain efficiency, (for a known drive profile) this study examines if this point of maximum powertrain efficiency changes due to the cold initial temperature. For this study, the battery warm-up is due to the heat generated by the ohmic losses (Joule heating), and not due to any external heating of the cell or pre-warming of the battery. While battery utilization varies with energy management, the battery power limits recommended by the BMS are strictly adhered to. Differences in battery utilization result in differences in engine utilization, over a fixed drive cycle and fixed distance.

DESIGN OF EXPERIMENT

Modeling and simulation techniques will be used to determine the impact of energy management strategies on battery temperature rise, engine temperature rise, and ultimately on the PHEV fuel efficiency over a fixed drive cycle , driving distance.

A powersplit plug-in hybrid vehicle, built in AUTONOMIE [35], is used for this experiment. The vehicle is a Prius powertrain with the battery replaced by a 41 Ah Li-ion battery. Specifications for the battery which replaces the Prius battery pack, is included in Table 7 on the next page.

Table 7: PHEV Battery Specifications

Parameter	Value
ESS power (kW)	60 kW at 50% SOC for 30 seconds (physical battery)
Battery energy (kWh)	10.66
Battery Capacity (Ah)	41
Total vehicle test mass (kg)	1,549

The vehicle runs over consecutive LA92 cycles over a fixed distance. The initial temperature of the vehicle, engine and the battery at the start of the simulation, is -6 °C. It should be noted that reference to 'cold battery' or 'cold engine' indicates that the initial temperature of the said components is -6°C. The battery and engine temperatures increase with time, providing a larger power envelope and higher efficiency, respectively.

The engine, for the vehicle under consideration, turns ON based on a certain value of wheel power (road load) demand, i.e. the engine turns ON when a certain value of wheel power demand threshold is crossed. Different blended mode scenarios (different engine and battery utilization scenarios) are created by changing the vehicle controller parameter which turns ON the engine based on vehicle road load demands (wheel power demand). The engine also turns ON due to the generator speed limit. For each energy management (different engine turn ON thresholds based on road load demand), fuel consumption and battery utilization are compared. When the vehicle operates in the CS mode, the wheel power demand threshold, at which the engine turns on, is the same, in order to balance the battery SOC.

The study is conducted in three parts:

For the first part, in order to isolate the impact of battery temperature rise and engine temperature rise on the PHEV fuel and electrical energy consumption, 4 sets of simulations are performed. For each set of simulations, the vehicle is subjected to 40 miles of LA92 driving for the same set of engine- ON thresholds. The four sets of simulations are:

Baseline simulations using a scenario with an engine, and a battery at normal ambient (20 °C) temperature.

Simulation with a cold battery (-6°C) and an engine at 20 °C, to isolate the impact of a cold battery.

Simulations with a battery at 20°C and an engine at an initial temperature of -6 °C, to isolate the impact of a cold engine.

Simulations with both a cold battery and a cold engine (both at -6°C).

In the second part, powertrain efficiency is calculated for the normal ambient conditions for different engine ON thresholds and compared to the powertrain efficiency when both the battery and the engine are cold. For the case of the cold engine and cold battery, the point of highest powertrain efficiency, which represents the trade-off between engine efficiency improvement and battery utilization, is identified. The vehicle is subjected to 40 miles of LA92 for this part of the study.

In the last part of the study, the impact of system parameters, like cycle aggressiveness, drive distance, battery power on the cold temperature performance of the vehicle are evaluated. The cold temperature behavior of the engine and the battery are modeled using data gathered from cold temperature testing, and the modeling methods and assumptions are outlined below.

ASSUMPTIONS

In a real vehicle, the electrical and gasoline fuel economy at cold temperature is impacted by the lower efficiency of the rest of the powertrain (apart from the engine and the battery). Since this study is a comparison of vehicle behavior under different settings of engine ON due to wheel power demand, decrease in efficiency of the rest of the powertrain is a common factor, which can therefore be neglected. Also, engine (ECU) operation at cold start (rich combustion, spark retard) to increase engine temperature and exhaust temperature for catalyst light-off has not been modeled. As stated earlier, numerous methods have been implemented to provide external heating to the battery. For the cold temperature scenario, it is assumed that there is no external heating method. The rise of battery temperature is on account of the heat generated by the battery itself (joule heating). It should be noted that the aim of this study is to compare different engine and battery utilization scenarios for their impact on battery temperature rise, engine temperature rise at cold temperature. Therefore, the above assumptions do not impact the results of the ‘apples to apples’ comparison. Details of the battery and engine thermal model are laid out in the next section.

The energy required to heat the cabin is a significant accessory load for cold temperature operation, and has an impact on the fuel efficiency of the vehicle. For this study, the following assumptions have been made to account for the energy required to heat the cabin:

The vehicle has a PTC heater core as well as a regular heater core to heat the cabin using engine coolant heat.

The engine coolant is used to heat the cabin of the coolant temperature is above 65°C. If the coolant temperature is less than 65 °C, the PTC heater is used to provide heat to the cabin.

While actual data on exact heating load demand versus time could not be obtained, assumption on accessory load power demand is based previously published data [36], [37]. It is assumed that the cabin heating accessory load is constant at 4 kW for the first 100 seconds of the cycle, and then reduces gradually reduces to 400 W as the cabin warms up (Figure 15 depicts the load profile for the first 600 seconds). As stated earlier, the PTC heater and the engine share the cabin heat load based on engine temperature.

MODELING OF THE THERMAL BEHAVIOR OF THE ENGINE AND THE BATTERY

MODELLING OF BATTERY TEMPERATURE RISE

As stated earlier, the battery temperature rise is solely a function of heat generated by the battery, based on battery utilization. Battery temperature data from cold temperature evaluation of the JCS VL41M [38], [39] (41 Ah, 260 V Nominal), has been used to generate function which calculates temperature rise as a function of $\int A^2 dt$ where A is the battery current in Ampere.

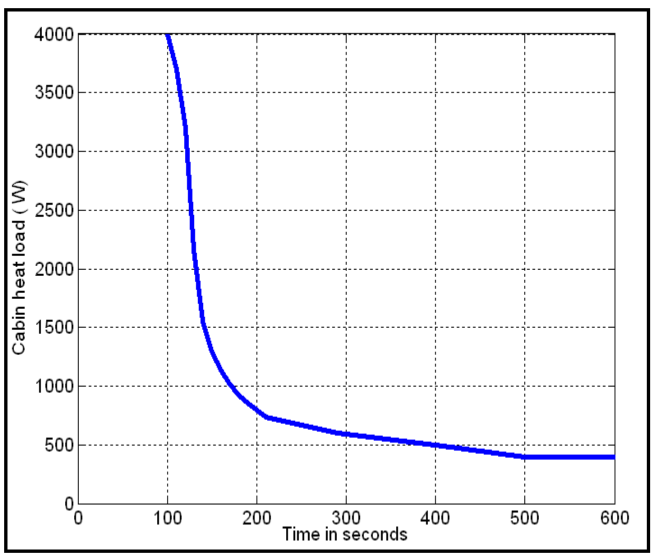


Figure 15: Cabin heat load demand for the first 600 seconds

Figure 16 shows actual recorded temperature rise which has been used to generate the equation (6).

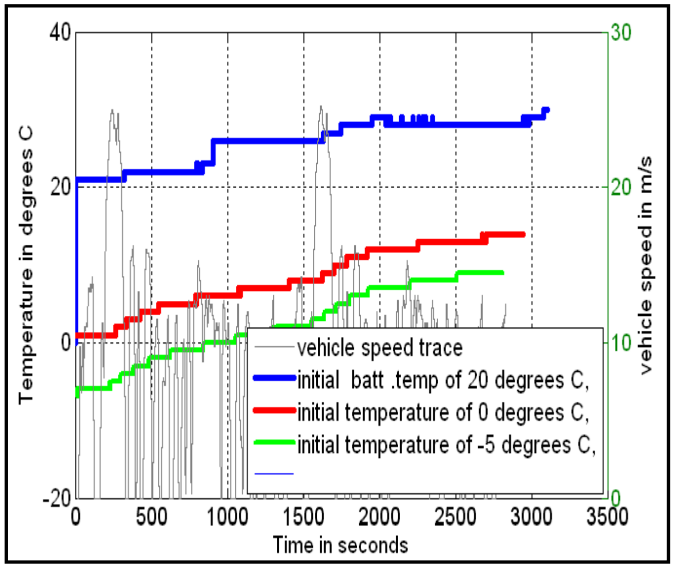


Figure 16: Battery temperature data from the testing of the PHEV 41 Ah battery, used to model battery temperature rise behavior

For this simple temperature rise model, it is assumed that battery temperature rise is solely driven by the battery current, and that other factors which impact temperature rise (changes in ambient temperature etc) can be neglected, in comparison to the battery current. The battery cells are surrounded by the coolant bladder/jacket, and hence the coolant jacket acts as an insulator preventing external factors from impacting the cells. The coolant is not being circulated at the cold temperatures. While other more accurate methods of modeling battery temperature rise, including finite element analysis, are possible, such detailed modeling is not needed for the comparative study being considered in this study. The relation between temperature rise and $\int A^2 dt$ is given by the following equation:

$$T = T_0 - aT_0 \int A^2 dt + b \int A^2 dt \qquad (6)$$

where

T = Battery temperature.
T_0 = Initial battery temperature (-6$^o C$).
a, b = Constants with values 0.06×10^{-6} and 2×10^{-6} respectively.

MODELING OF ENGINE THERMAL BEHAVIOR

Response surface modeling techniques (RSM) were applied to experimental vehicle data collected over several cycles while operating in a 266°K ambient temperature test cell over both the urban dynamometer driving schedule (UDDS) and the US06 Federal Test procedures. Using the data collected, engine speed, load, and engine coolant temperature were selected as input variables to the fueling estimate, and the engine fueling rate was measured at each value of the input variables during the cycle. These data were then used to generate the response surface output of BSFC. . Figure 17 gives an overview of the engine operating points used to create the fueling RSM. The response of engine fueling rate as a function of the engine speed, load, and coolant temperature was best fit modeled as a quadratic polynomial including several interaction terms.

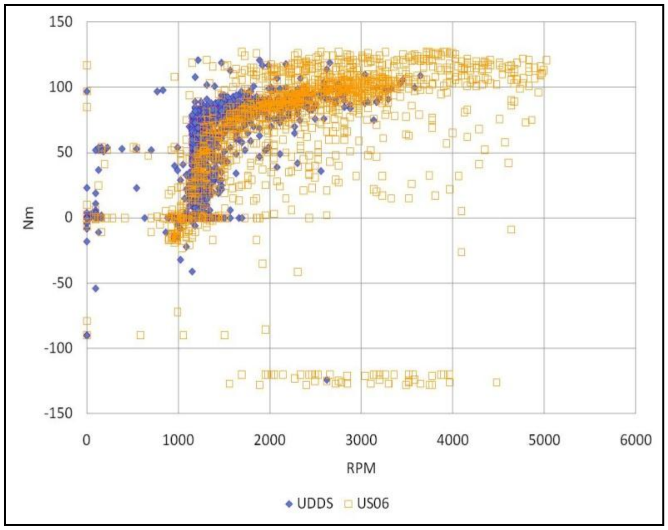


Figure 17: 2008 Toyota Prius Hymotion PHEV conversion 266 K cold start UDDS and US06 cycle cold start speed/brake load test points.

Results of the integrated model fueling rate versus actual data for a 266°K cold start UDDS cycle are shown in Figure 18. From this plot of fuel consumed versus time, the fueling estimate can be seen to match the experimental data very closely. The coolant temperature estimate also shows a reasonable match with the experimental data over four back-to-back UDDS cycles. Figure 19 shows the model fit relative to both oil and coolant temperature. The Pearson's co-relation coefficient for the fit (R square) is 0.99. For details on the modeling of engine thermal behavior, interested readers are referred to [28].

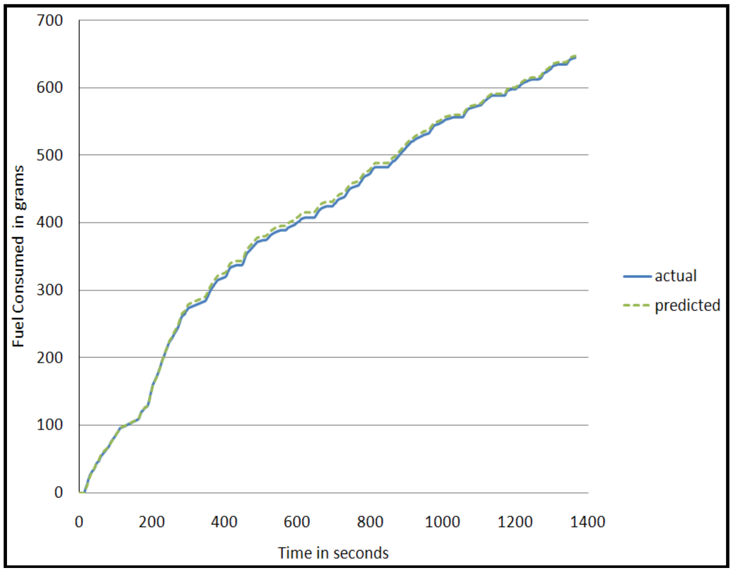


Figure 18: Model predicted fuel consumed, 266 K UDDS cycle vs. actual recorded fuel consumed. Model < 0.4% predicted integrated value from actual data.

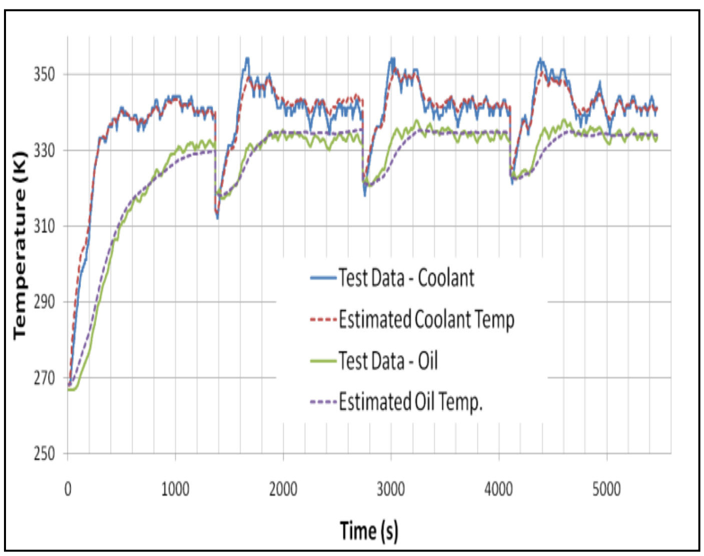


Figure 19: Estimated oil and coolant versus actual data.

SIMULATION RESULTS AND ANALYSIS

IMPACT OF COLD BATTERY, COLD ENGINE ON ELECTRICAL AND FUEL CONSUMPTION FOR A GIVEN DISTANCE

Figure 20 is a plot of fuel energy consumed on the Y axis and battery energy consumed on the X axis, for 20 miles of LA92 driving for engine ON at 15, 20 and 25 kW wheel power demand, at normal battery and engine temperatures (Blue line).The energy and battery consumption for 20 KW engine turn –ON due to a cold battery at an initial temperature of -6°C (engine at 20 °C), cold engine at initial temperature of -6°C (battery at 20°C) , and both cold engine and cold battery is shown by the purple, green and red dot.

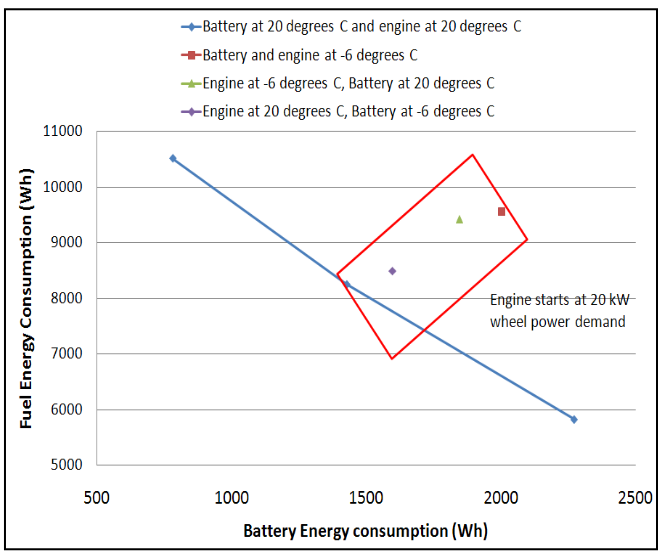


Figure 20: Impact of low temperature of battery and engine (individually and together) on fuel and battery energy consumption for a given distance, and control parameters.

From the plot, it can be observed that when comparing the impact of a cold engine (hot battery) and cold battery (hot engine), the impact of the cold engine and its low efficiency is significantly higher than that of the power restrictions of a cold battery. This can be attributed to two reasons:

1. PHEV batteries have a high P/E ratio, resulting in surplus power given that the battery has been sized for energy to last a certain equivalent electrical range. Therefore, in spite of power restrictions by the BMS at low temperature, the battery can provide sufficient power. This is especially true at an initial temperature of -6°C.

2. Use of PTC heater for the cold engine scenario results in additional use of battery energy, resulting in increase in electrical energy consumption along with increase in fuel energy consumption.

Figure 21 shows the variation in fuel and battery energy consumption for the four scenarios of component temperatures outlined above due to variation in the wheel power demand for engine ON (from 5 kW to 30 kW) for 40 miles of LA92 driving.

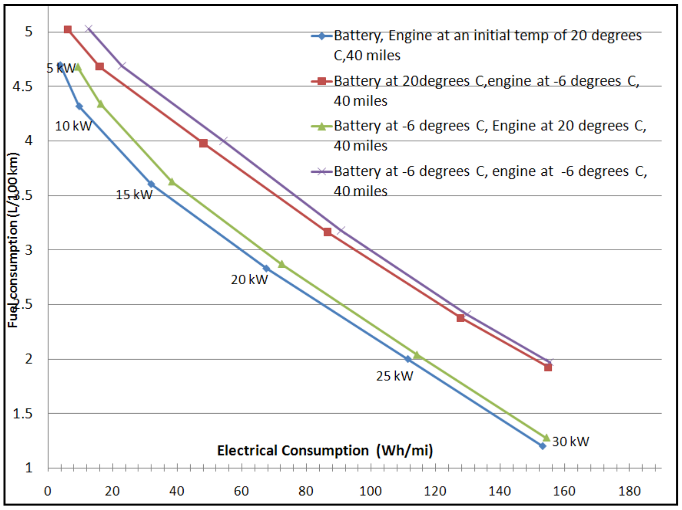


Figure 21: Impact of low temperature of battery and engine (individually and together) on fuel and battery energy consumption for a given distance, different control parameters.

From the above plot, one can see that when the engine turns ON at lower wheel power demands (e.g. 5 kW, 10 kW), the engine warms up faster and therefore the red curve (where the engine ONLY is cold) leans towards the blue (both engine and battery are at normal temperature) curve. In this case, the battery does not warm up fast if the engine turns on at a low power threshold, and therefore the green curve leans away from the blue curve. Similarly, if the engine turns on at a high power threshold (e.g. 25 kW, 30 kW), the engine remains at a lower temperature, and therefore inefficient, and therefore the red curve leans away from the blue curve. The battery temperature rises quickly on account of heavy utilization and the green curve leans towards the blue curve. The curve when both the engine and the battery are cold is a resultant of the green and the red curves. Figure 22 shows the engine and battery temperature rise for the 10 kW and 25 KW engine ON case (both battery and engine are cold), Figure 23 shows the cumulative fuel usage and SOC discharge. Similarly, figure 24 shows the battery power restrictions due to the difference in battery temperature rise for the case in which engine turns on at 10 and 25 kW wheel power demand respectively.

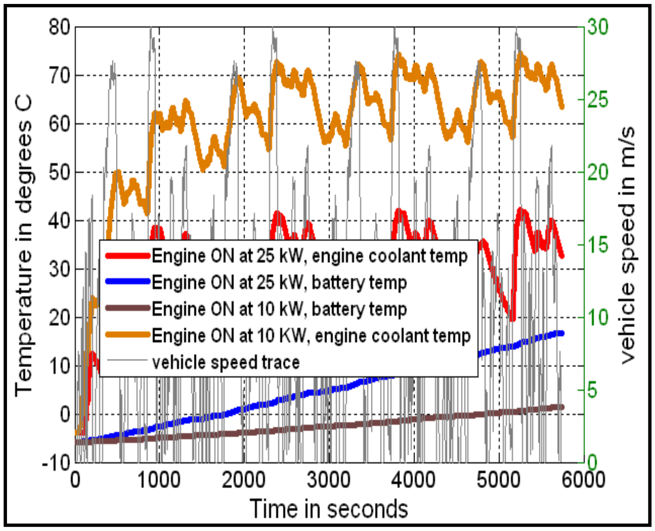


Figure 22: Engine (coolant) and battery temperature rise for engine ON at wheel power demand of 10 kW and 25 KW over 4 LA92 cycles.

Based on the above curves, one can conclude the following:

1. The impact of low engine efficiency is greater than the impact of battery power restrictions at cold temperature, irrespective of engine turn ON power.

2. In order to reduce the impact of a cold engine, it is expected that the engine be used often (lower engine ON threshold), while in order that maximum regen be captured, it is expected that the engine usage be reduced (higher engine ON threshold).

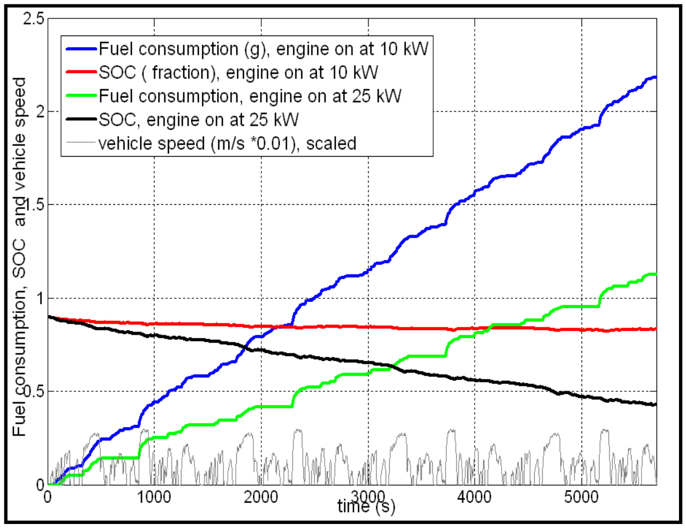


Figure 23: Fuel consumption and battery SOC discharge

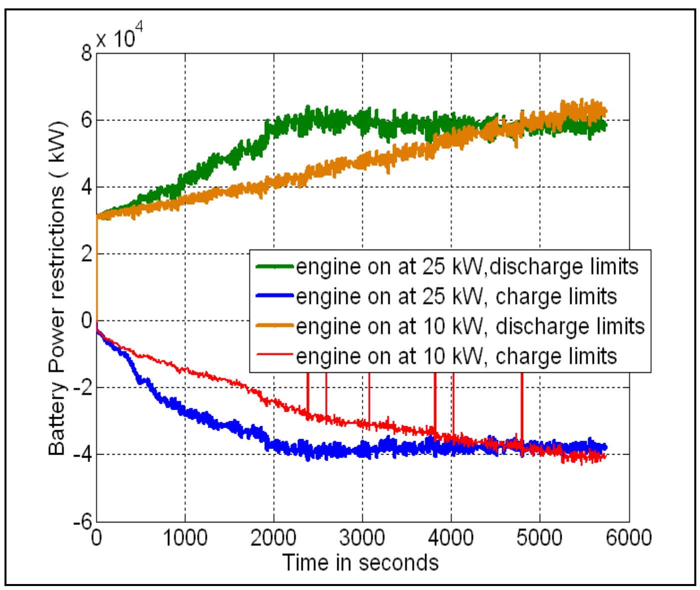


Figure 24: Battery power envelope increasing at different rates based on different battery and engine utilization for engine ON parameter of 10 kW and 25 kW road load.

Therefore, there must be an engine ON threshold which provides the optimum of both engine warm-up and battery warm-up, such that there is improvement in engine efficiency and enough regen energy captured due to quick rise in battery temperature. This wheel power demand for engine turn ON parameter will provide the maximum powertrain efficiency, for a given drive profile over a drive distance. If the engine is turned on later than the optimum engine ON point, the engine will not warm up sufficiently, causing low efficiency related engine losses. If the engine is turned ON sooner than this point, the battery temperature rise is insufficient, and this causes limitations to the regen energy captured, again reducing powertrain efficiency.

<u>Powertrain efficiency for different engine ON parameter settings, to identify the trade-off between engine and battery utilization.</u>

For a given driving profile, the engine ON parameter which offers the best trade-off between battery temperature rise and engine efficiency improvement is the point at which powertrain efficiency is maximum, where powertrain efficiency is defined as

$$Power\ train\ efficiency = \frac{Energy\ at\ the\ wheel}{Fuel\ Energy + Battery\ Energy} \tag{7}$$

For different engine ON parameters, the energy at the wheel will remain constant. Variation in engine ON parameter will result in a variation in engine utilization and battery utilization. A small power threshold for engine ON will result in large amount of engine usage (fuel energy), but result in more efficient engine operation on account of quick engine temperature rise, while a high power threshold will result in lower engine usage and low engine temperature rise.

With increasing battery usage (increasing delta SOC per trip), engine energy consumption decreases. Due to high battery efficiency (and poor engine efficiency, when compared to battery efficiency), power train efficiency increases proportional to increase in battery SOC swing or higher engine ON threshold. For the engine ON thresholds which result in a SOC swing of 60% (maximum usable battery energy), power train efficiency depends on engine efficiency, regent energy captured, and is relatively independent of battery usage. Therefore in the analysis that follows, engine ON thresholds which result in a SOC swing of around 60% are considered. The engine ON thresholds used for Figure 21 is for understanding engine and battery warm-up behavior and the impact of engine ON parameter on the same. Figure 25 shows the powertrain efficiency for different engine ON parameters, for a cold battery and cold engine initial condition, as well as when both the battery and engine are at normal ambient.

The following observations can be made from figure 25:

1. The overall powertrain efficiency decreases significantly due to cold conditions. For a given engine turn ON threshold based on wheel power demand (say engine turn ON at 31kW wheel power demand), the decrease in powertrain efficiency is due to decrease in engine efficiency, decrease in regen power, and the higher PTC load dis-charging by the battery.

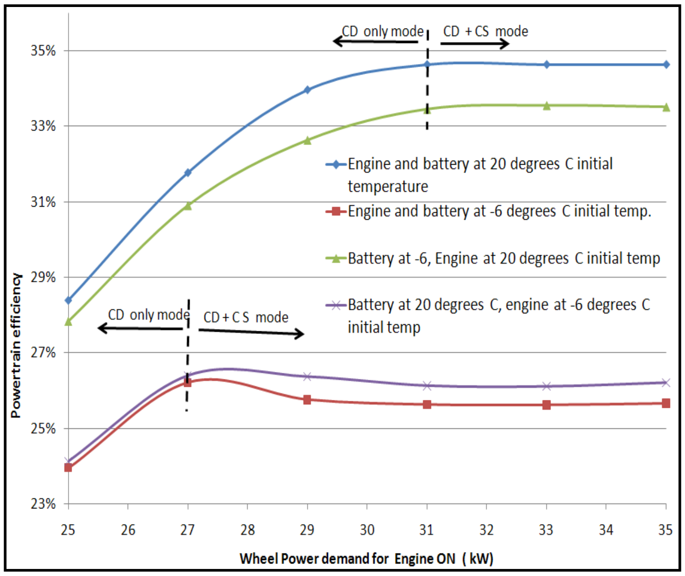


Figure 25: Powertrain efficiency over different engine turn-on thresholds, with cold initial temperatures for the battery and or the engine.

2. For the cold ambient conditions, an engine ON of ~27kW provides CD range for 40 miles (trip distance), while for normal ambient conditions, an engine ON of ~31 kW provides a CD range of 40 miles. Thus, for the cold conditions, the engine has to be utilized more, to provide 'iso-CD range' operation for the consumer.

3. For 'iso-CD range', the engine comes on at a lower power threshold at cold conditions, which means more engine energy is used as compared to hot conditions, which would translate to less energy from the battery. This is due to the PTC load on the battery; less battery energy goes to the wheels, resulting on more engine energy being needed, thus resulting in the need for engine ON at a lower power threshold.

4. For the case when the battery and engine are cold, maximum powertrain efficiency is seen for 27 kW, after which powertrain efficiency decreases, unlike the case when both battery and engine are hot. Additional battery usage (higher engine ON threshold) results in lower engine temperature in CD mode (figure 26), lowering the engine efficiency and increasing fuel consumption (figure 27). If the battery usage is less, the powertrain efficiency decreases as well since the battery is not used completely, for example when engine starts at 25 kW (figure 25, figure 28). Therefore, the trade-off between engine and battery utilization, for the given vehicle, occurs at ~ 27 kW of the control parameter, providing the most powertrain efficiency. It should be noted that this is also the value of the control parameter that results in least distance travelled in CS mode. But, unlike the case for normal ambient conditions, the powertrain efficiency does not remain more or less constant with increase in CS operation, but decreases, although the decrease is about 2%.

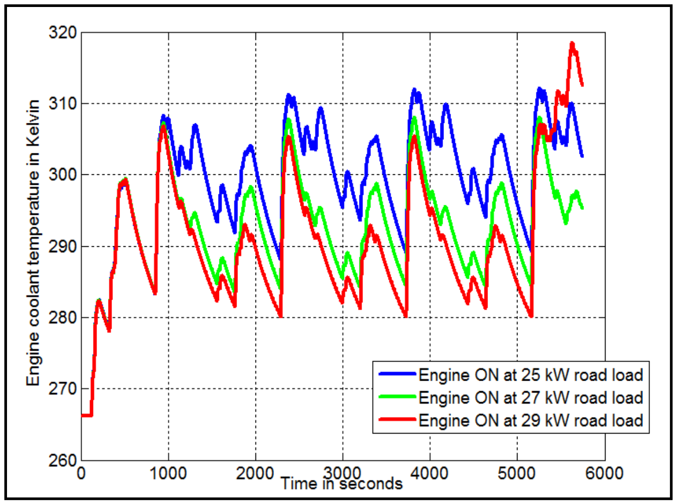


Figure 26: Engine coolant temperature for three values of control parameter – Engine ON at road load demand, for cold engine and cold battery

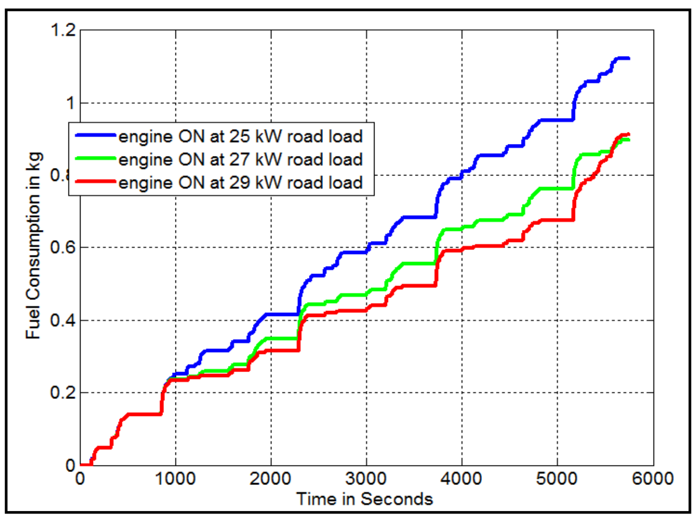


Figure 27: Fuel consumption for three values of control parameter – Engine ON at road load demand, for cold engine and cold battery

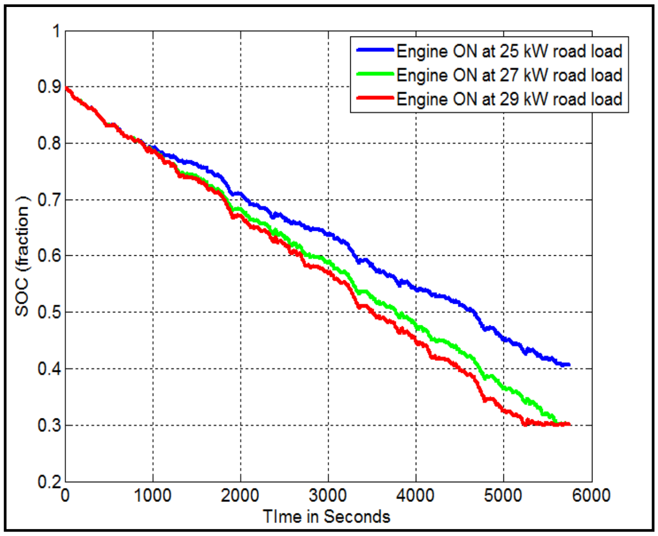


Figure 28: SOC variation for three values of control parameter – Engine ON at road load demand, for cold engine and cold battery.

IMPACT OF VARIOUS SYSTEM PARAMETERS ON THE COLD TEMPERATURE FUEL AND ELECTRICAL ENERGY CONSUMPTION

<u>Impact of driving distance</u>

Figure 29 compares the Fuel and Electrical energy consumption per mile, for the above vehicle driving 10 miles of LA92 and 40 miles of LA92. The dotted lines represent the results for 10 miles of driving.

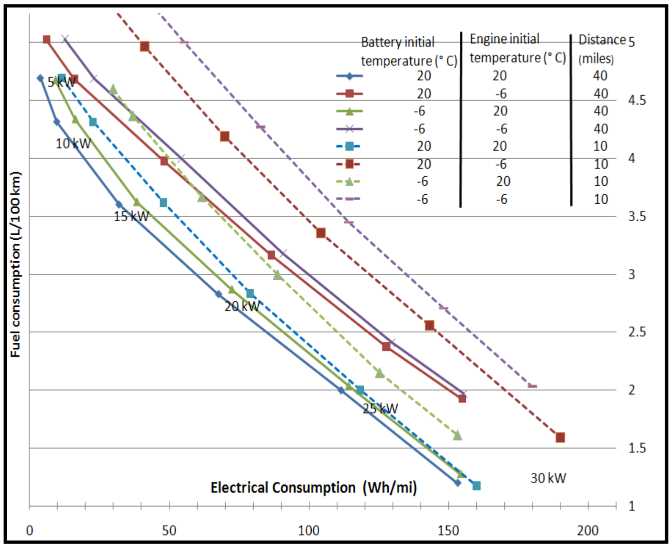


Figure 29: Fuel and electrical energy consumption for 10 miles and 40 miles of driving, for different engine ON thresholds.

From the above plot, the following observations can be made:

1. For a driving distance of 10 miles, the impact of cold battery and cold engine is amplified. This can be anticipated since a shorter driving distance would mean lower time for either the battery or the engine to warm-up.
2. The trends discussed earlier for the 40 miles case (impact of battery cold temperature increases with higher engine usage and impact of cold engine temperature increases with lower engine usage or engine turn ON at a higher threshold) are still observable.
3. For the 40 miles driving distance, the impact of a cold battery was negligible, when compared to the impact of a cold engine. Such is not the case when the vehicle is driven 10 miles. Therefore, preheating the battery would provide substantial benefits for shorter driving distances.

4. A comparison of 20 miles and 40 miles of driving would be somewhere in between the 10 mile and the 40 mile case.

Impact of battery power limitations

The battery power restrictions, as a function of temperature, were varied, as shown in figure 30. The battery power limits were halved and doubled, to see the impact on cold temperature behavior. Figure 31 shows the impact of battery power restrictions on fuel and gasoline energy consumption.

As seen from figure 31, the impact of changing power restriction on the fuel or electrical consumption is minimal. It can be anticipated that the effect of changing power restrictions will be more if the driving distance is short, for example 10 miles or 20 miles.

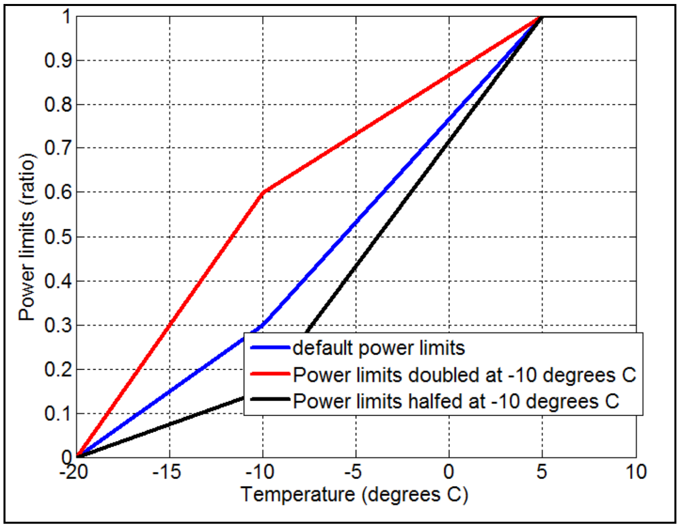


Figure 30: Battery power limit variation at cold temperature.

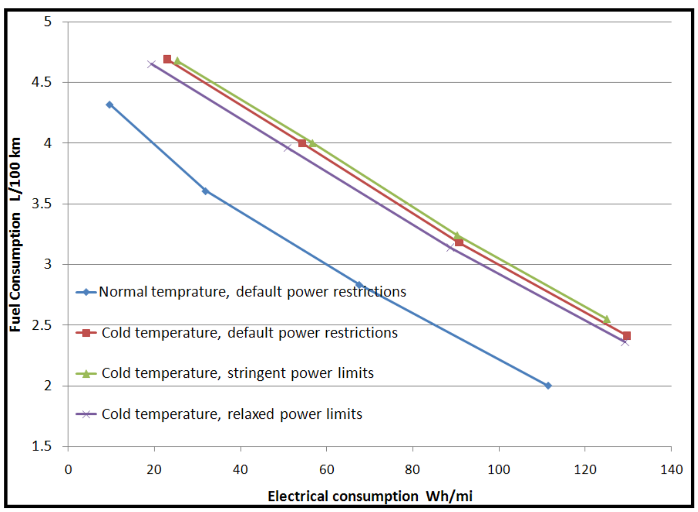


Figure 31: Impact of change in battery power restrictions at cold temperature for 40 miles, LA92.

<u>Impact of drive cycle aggressiveness</u>

All results above have been presented for the LA92 cycle, which represents typical urban driving. It is important to understand the impact of cold battery and engine temperature for more aggressive driving (US06) and a milder drive cycle (UDDS). Figure 32 below shows the electrical and fuel energy consumption, on a per mile basis for the two cycles in comparison to the LA92.

The % increase in fuel consumption, when the engine turns ON at 10 kW, 15 kW, 20 kW and 25 kW road load power , for the UDDS, LA92 and the US06, is given in Table 8. A table can be similarly constructed for the electrical consumption. From the table, it can be seen that the impact of cold temperature on fuel consumption decreases with aggressive driving. This is expected, since higher road load demand leads to higher utilization of the engine as well as the battery, causing quick temperature rise and lowering the impact of cold battery and cold engine.

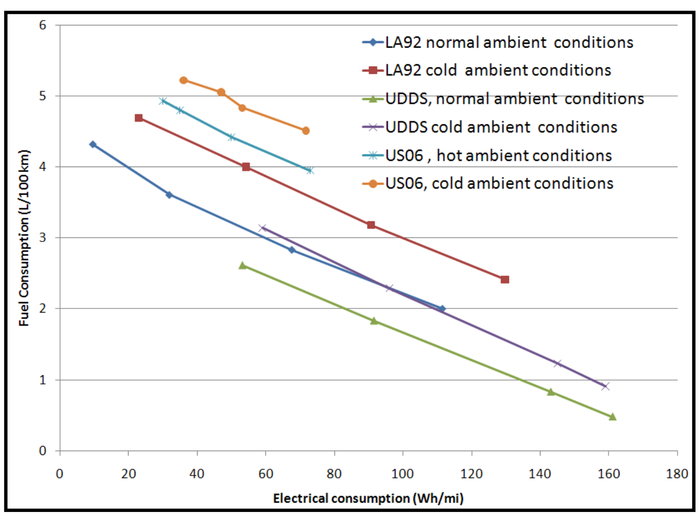


Figure 32: Impact of cold temperature on fuel and electrical consumption for mild and aggressive driving.

Table 8: Percentage Increase in Fuel Consumption due to Cold Conditions for the different engine ON thresholds

Cycle	10 kW	15 kW	20 kW	25 kW
UDDS	25%	25%	48%	89%
LA92	8.5%	10.96%	12.35%	20.61%
US06	5.1%	9%	8.2%	14.7%

SUMMARY AND CONCLUSIONS

This study analyzed the impact of cold battery and engine temperature on the fuel and electric consumption of a power-split PHEV with a Prius powertrain. The battery was replaced by a 41Ah, 10 kWh PHEV battery. Engine thermal behavior was modeled using response surface modeling of cold temperature dynamometer testing of an after-market conversion Prius. Battery temperature rise was modeled from actual data gathered during the cold temperature testing of the VL41M. For this experiment, there is no pre-heating or external heating of the battery.

The impact of a cold battery and cold engine (battery at normal conditions) was isolated. Battery and engine utilization was varied by varying the wheel power demand threshold at which the engine turns ON. Impact of variation in engine and battery utilization on cold temperature fuel and electrical energy consumption, for 40 miles of LA92 driving, was analyzed.

In order to increase engine efficiency, higher utilization of the engine is needed, which results in slow rise in battery temperature due to low battery utilization. High engine efficiency translates to fuel savings, while high battery utilization results in higher battery power (regen and propulsion) available at cold temperatures. An optimum increase in engine efficiency and battery temperature rise would result in the best powertrain efficiency. The powertrain efficiency at cold engine and battery conditions was calculated for different engine and battery utilization scenarios, and the optimum of engine warm-up and battery temperature rise was identified.

Finally, the impact of aggressive driving, driving distance and battery regen limitations on the cold temperature fuel and electrical energy consumption was quantified.

The following conclusions can be made from the study:

1. Cold temperature has significant impact on engine efficiency and battery power restrictions, resulting in higher fuel and electrical energy consumption for a PHEV.
2. The impact of low engine efficiency is more pronounced, when compared to battery power restrictions, for an initial cold temperature of -6°C. Therefore, there is added incentive to turn ON the engine often at cold temperature starts. Engine turn –ON at start-up, and keeping the engine ON at low power thresholds (until the engine is warm) might have fuel economy benefits for the blended mode operation. Quick engine temperature rise also results in a significant decrease in electrical accessory load on account of the PTC heater. This scenario has not been considered in the study. The same behavior might be recommended for catalyst warm-up as well.
3. From the perspective of power train efficiency, the engine ON threshold for optimal powertrain efficiency is lower for cold temperature conditions, on account of the

tradeoff between engine and battery utilization and its impact on engine efficiency improvement due to temperature rise.

4. The heater (PTC) load is a significant electrical accessory load (if the engine coolant temperature is below 65°C), and therefore, change in the battery power limits (as a function of temperature) did not have much impact on fuel or electrical energy consumption. This is because the PTC load overshadows any change in regen energy due to changing regen power limits.
5. Increase in driving distance per trip, the impact of cold temperature on the fuel economy decreases.
6. Impact of cold temperature on fuel consumption decreases with aggressive temperature.

CHAPTER IV

PROJECT MANAGEMENT RESPONSIBILITIES

Figure 33 shows the natural progression of a Department of Energy funded project at Argonne National Laboratory. There are five key steps in every project – idea generation, getting the idea (project) selected into the final list of projects for which funding would be sought, securing the actual funding, and then planning and execution of the project. The author was the Principal Investigator (PI) for both the projects described in the earlier chapters, and therefore had overall responsibility for the five project management steps. This chapter will go into the details of each step.

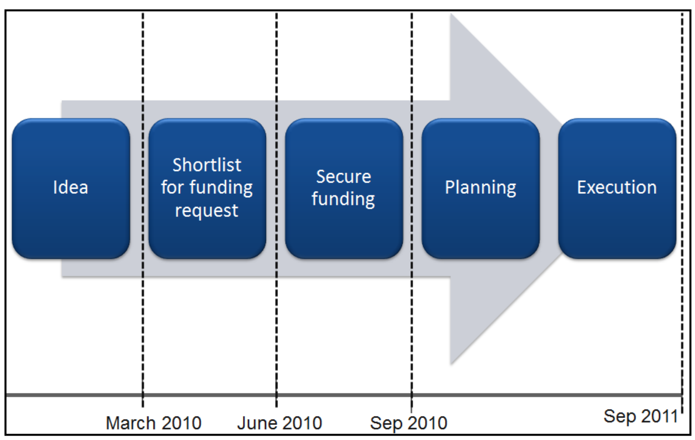


Figure 33: Research Project progression and timeline for a Department of Energy funded project.

IDEA GENERATION FOR THE PROJECT

The research idea is normally generated by the Principal Engineer, or the group manager. Many a times, certain projects are requested by the sponsor, in which case, the idea is formalized through a discussion between the PI, the manager and the sponsor.

Ideas generated by the PI are in a manner similar to any research project; the PI, being familiar with the field of research, knows the relevant, important technical questions or topics that need to be answered. By assessing the resources and facilities at his/her disposal, the PI does a mental 'shortlisting' of project topics that have significant research value, and can be completed within a suitable time frame and with the hardware and people resources available (Fig 34). For ideas beyond those possible with immediate resources at hand, discussion with the manager is encouraged.

SHORTLISTING OF POTENTIAL PROJECTS BY THE SECTION

The manager of the section (in the case of the candidate – Vehicle Systems), holds multiple meetings with the PIs in the section, to finalize on a list of potential projects that would be considered for funding. While the manager has the final authority over the list of projects, general criteria for shortlisting of the projects (Figure 35) include consideration of the overall section goals and priorities, the resources and facilities (hardware and personnel) at disposal, and representation of all areas of research within the section. The manager has to decide on a target funding number ($ amount) to seek from the sponsor, as well as any increase in the staff that must be considered for the projects. Since the PIs are in the best position to judge the need to hire additional staff based on needed skills and manpower, the manager seeks the opinion of the PIs before making such a decision.

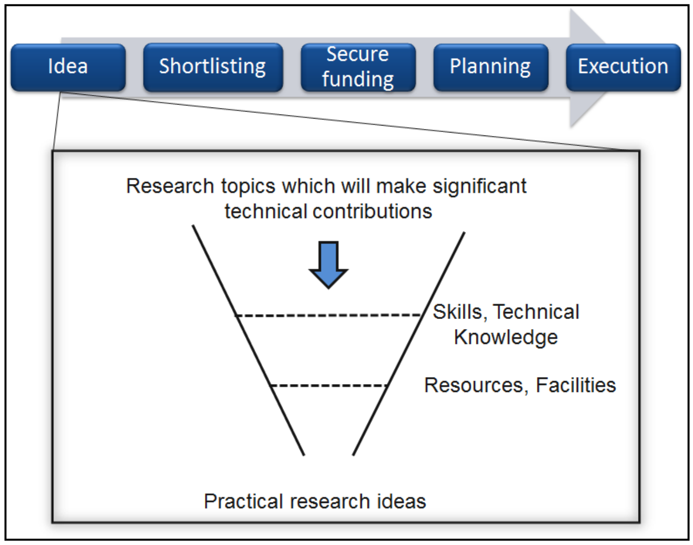


Figure 34: Idea generation by the PI or the manager

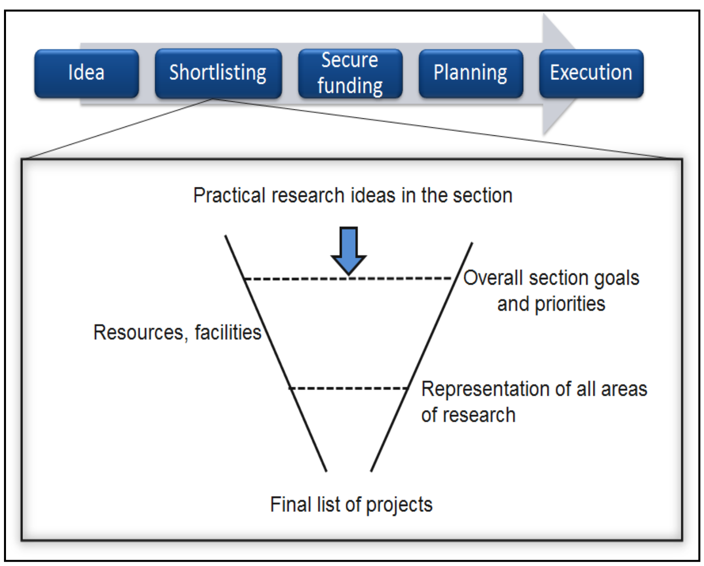


Figure 35: Shortlisting of potential projects in the section

SECURING THE FUNDING FROM THE DOE SPONSOR

Before the beginning of the fiscal year, the manager visits the relevant sponsor at the Department of Energy [40] to discuss the list of projects. At the Office of Vehicle Technologies in DOE, each sponsor is responsible for a key research area, for example batteries, engine and combustion research, vehicle systems, etc. The manager and the PIs explain the technical importance of the shortlisted projects, and their relevance to overall mission and objectives of the DOE office, to the sponsor. The sponsor assimilates the project wish list from all national laboratories working in the area and collectively decides which projects to fund. There are many criteria which go into the decision of the sponsor, including the relevance of the project to overall DOE goals and priorities, collaboration with industry and academia for the particular project, long term research value, etc.

PLANNING OF A PROJECT WHICH WILL BE FUNDED

The PI is responsible for the planning of a project whose funding has been assured by the DOE sponsor. The planning process has to happen before the start of the fiscal year (September) when the actual execution of the project commences. Project planning for the PI involves 4 key aspects:

1. Budget.

2. Personnel.

3. Time line.

4. Reporting results.

The budget outlay of a project depends on personnel, time line and other resources. As such, planning of the three has to be done simultaneously in an intertwined process. The following subsections provide details on the intertwined relationship between budget planning, personnel identification and time line planning.

BUDGET

The PI prepares an estimated budget of the project based on prior experience with other projects. The PI discusses this budget estimate with the manager, and then with the manager's agreement, the budget estimate is provided to the DOE sponsor when soliciting funding for the project. The DOE sponsor may decrease the budget based on his or her discretion. One the final budget numbers for a particular project are disclosed by the DOE sponsor, it is the PI's responsibility to plan the project to fit the available budget. To do that the PI has to gather a team (personnel) and have the team work within a finite amount of time (time planning).

PERSONEL (TEAM BUILDING)

The PI solicits participation from peers who have the necessary skills needed to be a part of the project. This step is performed when the PI is initially proposing the project to the manager, before securing funding from DOE. A verbal commitment from the peers is sufficient at this stage for the PI to propose the project to the manager. It is the manager's responsibility to make sure that resources in the section are not overstretched with a limited number of people accepting participation in multiple projects. If the PI has staff which reports to him, then he has full authority to decide their participation in the project. Argonne National Laboratory being an organization with a relatively small hierarchical structure, most of the research staff is at similar grade level, and therefore work as peers. PIs who maintain good working relationships with peers normally have an easy time getting them to participate in the project.

Once the project funding is guaranteed, the PI holds a kick off meeting with the team members. In this meeting, the participation of each member is laid out in detail, with work responsibilities and time allotted to the work. This discussion enables the PI to allot budget for each person in the team. Once the team members have agreed to the work responsibilities and time of participation in the project, the PI has the authority to ensure that the team members only charge the pre-decided amount of time to the project budget. The kick off meeting is usually discussed over a time line, which has been planned by the PI before the meeting.

PLANNING DIFFERENT STEPS OF THE PROJECT AS A TIMELINE

Before the kickoff meeting, the PI generates an initial draft of the project time line, using available tools like Microsoft Project, etc. The time line is discussed in detail at the kickoff meeting, and details are hashed out with the team members.

Figure 36 shows the time line planning of the Net Present Value (NPV) project. At the kick off meeting, the time line is finalized, and resources are allotted to each task.

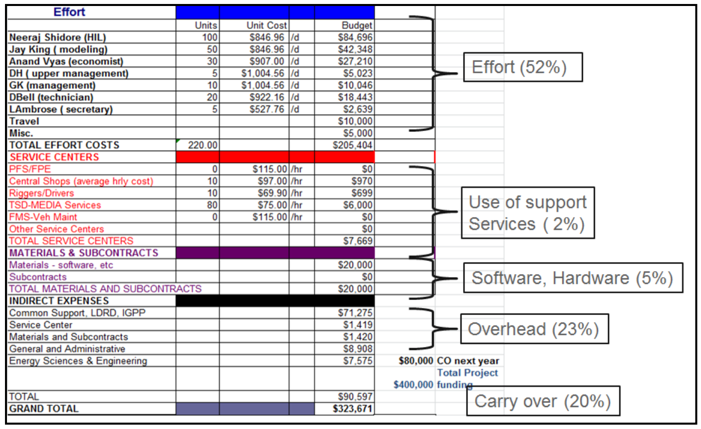
		Task Name	Duration	Start	Finish	Predecessors	Resource Names
1		− Impact of battery life on NPV savings of PHEVs	165 days	Mon 10/4/10	Fri 5/20/11		
2		+ Hardware ready	21 days	Mon 10/4/10	Mon 11/1/10		NS
5		+ Battery HIL safety plan	15 days	Mon 11/1/10	Fri 11/19/10	2	NS
8		+ Virtual vehicle ready	40 days	Fri 9/3/10	Thu 10/28/10		JK
15		Battery life assuptions ready	10 days	Mon 11/22/10	Fri 12/3/10		NS
16		Design of Experiment review	1 day	Mon 12/6/10	Mon 12/6/10	15	
17		− Actual testing of the battery for the powersplit PHEV	54 days	Tue 12/7/10	Fri 2/18/11	5,16	NS,DB
18		Shake down tests - make sure hardware, data logging, postprocessing OK	7 days	Tue 12/7/10	Wed 12/15/10		
19		Engine ON at 1st threshold - 3 runs, 2 days per run	6 days	Thu 12/16/10	Thu 12/23/10	18	
20		Engine ON at 2nd threshold	6 days	Mon 1/3/11	Mon 1/10/11	19	
21		Engine ON at 3rd threshold	6 days	Tue 1/11/11	Tue 1/18/11	20	
22		Engine ON at 4th threshold	6 days	Wed 1/19/11	Wed 1/26/11	21	
23		sanitize all data and test post processing results	5 days	Thu 1/27/11	Wed 2/2/11	22	
24		Review results with team	1 day	Thu 2/3/11	Thu 2/3/11	23	
25		Send data to JCS for battery life estmiation for battery utilization	10 days	Fri 2/4/11	Thu 2/17/11	24	
26		Review JCS feedback with team	1 day	Fri 2/18/11	Fri 2/18/11	25	
27		NPV analysis after testing and life data from JCS available	15 days	Mon 2/21/11	Fri 3/11/11	17	AV,NS
28		Report Generation/Paper	15 days	Mon 5/2/11	Fri 5/20/11	27	NS

Figure 36: Microsoft Project Planning of the Net Present Value Project

REPORTING RESULTS

The PI identifies key technical conferences and journals that would be targeted to report the research findings of the project. Apart from technical presentations, the PI is also responsible for presenting the results to the DOE sponsor at the end of the fiscal year, and keeping the sponsor updated throughout the year.

As stated earlier, the PI is responsible in planning the project within the budget granted by the Department of energy. Also, the kick off meeting, where the participation of each team member is finalized, in terms of technical contribution as well as time allotted to the project, helps the PI plan the budget outlay. Figure 37 below shows an example of the planned budget for the Net Present Value Project, based on the time line in Figure 36.



Effort						
	Units	Unit Cost		Budget		
Neeraj Shidore (HIL)	100	$846.96	/d	$84,696		
Jay King (modeling)	50	$846.96	/d	$42,348		
Anand Vyas (economist)	30	$907.00	/d	$27,210		
DH (upper management)	5	$1,004.56	/d	$5,023		
GK (management)	10	$1,004.56	/d	$10,046		
DBell (technician)	20	$922.16	/d	$18,443		
LAmbrose (secretary)	5	$527.76	/d	$2,639		
Travel				$10,000		
Misc.				$5,000		
TOTAL EFFORT COSTS	220.00			$205,404		
SERVICE CENTERS						
PFS/FPE	0	$115.00	/hr	$0		
Central Shops (average hrly cost)	10	$97.00	/hr	$970		
Riggers/Drivers	10	$69.90	/hr	$699		
TSD-MEDIA Services	80	$75.00	/hr	$6,000		
FMS-Veh Maint	0	$115.00	/hr	$0		
Other Service Centers				$0		
TOTAL SERVICE CENTERS				$7,669		
MATERIALS & SUBCONTRACTS						
Materials - software, etc				$20,000		
Subcontracts				$0		
TOTAL MATERIALS AND SUBCONTRACTS				$20,000		
INDIRECT EXPENSES						
Common Support, LDRD, IGPP				$71,275		
Service Center				$1,419		
Materials and Subcontracts				$1,420		
General and Administrative				$8,908		
Energy Sciences & Engineering				$7,575	$80,000	CO next year
					$400,000	Total Project funding
TOTAL				$90,597		
GRAND TOTAL				$323,671		

Figure 37: Budget planning for the Net Present Value Project

As can be seen from Figure 37, there are four major areas in which the project budget is split up:

1. Effort: Effort is the actual expenses towards the people involved in the project. For each person, the number of days that would be charged to the project is pre-determined in the kick off meeting, and is stated in the budget sheet under the column –Units, i.e. each unit is 1 day. For example, Neeraj Shidore would be charging 100 days to the project, Jay King would be charging 50 days to the project, and so on. The number of days is determined by the contribution of each member to the project. Apart from the actual team members, each project covers some part of the management and secretarial help. Each person, based on the pay grade, has a certain cost associated with each unit (day). For example, for each day that Neeraj Shidore spends on the project, he charges $846.96 to the project. It should be noted that this is not his take home salary, but reflect the amount of money the laboratory allots to a person with a similar pay grade. As can be seen

from figure 37, Unit cost varies with position and responsibility within the organization. Travel and some other incidental expenses are also covered under effort. For the NPV study, the total effort was $205,400.

2. Service Centers: Certain laboratory service centers might be used for the project, for example Central Shops if some hardware fabrication is needed, riggers to move hardware around and so on. Since such expenses can be anticipated in advance, some money is allotted to such anticipated services.
3. Materials and Subcontracts: A budget has to be allotted for the software that will be used for the project. If outside expertise is needed (e.g. University), the PI is then responsible for budgeting a subcontract.
4. Indirect Expenses: These reflect the laboratory overhead. A certain section of the overhead goes to the division, a certain section to the laboratory.

For each project, 20% of the allotted project money is allowed to be retained for next fiscal year (carry over). For the NPV project, $400,000 was the total budget approved by DOE. In order to keep 20%, i.e. $80,000 for next fiscal year, it is the PI’s responsibility to plan the project within $320,000. The PI does this through planning process involving the time planning; kick off meeting with team members, etc.

If the money allotted by DOE is significantly lower than the money actually requested by the PI and the manager, the PI, the manager and the DOE sponsor mutually agree to reduce the scope of work to fit the budget.

EXECUTION

The PI is responsible for the execution of the project. Similar to the planning phase, there are key responsibilities in the area of budget, personnel, time management and reporting the results.

BUDGET

At the end of each month, the secretary provides the PI an updated version of the budget numbers presented in figure 37. Money spent on each task (effort, service centers, overhead etc.) for the month, for the previous months are specified in subsequent columns. End of the year numbers are also projected to help the PI anticipate if the project will be completed within budget or not.

If the PI identifies that any of the team members is charging more than early agreed upon to the project, he can limit the amount charged to the project with the manager's consent. Also, if un-anticipated expenses are encumbered during the year (for example: break down of costly hardware equipment which results in a sharp increase in hardware purchase expenses), which will result in significant budget shortfalls, the PI can request additional budget allocation from the manager. It is the manager's responsibility to move money around within all the projects to make sure that genuine budget shortfalls due to unanticipated events are covered.

PERSONNEL

It is the PI's responsibility to make sure that all the project team members carry out their respective contributions to the project. In most cases, all team members are willing participants in the project and therefore each member acts as a team player, displaying professional responsibility and ethics. This is especially true at a research laboratory such as Argonne, where the technical staff is highly educated (all have a Master's degree or higher) and professional in nature, and driven by the urge to contribute to science. It should also be noted, that many a times, the PI of a particular project, is also a contributing team member of another project. The formation of 'peer' teams for research projects therefore naturally enables a sense of camaraderie and fosters team spirit.

In a particular case, where the PI senses that a team member is not meeting previously agreed upon goals, the PI can request the section manager to intervene.

PROJECT TIME LINE

The PI makes sure that the time line agreed upon in the planning phase is met. If there is any reason for the project to fall behind schedule (e.g. hardware failure), it is the PI's responsibility to bring the project back on track, by motivating team members to spend additional time on the project. The PI regularly briefs the manager and the DOE sponsor on the status of the project. Any delays, with the corresponding reasons, are reported.

A part of the project time line includes peer review of the project. The PI and the project team present the status of the project to the entire section, for review. Suggestions from the meeting are taken into account by the PI, and incorporated into the project plan, if found suitable. If the manager, who also attends the peer review, gets a sense that most of the section is not satisfied with the direction or progress in a particular project, a course correction plan from the PI can be requested. Normally, the peer review of a project happens at three stages:

1. After the initial team planning (kick off meeting): The project plan is presented to the section staff. The staff gets to comment on the concept behind the research, as well as the design of experiment.
2. After initial results are obtained: The initial results are discussed with the section. The section staff gets to comment on method and quality of the experimentation, and on the analysis as well. Suggestions are made by the section on additional analysis, or on correction of certain methods, etc. Additional simulation or testing can be done based on the suggestions of the section staff.
3. Final results and analysis: The analysis and the results are presented as a final presentation. The section staff, already familiar with the project by now, makes sure that there are no glaring mistakes in the philosophy behind the experiment, the testing and the analysis.
4. Dry run of a presentation: If the PI plans to give a project update to the DOE sponsor, or present project results at a technical conference, the PI gives a ‘dry run’ of the presentation to the section. Issues like presentation time, quality and correctness (grammar, punctuation etc.) of the slides, is looked at.

The PI schedules the above peer reviews as a part of the project time line.

REPORTING RESULTS

The PI selects conferences or journals to publish the work done as a part of the project. It is also the PI's responsibility to write the paper and have the team members contribute each of the sections. Normally, the paper is presented at the conference by the PI.

The PI usually makes a couple of visits to the sponsor to update them on the status of the project. The PI also makes an end of the year visit to give a final presentation about the status of the project to the sponsor. In addition, the PI presents the research to visitors from the industry and academia during visits to the Laboratory.

EXAMPLE OF PROJECT PLANNING AND EXECUTION

The candidate was the PI of the said project. The idea to link battery life, vehicle fuel economy together using the net Present Value concept was a unique method of vehicle control strategy evaluation at the time of the project. Following are the key steps in the planning and execution of the said project:

PERSONNEL

A funding of $ 400 K was requested to DOE for the project and was approved. The following team was gathered by the PI to participate in the project:

1. A vehicle modeling and simulation specialist: To build a simulation model of the vehicle .This vehicle model was used for hardware in the loop battery evaluation.
2. Hardware in the loop expert (the PI): To conduct the HIL tests on the SAFT VL41M battery.

3. An economist: To develop the Net Present Value algorithm needed for this experiment, and to generate the results.
4. A technician: To help the PI with the hardware set-up and execution of the experiment.
5. A battery life estimation expert from Johnson Controls – SAFT: To provide guidance on battery life prediction. The expert advice was on a volunteer basis due to the limited nature of involvement.

TIMELINE

A rough time line proposed by the PI was finalized at the kick off meeting. Figure 36 above shows a screen shot of the project time line. The project was executed per the time line. Chapter II lists the project execution and results in detail.

BUDGET

Based on the time line, the PI generated a budget sheet for the project, as shown in figure 37. As mentioned previously, the PI had to manage within a budget of $ 400 K, while reserving 20% or $80 K for carry over into next year. All team members agreed to charge the decided number of days on the project.

It should be noted that the team members are participants in numerous projects, or are PIs of other projects themselves.

REPORTING RESULTS

The DOE sponsors were given regular updates on the progress of the project. In addition, the project was presented at the Department of Energy, Office of Vehicle Technologies Annual Merit Review [40] where the project was evaluated by an independent panel of judges, comprising of members of the academia and industry.

The project results were presented by the PI at the IEEE Vehicle Power and Propulsion Conference, 2010 and at the Society of Automotive Engineers (SAE) World Congress and Expo, 2011.

The SAE paper was selected by the SAE board of editors to be a part of the SAE Journal on Engines [41]. It should be noted that the other study performed by the candidate as a part of the Doctor of Engineering Internship, i.e. energy management for engine and battery temperature rise at cold ambient conditions, was also selected as a journal publication by SAE [42].

CHAPTER V

SUMMARY – TECHNICAL AND PROFFESSIONAL DEVELOPMENT DURING THE INTERNSHIP

During the internship at Argonne National Laboratory, the candidate was the Principal Investigator of two research project. He led a team of two to three engineers to perform the research. The technical merits of the research can be ascertained from the fact that conference papers, presented for both the projects, were later chosen to be a part of journal publications by the Society of Automotive Engineers (SAE). The candidate has also gained significant experience in project management, through time and budget planning as well as execution, to complete both the project successfully in the stipulated time period. An important aspect of managing projects is development of professional skills as a team player and a leader, both of which cannot be documented as explicitly as can be measured by actually seeing the candidate perform the task of a PI.

The candidate also presented the research findings at conferences, to DOE sponsors and lab management, and academia and industry, on various occasions. This led to development of presentation skills, which are important in a research community like a University or a National Laboratory.

The following sections summarize the technical and professional skills gained during the project at Argonne National Laboratory.

TECHNICAL DEVELOPMENT

The candidate gained knowledge in the following areas of advanced vehicle technologies during the internship:

1. Plug-in hybrid electric vehicles (PHEV) –
    a. Operation.
    b. PHEV vehicle Energy Management (vehicle control strategies).
    c. Sizing of powertrain components for a PHEV.
    d. Impact of battery life and temperature on fuel economy benefits.
2. Li-ion batteries for PHEVs –
    a. Theory (electrochemical operation of cells).
    b. Battery management system (BMS) operation.
    c. Current issues facing Li-ion technology-
        i. Life – battery capacity and power fade, cycle life, calendar life, equivalent life.
        ii. Cost.
        iii. Safety.
3. Engineering Economics –
    a. Conversion of fuel economy and electrical energy into equivalent economic indices, based on distance travelled.
    b. Calculation of Net Present Value and its use as an indicator of feasibility of a technology.
4. Engine –

a. Impact of temperature on efficiency.

b. Estimation of fuel flow rate (efficiency) as a function of temperature and engine utilization, using regression analysis on cold temperature testing on a chassis dynamometer.

PROFESSIONAL DEVELOPMENT

1. Project Planning:

   a. Defining technical goals of the experiment, presenting the technical goals to peers (colleagues) for scientific merit and relevance.

   b. Defining a design of experiment for the projects to achieve the said technical goals. Presenting the design of experiment to peers for suggestions.

   c. Team building: Based on the needs of the projects, the candidate approached engineers / scientists to participate in the research. He convinced the said engineers of the technical significance of the project to solicit their participation. As a part of this process, anticipated effort that each team member would eventually to the project budget was also decided. The candidate directed technicians for project related work.

   d. Time planning: The candidate created a detailed time line for the projects (using Microsoft Project) and presented it to the project team and his management. The time planning included important milestones, and assignment of responsibilities to team members.

e. Budget planning: The candidate was for making sure that the budget covered the effort of each of the team members, hardware procurement, technician time, laboratory and division overhead, and other anticipated expenses (conference registration, travel).

2. Project Execution: The candidate was responsible to ensure that the project was executed according to the plan. The responsibilities included keeping his manager updated on the status of the project, and providing information to the management for updating the sponsors.
3. Presentations and Publications: The candidate accompanied his manager to brief the DOE sponsors on the status and outcome of the projects. He also presented the status / results of the project at the Department of Energy's Annual Merit Review, where the project was be reviewed by an independent panel comprising of members from the academia and industry. The candidate presented the results of the experiment at technical conferences and was the lead author on journal papers related to the projects.

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VITA

Neeraj Shidore got his Bachelor of Engineering degree from Government College of Engineering, Pune, INDIA, in 2001. He obtained his Masters in Electrical Engineering from Texas A&M University in 2003, and his Doctor of Engineering degree in 2011. His research includes advanced vehicle technologies, including hybrid and plug-in hybrid electric vehicles.

Mr. Shidore may be reached at 9700 South Cass Avenue, Bldg 362, Argonne, IL 60543. His email address is neerajshidore@gmail.com